Sustainability of Irrigated Agriculture

Edited by

L. S. Pereira, R. A. Feddes,
J. R. Gilley and B. Lesaffre

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edited by

L. S. Pereira

Department of Agricultural Engineering,
Instituto Superior de Agronomia,
Universidade Técnica de Lisboa,
Lisbon, Portugal

R. A. Feddes

Agricultural Engineering Department,
Texas A&M University,
College Station, TX, U.S.A.

J. R. Gilley

Department of Water Resources,
Wageningen Agricultural University,
Wageningen, The Netherlands

and

B. Lesaffre

CEMAGREF,
Antony, France

Springer-Science+Business Media, B.V.

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PREFACE

Irrigated agriculture and the use of water resources in agriculture, face the challenges of sustainable development. Research provided recognized advances in the knowledge of processes relative to water use by crops, soil-water-solutes interactions, as well as in engineering and managerial tools and practices to mobilize, convey, distribute, control and apply the water for agricultural production. However, the achievements obtained in the users practice show the need for new developments leading to resources conservation, control of environmental and health impacts, modernisation of technologies and management, economic viability and social acceptance of changes.

These were the reasons to organize a NATO Advanced Research Workshop which results are described in this book. Authors are among the leaders in the international scene on the most significant areas of irrigated agriculture and of water resources utilization in agriculture. The contributions cover most of the disciplines which converge to irrigated agriculture. Besides multidisciplinarity, the different origin, experience, background, and practice of the authors provide a wide but in-depth analysis of the various aspects of water resources utilization in agriculture.

The papers review scientific , technical and managerial aspects, and highlight main problems, issues and future developments. The different problems related to sustainability are covered, including those of environmental, technical, economical, institutional and social nature. Particularly, the advances in irrigation science and engineering, both on-and off-farm, are dealt with. Special attention is paid to the different components of water quality management and to the transfer of technologies and to capacity building.

Based on the discussions held during the Workshop, a Research Agenda on sustainability of water resources utilization in agriculture has been prepared, which is included in this volume. The editors hope that the research priorities identified will help the scientific and research communities to reorient innovation towards the sustainability challenges.

To ensure coherence between the invited papers, all have been reviewed and edited, assuring scientific soundness of the contributions. The editors thank the authors for reviewing the papers of their colleague authors and for incorporating in their papers the final editorial comments. The quality of this volume also results from the careful preparation of the camera-ready manuscripts by Mrs. Maria Manuela Correia and Mrs Sylvie Vivien-Huet. The authors also acknowledge the sponsor institutions, appropriately identified on the next page.

L.S.P.
R.A.F.
J.R.G.
B.L.

RESEARCH AGENDA

RESEARCH AGENDA ON SUSTAINABILITY OF WATER RESOURCES UTILIZATION IN AGRICULTURE

L. S. PEREIRA, J. R. GILLEY, M. E. JENSEN, R. A. FEDDES and B. LESAFFRE
Technical University of Lisbon, Portugal,
Texas A&M University, Station College, USA,
Research Consultant, Fort Collins, CO, USA
Agricultural University of Wageningen, Dept. Water Resources, The Netherlands
Cemagref, France

Executive Summary

Sustainable development meets the needs of the present population without compromising the ability of future generations to meet their needs. This conceptual approach is accepted worldwide and fully applies to the use of water resources in agriculture in general and in irrigated agriculture in particular.

The present 5.3 billion world population is projected to increase to 9 billion over the next 40 years. An estimated 95% of the growth to the year 2050 will be in developing countries. The associated increase in food requirements coupled with increasing constraints on water available presents a tremendous challenge for present generations working to overcome poverty in less developed countries without compromising living conditions for future generations.

World food production must more than double in the next few decades. The increasing demand for food will occur at the same time as a large part of the world population suffers from food shortages and heavy malnutrition. Much of the required increase in food production over the next thirty years will be in developing countries.

Fortunately, the potential exists for expanding food production. Actual cereal yields in the developed countries is now over 4 ton/ha, while in developing countries it is only 2.3 ton/ha. Irrigated land accounts for 18% of the cultivated land, but produces 33% of the world's food supplies. Thus, to meet the expanding food demand there is a need for increasing the average yields and for expanding irrigated agriculture.

Land resources are limited and, particularly in Africa, land degradation is increasing rapidly. A large part of rainfed agriculture is already extremely vulnerable to drought, soil loss and disruption of water resources. Many of these agrosystems are ecologically fragile and require soil and water conservation measures and techniques to prevent

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degradation and maintain yield potentials. Land resources in irrigated or potentially irrigated areas also suffer from mismanagement, flood hazards and salinization; however, they still have the potential for increasing food production. It is expected that appropriate intensification and expansion of irrigated areas may account for more than 50% of food requirements by the year 2025.

Water resources play a major role in expanding irrigated agriculture and associated food production. While water resources are limited, there is a large potential for meeting the water needs for agricultural production. In the Middle East and North Africa the present water withdrawals correspond to more than 70% of the existing internal renewable water resources, while most of the world does not presently use more than 10% of water resources that can be mobilized.

Existing technologies and management techniques for improved water utilization in agriculture will play an important role in meeting the enormous challenge of population growth and increased food demand. Nevertheless, there is a tremendous gap between research and its implementation. Further, there is a need to redirect research to more fully meet the requirements of sustainable water resources utilization in agriculture. This research and associated information transfer should lead to technologies that would conserve the natural resources, land and water in particular, and be environmentally non-degrading, technically appropriate, economically viable and socially acceptable.

The NATO Advanced Research Workshop on "Sustainability of Irrigated Agriculture (Sustainability of Water Resources Utilization in Agriculture)", co-sponsored by the STD Program of the European Union, CIHEAM, CTA, CEMAGREF and JNICT was held in Vimeiro, Portugal, 21-26 March 1994. The purpose of the workshop was to provide in-depth discussion among researchers and professionals of different disciplines coming from developed and developing countries. A total of 43 papers were presented and discussed under the following topics:

I. **Sustainability of world irrigation systems**
II. **Water management and water policies**
III. **Sustainability of indigenous water and soil conservation systems**
IV. **Irrigation water management and scheduling**
V. **On-farm irrigation systems**
VI. **Irrigation scheme management**
VII. **Sustainability and environmental concerns**
VIII. **Technological transfer**

This Research Agenda evolved from group discussions. It is based on a common understanding of the challenges that our generation faces to ensure sustainable agricultural development, both in developed and developing countries.

The resulting primary research topics and priorities are listed below. The priorities were established by voting of the workshop participants. Further information on each of the research issues is given in the indicated Tables.

Priority	*Research Topic*
1	**Environmental and health impacts** (Table 2)
1	**Water quality management** (Table 3)
2	**Rehabilitation and modernization of irrigation systems** (Table 3)
3	**Technology and rules for use of waste and saline water** (Table 3)
3	**Policy issues** (Table 4)
3	**User participation for planning and managing irrigation and drainage systems** (Table 4)
4	**Basin wide integrated water resources planning** (Table 2)
4	**Human resources development** (Table 4)
5	**Irrigation and drainage system performance** (Table 5)
5	**Water savings methodologies** (Table 5)
6	**Rainfed agricultural water management and water harvesting** (Table 5)
6	**Economics of development of both irrigated and rainfed agricultural schemes** (Table 5)
7	**Land and water institutional issues** (Table 5)
8	**Availability of land and water resources** (Table 5)

These research topics include the different components and implications of sustainability such as: resource conservation; technical appropriateness; environmental concerns; economic viability; and social and institutional adequacy. They also relate to: management techniques; innovative technologies; evaluation, assessment and monitoring methodologies; and measures, rules, guidelines and training tools. They cover broad areas of concern, of interest both to the developed and developing countries and, thus, provide opportunities for cooperation among researchers and institutions worldwide.

1. Introduction

Throughout history, water resources and irrigation development have played a major role in human development. Civilizations have risen, and fallen, as a result of irrigated agriculture. Worldwide, water is the major factor limiting crop yields and food production. Irrigation has been critical to increasing crop yields and production by eliminating or reducing plant water stress. However, irrigation development has introduced major changes in the environmental and socio-economic conditions of an area. In the process, existing equilibria are disturbed and over time, new ones are established. The underlying premise is that the new conditions established under irrigated agriculture satisfy humankind's objectives better than those practiced before.

While only one-sixth of the world's cropped land is irrigated, this area produces approximately one-third of the world's food supply. Over one-half of the increase in food production over the last 25 years has come from irrigated land and further irrigation will undoubtedly continue to play a critically important role in assuring the food security of the world's expanding population. Irrigation also contributes significantly to poverty alleviation and general improvement in the quality of rural life. Further, it enhances the productive capacity in otherwise harsh environments and reduces the need for horizontal expansion of rain-fed agriculture onto marginal lands. This is especially true in developing countries, many of which depend heavily on irrigation for their further development and, in addition, presently experience the largest population growth rates.

Irrigation development, while contributing to the economic well-being of many countries, also has potential negative effects. While many of these can be minimized or avoided altogether by better planning, or mitigated by appropriate measures, questions have arisen as to whether irrigation is capable of continuing the high levels of agricultural production in the long run without undue damage to the environment.

Interest in sustainable development has arisen as a consequence of national, regional and subsequently global concern about the environment. The concept of sustainability is not new, but has recently received considerable attention, especially when comparing the irrigated agricultural practices between developed and developing countries of the world. According to FAO: "Sustainable development is the management and conservation of the natural resource base and the orientation of the technological change to ensure the attainment and continued satisfaction of human needs - food, water, shelter, clothing, and fuel - for present and future generations. Such sustainable development, including agriculture, forestry, and fisheries, conserves genetic resources, land and water resources, is environmentally non-degrading, is technically appropriate, is economically viable, and socially acceptable".

The essence of the concept of sustainability is the legacy that the present generation will leave for future generations. This immediately raises the question of what population should be considered when exploring the future. In this context, the world's present population and its growth rate cannot be ignored. Given the current population growth rate of 1.7 percent per year, the present world population of 5.3 billion is projected to reach 9 billion over the next 40 years. Further, the most striking fact is that an estimated 95 percent of the projected world population growth to the year 2050 will take place in developing countries. Because the food production per capita is strongly influenced by population growth, broad family planning policy options for slowing population expansion world wide must be pursued urgently.

To feed this rapidly growing population, food production must be increased by enlarging the area served by irrigation, or by intensifying agricultural production on the existing irrigated and rain-fed lands. Irrigated agriculture has expanded, horizontally into areas where conditions for production are less favorable, and vertically, by increasing production per unit area of land through intensification. Much of the additional agricultural production has been achieved through the development of new irrigation projects and products, and the use of high-yielding varieties, which require optimum management of land and water. Unfortunately, growth in grain production has slowed during the past few years.

These trends point to the danger of a decline in per capita agricultural production, which will become even more dramatic with the increasing world population. Hence, the world food and water problems may worsen with time. The growth in demand exceeds that of production in the developing countries, and further, this spread may increase when accounting for the increased expectations of future generations. Food self-sufficiency is a concept closely linked to that of independence, a term whose meaning is also changing in today's world.

During the past four decades, development of irrigated agriculture provided a major part of the increase in production necessary to meet population demands. By the mid-1980s, over 35 percent of the total crop production came from less than 15 percent of the arable land which was irrigated. On a global basis, the average rate of irrigation expansion was about 1 percent per year in the early 1960s and reached a maximum of 2.3 percent per year from 1972 to 1975. The rate of expansion began to decrease in the mid-1970s and is now about 1 percent per year.

The reasons for this decrease in expansion are many. Two of the most commonly cited causes are the high cost of irrigation development, and the decline of the world price for major cereals. Further, and perhaps most importantly, as much of the land suitable for irrigation development and available water supplies have already been developed, progressively more expensive, economically less favorable and environmentally more sensitive areas are left for further expansion.

Scarcity of water is a major constraint for further irrigation development in arid and semi-arid countries. In many countries, all available water sources which can be economically used have already been developed or are in the process of development. As the competitive demands for water continue to increase it is imperative that this limited resource be used efficiently for agricultural and other uses. In some scarce areas, more water will be diverted from agriculture to meet expanding needs for domestic and urban uses because of population growth.

Water resources play a major role in feeding the world's population and these finite water supplies face an ever expanding demand from many competing water users. Existing irrigation methods and practice are being placed under increased scrutiny from many fronts. Irrigation research must now focus on other alternatives such as increasing crop production per unit of irrigated land and per unit of water consumed by evaporation. Yet, the fact remains that new irrigation development and improved management of existing water systems, particularly in developing countries, must be capable of providing needed food and fiber production while at the same time addressing key environmental issues.

Accordingly, this workshop was established to bring together the world's leading irrigation authorities to discuss the future of irrigated agriculture and to establish the future research agenda. The workshop objective was to integrate existing science and technology into improved irrigation system performance and agricultural water management and to provide recommendations for future research directed toward sustainability of water use in agriculture. The material which follows summarizes the results of this workshop.

2. Objectives and Methods

2.1. OBJECTIVES

Following the introduction of the sustainable development concept in 1987 by the World Commission on Environment and Development, the word sustainability has been used frequently and, unfortunately, users have not always considered the full consequences of the challenges involved.

The concept of sustainable development implies "a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential, to meet human needs and aspirations". The word change calls for questioning how current research in fields of irrigation, drainage and agricultural water management are providing information for sustainable development. Shall the research community maintain the same approach or is it necessary to readdress questions, reconsider solutions, or take new priorities for action?

In order to answer this interpellative change an Advanced Research Workshop was proposed. The workshop concept received immediate support from individuals from leading academic, research and development institutions in the fields of irrigation, drainage and agricultural water management. The objectives of the Workshop were quite simple:

- to integrate existing and potential science and technology into improved irrigation system performance, in order to ensure sustainable irrigated agriculture
- to provide recommendations for future research toward the sustainability of water use in agriculture.

2.2. METHODS

To meet the above objectives, the Workshop organization provided for the following:

- the presentation and discussion of papers covering:
  - the sustainability concerns of world irrigation systems and soil and water conservation systems;
  - innovative developments relative to irrigation water management, on-farm irrigation systems, conveyance and delivery systems;
  - environmental, health, economic, social, institutional and policy aspects relating to irrigation and water resources utilization in agriculture;
  - issues on water resources planning, management and waste water policies;

- questions relating to technology transfer and institutional building.

— the free and participatory discussion of issues resulted in the development of a prioritized Research Agenda. This was accomplished through paper presentations, panel discussions, group discussions and a final plenary session.

The format of the Workshop is presented in Annex I.

The themes for discussion were presented in papers by invited speakers who identified the main highlights for discussion. The manuscripts were included in a ring book provided to each participant. The themes were presented for discussion under the following topics:

I. Sustainability of world irrigation systems
II. Water management and water policies
III. Sustainability of indigenous water and soil conservation systems
IV. Irrigation water management and scheduling
V. On-farm irrigation systems
VI. Irrigation scheme management
VII. Sustainability and environmental concerns
VIII. Technological transfer

The papers are listed in Annex II. The list of participants is provided in Annex III. Participants came from research, development, management and engineering in areas of irrigation, drainage, soil and water conservation, water management, hydrology, soil sciences, environment, economics, social sciences and research management. They came from 23 developed and developing countries, and from several international organizations involved in irrigation and agricultural development. Their broad backgrounds and individual experience provided for in-depth discussions and diversified approaches.

The resulting Research Agenda presented hereafter was developed from free participation of all the Workshop attendants. The priorities were selected through voting in the last plenary session, following group discussions and voting and harmonization of the issues selected by the groups. To ensure the best independence of the choices made by the participants, the editors of this Agenda did not take part in any selection phase.

3. The Research Agenda

3.1. IDENTIFIED ISSUES

During the group discussions, each participant proposed different issues relative to the themes and topics under discussion. These propositions were progressively integrated and grouped, and priorities were assigned to the resulting items. Finally, all items were integrated into three main groups:

Resource Base Issues

Irrigation and Drainage Systems

Institutional, Socio-economic and Policy Issues

Priorities were established through a voting process by the participants. The corresponding global results are presented in Table 1.

Several comments on the overall results are needed:

— The resulting grouping of identified issues into the three broad categories is completely different from the topics proposed for discussion. This was a result of intensive discussions by the participants, without any agenda that might impose limits to the discussions or to the issues. The discussions were focused toward future research on sustainability of water use in agriculture based on the present scientific and technological developments.

— Issues identified and included in Table 1 fully agree with main concepts of sustainability as proposed by the world Commission on Environment and Development and the FAO. In fact, items clearly cover the components relative to resource conservation, technical change, environmental friendliness, economic viability and social, institutional and policy adequateness.

— Some issues identified by different groups are similar, but differ in wording and focus. An independent assessment of the issues identified could have resulted in fewer overall topics.

TABLE 1. Identified issues for sustainability of water resources utilization in agriculture

	Resource Base
Priority	
1	Environmental and health impacts
4	Basin-wide integrated water resources planning
6	Rainfed agriculture water management and water harvesting
8	Availability of water for agriculture
	Irrigation and Drainage Systems
Priority	
1	Water quality management
2	Rehabilitation and modernization of irrigation systems
3	Technology and rules for use of waste and saline water
5	Water savings (reducing water demand and waste)
5	System performance
	Institutional, Socio-Economic and Policy Issues
Priority	
3	User participation in planning and management of irrigation and drainage systems
3	Policy issues
4	Human resource development
6	Economics of development, irrigation schemes and rainfed agriculture
7	Institutional issues

3.2. PRIORITY ISSUES

Voting in the plenary session identified the following priority issues. Further information on each of the research issues is given in the indicated Tables. The same priority indicates a tie amongst participants.

Priority	*Research Topic*
1	**Environmental and health impacts** (Table 2)
1	**Water quality management** (Table 3)
2	**Rehabilitation and modernization of irrigation systems** (Table 3)
3	**Technology and rules for use of waste and saline water** (Table 3)
3	**Policy issues** (Table 4)
3	**User participation in planning and managing irrigation and drainage systems** (Table 4)
4	**Basin-wide, integrated water resources planning** (Table 2)
4	**Human resources development** (Table 4)

3.2.1. *Resource Base Issues*

The research items identified as the priority issues by the participants with the Resource Base Issues are presented in Table 2.

TABLE 2. Priority issues relative to resource base

Environmental and Health Impacts
A. Evaluate the potential of irrigation as a means for environmentally sustainable land use and food production.
B. Develop appropriate tools for assessing and controlling the impacts of using low quality water in irrigated agriculture.
C. Determine the potential adverse environmental impacts resulting from neglecting maintenance and repair of irrigation systems or abandoning systems.
D. Expand the epidemiological studies of agrochemical waste water and drainage water reuse.
E. Develop appropriate techniques for the maintenance of waste water systems and the control of water-related diseases, including monitoring health hazards.
F. Develop biological vector control and environmental management for vector control.
G. Improve land evaluation criteria and methodologies used in irrigation planning to include the assessment of the impacts on the environment.
Basin-Wide Integrated Water Resources Planning
A. Conduct studies to establish the political economy of water resources development for agriculture and rural areas.
B. Develop criteria, policies and procedures for transboundary basin planning and management.
C. Develop basin-wide integrated water resources planning and management including soil and water conservation.
D. Develop strategies for water harvesting on arid and semi-arid lands.
E. Improve the knowledge of drought and develop mitigation methodologies.
F. Investigate the mechanisms for monitoring and controlling surface and ground water salinity.
G. Develop appropriate technologies for water reuse in developing countries.

The perspective of resource conservation in connection with the control of adverse environmental impacts was strongly supported. Particular attention was given to water management and to the need for using non-conventional water resources in agriculture to face increasing water scarcity and competition for water. The need for considering land resources in connection with water resources was stressed, as well as the need for considering soil and water conservation measures as an integrated part of basin-wide water resources planning and management.

Items proposed call for enhanced methodologies of evaluation, assessment and monitoring of environmental and health impacts, as well as for a better understanding of related processes. The need for indepth and scientifically based methods was recognized, as well as the development of appropriate tools including guidelines, field evaluation procedures, models and decision support tools.

3.2.2. *Irrigation and Drainage Systems*
The items selected as priority issues within the Irrigation and Drainage Systems are listed in Table 3.

Priority issues include all aspects for controlling the adverse impacts of irrigation and drainage on water quality. This covers field and laboratory evaluation, assessment and monitoring, development of guidelines and tools, and providing for the implementation of appropriate practices by irrigators.

The need for developing new technologies and management practices for irrigation systems at the farm and scheme levels is particularly stressed. This requires enhanced field research and a large variety of tools covering field techniques such as land levelling, equipment for water control and regulation, models, remote sensing, Geographical Information Systems, Decision Support Systems, as well as field evaluation techniques. Particularly innovative is the fact that those tools are considered under a broad and integrated approach relative to food production, water savings, resource conservation, environmental impacts, and socio-economic effects.

The problems of water quality management and of modernization of irrigation systems received a particular attention in regards to arid and semi-arid lands, where the scarcity of water resources and the vulnerability of soils to salinization calls for special measures to make irrigated agriculture sustainable. Thus, appropriate management tools must be made available to use saline and low quality water without decreasing the production potential and the carry-over capacity of these fragile agro-ecosystems.

3.2.3. *Institutional, Socio-Economic and Policy Issues*
The priority issues identified in this category are presented in Table 4 and primarily concern the need for developing conditions required for implementing appropriate innovation in field practice.

TABLE 3. Priority issues relative to irrigation and drainage systems

	Water Quality Management
A.	Expand water quality monitoring including the development of reduced cost methods of assessment and standards for chemical, physical and biological loads.
B.	Develop economic and effective mechanisms for disposal or reuse of drainage water, salts and agricultural wastes in arid and semiarid lands.
C.	Develop tools to relate the productivity of irrigated agriculture with the efficient delivery of water.
D.	Develop simple methods for waste water treatment for agriculture reuse.
E.	Develop best management practices to minimize water quality degradation in irrigated agriculture.
F.	Improve knowledge on pollution from agrochemicals including assessment, monitoring and control methods.
	Rehabilitation and Modernization of Irrigation Systems
A.	Enhance and adopt procedures for integrated planning and management of irrigation and drainage systems.
B.	Develop locally-adapted water-efficient on-farm irrigation technologies.
C.	Expand the use of low cost technologies for canal construction and improvement, and appropriate techniques for improved water regulation and control.
D.	Include life-cycle benefits and costs of appropriate on-farm irrigation systems in research and development programs for modernizing irrigated agriculture.
E.	Develop guidelines for evaluation and implementation of integrated irrigation and fertilizer management including fertigation, chemigation and irrigation scheduling.
F.	Evaluate the impacts of irrigation modernization on irrigation efficiency and water distribution.
G.	Develop strategies for sustained increases in output per unit input of water and land.
H.	Develop methods to evaluate and control sediment in irrigation and drainage systems.
	Technology and Regulation for Use of Saline and Waste Water
A.	Improve knowledge on salinity and solute processes under irrigated agriculture.
B.	Develop methods, techniques and guidelines for use, control and management of low quality water for irrigation.
C.	Expand research on adaptation of crops to use low quality and saline water.
D.	Develop criteria and guidelines for the use of saline water and for saline water table management.

It was recognized that existing programs for transferring the managerial responsibilities of irrigation and drainage systems to users are not always successful. This problem will require innovative solutions of policy, institutional and economic nature, as well as those relative to the social behavior of farmers. Particular importance was attached to the fact that innovations, both of technical and managerial nature, have to be introduced according to indigenous knowledge and social values and behavior.

Human resources development, including training from the farmer level to the University level, extension services, technology transfer, and other educational tools were considered very important and require specific and innovative approaches.

TABLE 4. Priority issues relative to institutional, socio-economic and policy

User Participation in Planning and Management of Irrigation and Drainage Systems	
A.	Analyze and provide for improvement of programs aiming at the transfer of responsibility from government to users relative to the operation, maintenance, and management of irrigation and drainage systems.
B.	Establish guidelines for user organizations to administer water for different uses.
C.	Recognize the indigenous knowledge and the human reluctance to change, and provide for dissemination, acceptance and capacity building.
Policy Issues	
A.	Develop appropriate procedures for allocation of surface and ground water for different purposes and uses.
B.	Establish water laws and rights which provide for equity in water distribution and allocation.
C.	Develop legal instruments and procedures for implementing water conservation and efficient management practices.
Human Resource Development	
A.	Expand training, at all levels, of personnel involved in planning, construction, operation, maintenance and management of agricultural, irrigation systems.
B.	Include sustainability concepts and concerns in relation to water development within college and university curricula.
C.	Improve technology transfer at all levels of irrigation and drainage management, including farmers.
D.	Improve mechanisms, including effective irrigation extension services, to promote and assure dialogue among water users, water user associations and water authorities.
E.	Conduct research and provide training on modernizing surface irrigation systems, both on- and off-farm.
F.	Enhance institutional arrangements which enable appropriate training and technology transfer on water management.

3.3. OTHER IMPORTANT ISSUES

Additional items which received overall lower priority are listed below and are given in Table 5. Some of the items in this group were ranked higher in some discussion groups but lower in others. The same priority indicates a tie amongst participants.

Priority	*Research Topic*
5	**Water savings (reducing demand and waste)**
5	**Irrigation and drainage system performance**
6	**Rainfed agricultural water management and water harvesting**
6	**Economics of development of both irrigated and rainfed agricultural schemes**
7	**Land and water institutional issues**
8	**Availability of land and water resources**

TABLE 5. Other important issues

Resource Base

i) RAINFED AGRICULTURAL WATER MANAGEMENT AND WATER HARVESTING

A. Conduct research on criteria for water control structures for erosion control, water spreading and water conservation.

B. Establish innovative methodologies for assessing benefits of soil and water conservation and water harvesting.

ii) AVAILABILITY OF WATER

A. Investigate the effect of global climatic changes on precipitation, evapotranspiration, plant growth, water availability and land resources.

Irrigation and Drainage Systems

i) WATER SAVINGS

A. Develop reduced water demand cropping systems.

B. Explore crops and cropping patterns adequate for low water quality.

C. Develop appropriate methods and tools for implementing water savings to cope with droughts.

ii) SYSTEM PERFORMANCE

A. Assess the impacts of external factors such as subsidies, standardization of irrigation equipment, climatic changes, etc., on system performance, both on- and off-farm.

B. Enhance methods for field evaluation of system performance including water supply, water quality, salinization, environmental impacts, crop yield, economic factors and social acceptability.

C. Develop methods for system monitoring which incorporate water storage, delivery and application, drainage systems and environmental, economic and social impacts.

Institutional, Socio-Economic and Policy

i) ECONOMICS OF DEVELOPMENT

A. Determine the role of irrigation in meeting global food requirements.

B. Determine social and economic aspects of increasing water use efficiency in agriculture.

C. Investigate impacts of water pricing on water demand and consumption.

D. Enhance economic and macroeconomic criteria for irrigation investment including public *versus* private investment, and develop adequate mechanisms to ensure financing of maintenance and rehabilitation.

E. Develop criteria to ensure the economical viability of existing irrigation schemes including water pricing and financial responsibility of users.

F. Perform comprehensive analysis of the subsidies system for irrigated agriculture and for the financial vulnerability of irrigated agriculture to external changes such as prices of agricultural products and natural disasters.

ii) INSTITUTIONAL ISSUES

A. Determine the impact of land tenure and reform on irrigation development and performance.

B. Investigate the mechanisms which can improve the coordination and division of responsibility between government, public and water user institutions and the irrigation industry.

C. Enhance the financial, institutional and other infrastructure which provides support services to farmers.

In certain regions and land conditions, these issues may be considered as priority, as is the case of soil and water conservation in areas threatened by soil erosion and land degradation, or to water harvesting in arid and drought-prone areas with limited capabilities to mobilize water resources.

Items on water savings and system performance complement those priorities relative to rehabilitation and modernization of irrigation systems, while those of economic and institutional nature complement the approaches relative to the priorities identified on institutional and socio-economic issues.

Concluding, it should be noted that the priority issues identified by the Workshop participants provide a well balanced approach to define regional and country level research priorities, and constitute a integrated guide on the effective issues toward sustainability of irrigated agriculture and, in general, of water resources utilization in Agriculture.

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PART I

SUSTAINABILITY CONCERNS IN IRRIGATED AGRICULTURE

IRRIGATED AGRICULTURE AT THE CROSSROADS

MARVIN E. JENSEN
President Honoraire, ICID
1207 Springwood Drive
Fort Collins, CO 80525 USA

1. Introduction

Dr. Pereira set the stage and outlined the goals for this NATO Advanced Research Workshop on **Sustainability of Irrigated Agriculture**. He and his co-conveners and the Portugal National Organizing Committee identified and assembled world renown irrigation specialists. The International Commission on Irrigation and Drainage (ICID) family provided many participants. In their papers, participants were asked to review the state-of-the-art of the science and technology of irrigation for the readers. The primary purpose, however, is to integrate science and technology to enable improving irrigation system performance and to provide recommendations for future irrigation research. Irrigated and rainfed agriculture must be integrated to meet future food requirements. Therefore, a parallel effort is needed on water conservation and management for rainfed areas.

Many recent publications describe major national and regional irrigation problems. The authors of the four papers that follow will summarize problems of sustainable development in their respective regions. They will focus on problems that seem to grow in importance and become more complex as new issues arise. Two of the major issues that will be discussed at this workshop are **sustainable development** and **maintaining environmental equilibrium**. Other issues include farmer-participation in the decision-making process. Irrigated agriculture and its supporting research programs cannot continue as in the past. Many irrigation-related problems exist because irrigation research has been inadequate and not focused on emerging problems. Irrigation technology is evolving continuously. Adopting new technology requires corresponding changes in irrigation management. Current solutions may not correct emerging problems. Solving new problems requires dynamic research programs that respond promptly to needs and changing priorities.

Irrigated agriculture is essential to feed today's world population, but natural resources will constrain further irrigation development. The rate of expansion of irrigated land is now less than population growth. Therefore, the potential exists for a widening food demand-production gap. The time is right for reassessing current irrigation research programs and objectives.

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 19–33.

Reassessing irrigation research is also important because the United Nations Technical Advisory Committee (TAC) for the Consultative Group on International Agricultural Research (CGIAR) has recommended increased resources be allocated to the conservation of natural resources (TAC, 1992 a and b). Simultaneously, donor contributions to CGIAR for agricultural research have decreased.

Scheduling of this workshop is timely because, today, **irrigation research is faced with important choices**. The purpose of this workshop is to identify and define research programs that will lead to sustainable irrigated agriculture. Participants are also expected to formulate more effective approaches for transferring technology to users. The purpose of this paper is to set the stage for our discussions by identifying some key issues for consideration by the participants.

2. The Setting

2.1. SUSTAINABLE DEVELOPMENT

There are many definitions of sustainable development. During the 15th International Congress on Irrigation and Drainage in The Hague, ICID President Hennessy recommended that ICID adopt the definition in FAO's action program on water and sustainable agricultural development (FAO, 1990; Hennessy, 1993). At the same session, Pallas (1993), FAO's Officer-in-charge of Water Resources Development and Management, discussed the role of planning and design of irrigation and drainage systems in sustainable development.

The TAC succinctly described **sustainable development** as:

> *"... successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources."* Walsh (1991), p. 7

Walsh (1991) further emphasized that since population growth is greatest in developing countries, agricultural specialists from these countries will face even greater challenges than those in developed countries:

> *"Agriculture, therefore, faces a double challenge—not simply to increase food production, but to assure that the resource base is not degraded."*

Sustainable development has other implications. To "sustain" means to maintain, to keep in existence, and to keep supplied with necessities. "Sustainable" means to be capable of being sustained or maintained. Abernethy (1992) emphasized that since sustainable refers to the future, a discussion of sustainability also means forecasting the future.

Forecasting the future involves long-term issues such as the *conservation of mass*. Importing water for irrigation also means importing the salts that are contained in all waters. Sustained irrigation development requires coping with both long-term water and salt balances while maintaining or improving soil productivity.

One workshop objective is aimed at research toward sustainability of water use in agriculture. However, we must recognize that in many water-scarce regions, there will be *less* water available for irrigated agriculture because of population growth and increasing demands for renewable water supplies.

2.2. INCREASING POPULATION PRESSURES

The current world population growth is 1.7 percent per year (IBRD, 1992). The world population of 5.3 billion and will increase to nine billion over the next 40 years. Irrigated land accounts for 18 percent of the cultivated land, but it produces 33 percent of the world's food (Lal and Stewart, 1992). Soil is a finite resource that is not renewable within most planning time frames. Therefore, the world per capita arable land will progressively decrease from about 0.23 hectare by the year 2000 to about 0.15 hectare by 2050 (Lal and Pierce, 1991).

The impact of population growth on the sustainability of food production cannot be overstated. Brown (1994) suggests that grain production is an indicator of the global food production. He reported that growth in grain production had slowed during the past few years. Per capita grain production has been decreasing and probably will continue to decrease in the near-term because of population growth.

Population growth cannot be ignored. An estimated 95 percent of the growth to the year 2050 will be in developing countries (IBRD, 1992). Bongaarts (1994) estimated that in 2050, the population in developing countries will be 8.6 billion, an increase of 4.5 billion from 1990. Since the production per capita is strongly influenced by population growth, he suggests three broad family planning policy options that should be pursued for slowing population expansion. One research-related policy involves human development. Clearly, the consequences of population growth and increasing food requirements constrained by limits on water consumption by agriculture provide new challenges to managers of water for agriculture in water scarce areas.

2.3. EXPANSION OF IRRIGATION

The rapid expansion of irrigated area after the late 1960s played a major role in increasing food production to meet growing needs of an expanding world population. The development of new irrigated lands slowed in the 1980s, but has continued to increase (Figure 1). However, irrigated land per capita peaked in the late 1970s and it, like per capita arable land, has been decreasing since then.

The decline in irrigation expansion during the 1980s has been attributed to various factors. Lower than expected performance and higher than expected costs are often cited as the main causes of this decline. However, Svendsen and Rosegrant (1992) concluded that the reduction in public investment in new irrigated areas in southeast Asia was an appropriate response to declining world rice prices and rapidly increasing capital costs of irrigation.

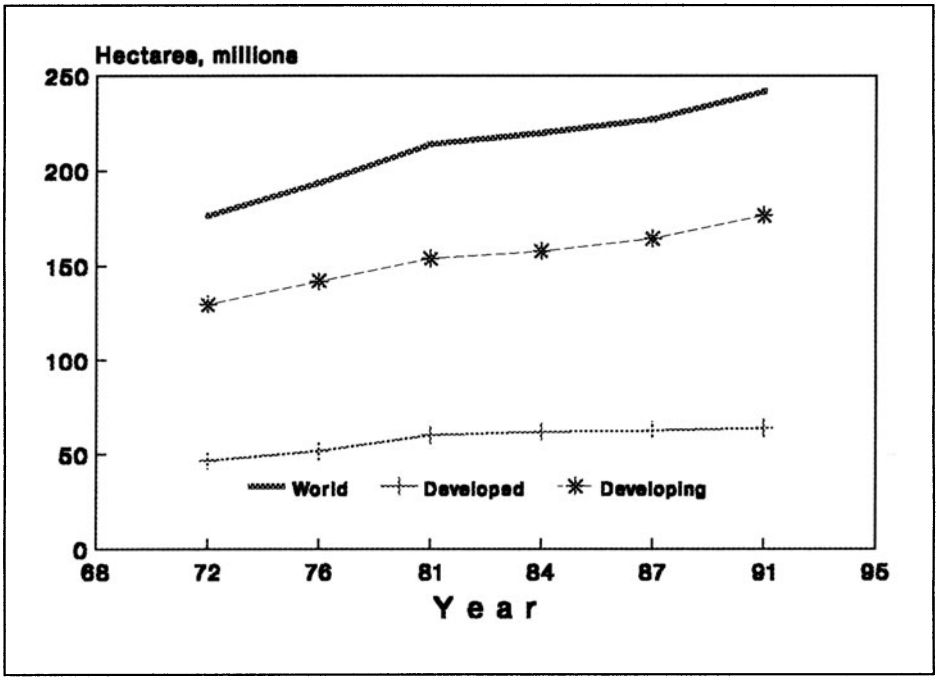

Figure 1. Expansion of irrigated agriculture from 1972 to 19912. Source: FAO (1986, 1989 and 1993)

In the long-term, adequate food production will require both increased production on existing irrigated land and further expansion of irrigation. The rate of expansion has slowed to 1.2 percent per year (Pallas, 1993). The expansion rate will probably decrease further because of natural resources limitations. More water will be required to meet domestic and municipal demands. In water-scarce areas, water will likely be diverted from irrigated agriculture. Environmental concerns are also affecting the allocation of water supplies.

Limits to continued population growth are real and food production must respect environmental and resource limitations. Agriculture faces an enormous challenge in providing adequate food for an expanding population while maintaining environmental quality.

In the short-term, economics will probably set the trend in irrigation expansion despite the development of new and improved irrigation technologies or food production projections. Faeth (1993), however, questions some economic assessments that have been made because they have not considered agricultural sustainability. He argues that:

> "*When agricultural sustainability is left out of economic policymaking, distortions that threaten sustainability look rational.*"...
> "*If a production practice takes a resource beyond its ability to replenish itself, that use of the resource would be unsustainable.*" pp. 1-3

Faeth presented two research-related recommendations:

> *"Research into sustainable farming practices should be given much higher priority and correspondingly higher funding."...*
> *"National economic indicators of the agricultural sector reported in official statistics and policy analyses should reflect the depletion and degradation of natural resources."* Faeth (1993), pp. 13-15

Faeth's second recommendation pertains to a major issue being considered at this workshop, and that is whether irrigated agriculture is sustainable. Irrigated agriculture *must* be sustained. Some new irrigated land will be developed, but not all existing irrigated land can be sustained. Not only must irrigated land be sustained, but because water will be scarce in many regions, production per unit of both rainfall and irrigation water must be increased.

2.4. INCREASING COMPETITION FOR WATER RESOURCES

Renewable average water resources are finite and constant as long as climate fluctuates within a known range (OTA, 1993). If climate does change, as many predict, it is another factor that must be considered in sustained irrigation. Competition for waterä is increasing, not only for urban growth, but for environmental concerns. It is inevitable that more water resources will be allocated to domestic, urban and industrial uses.

Water transfers from agriculture to urban and industrial uses have been underway in the USA for several decades. A recent example of a major transfer of water is the transfer of conserved water from the Imperial Irrigation District (IID) in California to the Los Angeles Metropolitan Water District (MWD). The IID is unique in that it isä the last irrigation project on the Colorado river in the USA and excess water drains to the Salton Sea. There is no return flow to the Colorado River. Therefore, improvements in project water conveyance and application efficiencies enable reducing the diversion of water from the river releasing water for other uses. This case is also unique in that the MWD is paying for improvements in the IID over a five-year period to enable a long-term transfer of water to the MWD (Reisner and Bates, 1990). The cost of the improvements and therefore the cost of the water to MWD will be $US 0.086 per cubic meter ($106/ac-ft).

In many countries, agriculture will be competing for renewable water supplies. Agriculture will be pressured to pay the same price for water as domestic and industrial users. The cost of storing and delivering water in many areas is already too high for growing some common crops at current commodity prices. As competition for water and prices increase, growers will quit irrigating low-value crops unless commodity prices increase to pay the cost of irrigation. Allocating less water to irrigated agriculture within a water-scarce region will reduce crop production if water use efficiency is not increased. It will also increase imports of food products and foreign currency requirements.

Several major long-term issues must be considered in assessing competing water uses because they affect the renewable supply. In the long-term, the ability to capture and manage renewable water resources may decline as watersheds are degraded because of deforestation. Deforestation increases the siltation of reservoirs reducing the usable storage space. Other problems such as waterlogging and salinity problems, though severe in many areas, generally are reversible. How will these long-term issues affect the future direction of irrigated agriculture research? The speakers that follow will describe major problems in their respective regions.

2.5. INCREASING WATER PRODUCTIVITY

An irrigation research program must consider the productivity of water "consumed" in evapotranspiration (ET). The productivity of water used in agriculture is the amount of marketable materials produced per unit of water consumed. I have used the term of *water use efficiency* (WUE) since the 1950s. WUE has been defined as the amount of marketable crop produced per unit of water consumed in ET. Although when expressed as mass per unit mass it is dimensionless, it is most often expressed as mass per unit volume of water (kg/m^3). *Irrigation water use efficiency* (WUE_i) is a similar term except the *increase* in crop production is compared with the *increase* in ET due to irrigation above that without irrigation (Bos, 1980).

In my Gulhati lecture at the 15th ICID Congress, I suggested that because of the current confusion associated with irrigation efficiency terminology, it was timely to redefine these terms as indices of the productivity of water for crop production (Jensen, 1993 a). I suggested that we begin reporting the productivity of water consumed on irrigated lands to reduce the misunderstanding that now exists. Production of marketable products per unit of water consumed will normally be greatest when water does not limit growth. Typically, the large evaporation component of ET on rainfed semiarid lands results in less production per unit of water consumed than on irrigated land. However, the cost of increasing production on rainfed lands through water conservation practices must also be compared with irrigation development.

Most crop production is linearly related to water consumption when water limits plant growth uniformly over its growth cycle. A similar relationship does not exist between water applied and crop yield except the first few increments of water that increase both ET and yield. As a result, water productivity values are similar over wide geographic areas. In contrast, production v. water applied can vary greatly. Thus, water productivity is a conservative and measurable parameter that can be used to evaluate the performance of both irrigated and nonirrigated agriculture.

During the past four decades, productivity has increased greatly. Increased productivity was caused by improved cultivars, use of more fertilizers and better cultural practices. Some differences in productivity occur between different climates. The climate may change the gradient of water vapor from within leaves to the atmosphere while the gradient of carbon dioxide to the internal plant cells is essentially constant (Tanner and Sinclair, 1993). The effects of humidity on productivity are not easily quantified because temperature and solar radiation also affect plant growth.

An important issue to be considered at this workshop is whether evaporation of irrigation water from wet soil can be reduced. This remains a major potential for improving the productivity of water used in irrigated agriculture. Applying water below the soil surface can reduce evaporation of irrigation water, but *not* evaporation of rainfall. Irrigation systems that use buried drip laterals and emitters are being installed for irrigating high-value crops and golf courses in arid areas of California.

2.6. INTEGRATING RAINFED AND IRRIGATED AGRICULTURE

Agricultural production on rainfed and irrigated lands must be considered as an integrated production system. In semiarid regions, more attention should be given to *supplemental irrigation*. Significant advances have been made in increasing water productivity on rainfed semiarid lands through various conservation measures. Typically, when irrigation water becomes available, farmers switch from dryland or rainfed farming practices to full irrigation. If water is cheap and plentiful, basic principles of conserving limited rainfall are neglected. Supplemental irrigated agriculture may not be economical if massive water distribution systems are required. Also, it may not be sustainable if high canal seepage losses are not recovered for reuse. Supplemental irrigation can be economical and sustainable where renewable ground water supplies are available, and when used on high-value crops.

2.7. UNDERSTANDING WATER USE

Water use and *waste* mean different things to different people. Recent semi-technical literature shows that some irrigation terms are not interpreted as we intended. Consequent misunderstandings are repeated, confuse decision-makers, and probably adversely affect their decisions. Participants at this workshop have an opportunity ascertain that the terms used in research reports are defined so that they are not misinterpreted.

In my Gulhati lecture, I suggested that as a first step, we should define water use in natural ecosystems more clearly. All uses of water are either *consumptive* or *nonconsumptive* or both. All nonconsumptive uses degrade water to some extent chemically, physically and biologically. Chemical changes usually increase dissolved solids such as salts and toxic materials. Physical changes may include reduced potential energy as water flows downhill or temperature changes. Biological changes may increase biological constituents such organic matter and disease vectors. Part of the water not consumed may not be available for reuse because it is diverted to an inaccessible location or because it has been mixed with saline waters.

Evapotranspiration is *not* waste. The principal use of water by both rainfed and irrigated agriculture is the evaporation from the soil and transpiration from plants called ET. Transpiration is a natural process accompanying photosynthesis. Techniques may minimize the evaporation component of ET, but they are expensive. There is no practical way to reduce transpiration in a given climatic regime without reducing plant growth and crop yields. Therefore, when water limits plant growth, reducing transpiration usually cuts yields linearly (Howell, 1990).

3. Actions to Consider During Workshop Discussions

3.1. CLARIFY PROCESSES AND TERMINOLOGY

Participants at this workshop should not spend much time on terminology. However, as we present and discuss papers, we should consider if irrigation terminology could be refined to improve our understanding of processes and enhance environment-related communications. One reason for addressing this issue is that donor agencies who support agricultural research are restructuring and more of the important decisions are being made by generalists than by agricultural specialists. Therefore, I would encourage the participants to consider two specific terms that have caused much confusion in the past. These terms are related to water use, water consumption, and irrigation efficiency.

3.1.1. *Water Use and Water Consumption*

Water use and water consumption are two terms that will be in many papers presented and discussed during the workshop. If the reader must *ask* if the "water use" means only water consumed by evaporation, transpiration or embodiment in a product, then we have not presented our material clearly. Some water uses, such as hydroelectric power generation, consume only a small fraction of the water used. In contrast, crop production on both rainfed and irrigated lands consumes a large fraction of the water used. Most water uses involve both consumptive and nonconsumptive components. The fraction not consumed is usually degraded by the concentration of the remaining dissolved solids.

In irrigation research, we need to quantify the proportion of irrigation water that is consumptive and the proportion that is nonconsumptive use. Is the water not consumed stored as ground water for later use or recycled to crops during the growing season? Of the water not consumed, how much drains from the irrigated area, and how much has quality been degraded chemically, physically and biologically?

3.1.2. *Irrigation Efficiency*

Irrigation efficiency is a commonly used term that needs to be improved because it has confused and misled the public and media the most in recent years. This term was defined 60 years ago by Israelsen (1932 and 1950) as:

$$E_i = \frac{\text{irrigation water consumed by the crops of an irrigation farm or project during crop growth}}{\text{water diverted from a river or other natural source into farms or project canals during the same time}}$$

The definition of E_i is not a typical efficiency term of output divided by input of the same quantity. Wolters (1992) recently presented a comprehensive review of various irrigation efficiency terms. Instead of "irrigation efficiency" I suggested changing the definition of the ratio of the water *consumed* by ET to that diverted to something other than efficiency (Jensen 1993 a). In an ongoing assessment of water use in a major irrigation project in the USA, we have found that we can reduce the misunderstandings and allegations of waste of water if the above term was redefined as a *consumptive use coefficient, C_u*, or CUC. The quantity of water consumed in irrigated agriculture, V_c, would be $V_c = C_u V_d$ where V_d is the volume of water diverted for irrigation. The volume of water not consumed, V_{nc}, would be $V_{nc} = (1 - C_u) V_d$.

I recommended that the use of "efficiency" be restricted to output/input ratios such as water delivered to the water input to the canals, watercourses and water storage facilities. The V_d required to provide water for consumption by crops will be influenced by the efficiency of the on-farm irrigation system and the proportion of canal and watercourse seepage that is recovered within the project. All or part of the water that is not consumed may be recovered and reused for agriculture or other purposes. Recovering water for reuse within the project without changing V_d will increase V_c and C_u. Some water not consumed may be irrecoverable or degraded to the degree that it is no longer suitable for irrigation.

The cost of achieving higher system efficiencies must also be considered. When the real costs of increasing the efficiencies of water supply and distribution and on-farm systems are passed on to consumers, there may be less pressure by critics of irrigation to increase efficiency per se.

3.1.3. *Irrigation Information Data*

As previously mentioned, FAO is developing global irrigation statistics as indicators of the state of irrigation in the world. Although not a primary objective of this workshop, as participants identify key parameters required in research studies, this information should be relayed to FAO. Participants may also want to suggest changes in some planned database parameters.

3.2. PLANNING FOR SUSTAINABLE DEVELOPMENT

The salt content of water supplies increases as pure water is removed by evaporation and transpiration and by the addition of materials dissolved from soils. We can no longer consider only the fraction of water supply delivered to farms that will be consumed. We must also consider the long-term impacts of the water that is *not* consumed. For sustainable development, we must also consider whether an acceptable salt balance will be maintained in both the soil and in the receiving water bodies.

All natural environments *consume* water by evaporation and transpiration. There must and will be tradeoffs in the allocation of limited renewable water supplies. The speakers who follow will elaborate on the **Sustainability of World Irrigation Systems** in various broad geographic regions. I have highlighted a few nonstructural general issues that currently affect sustainable development. These issues will become more critical in the future. We can reduce adverse effects if we can guide the allocation of limited research resources into more productive research and technology transfer programs.

3.3. BASIC CHARACTERISTICS OF IRRIGATION METHODS

Some authors have suggested that water consumption can be reduced by increasing irrigation efficiency defined as evapotranspiration divided by water diverted or pumped for irrigation. I frequently must remind people that "crops consume water" and *not* the irrigation systems. With exceptions for widely spaced plants, the amount of water consumed in ET is essentially the same whether the field is irrigated by surface, drip or sprinkler systems. The reduction in consumption and resulting increases in productivity of water will be achieved by reducing the evaporation component of ET of both rainfall and irrigation water. Use of buried drip irrigation laterals and emitters is one way to reduce the evaporation component. With surface and sprinkler systems, more evaporation occurs after each irrigation than with drip systems when annual plants, vineyards and orchard trees are small. However, fewer irrigations are required.

Drip or sprinkler systems are often recommended without considering all of the impacts of the change. There is no doubt that when water supplies are scarce and return flows not easily recaptured, there are significant advantages to changing to drip or sprinkler systems to achieve greater control of irrigation amounts and uniformity. Simultaneously, planners must consider the tradeoff between increasing water application efficiencies and the associated increase in energy and maintenance requirements. This is especially important where the excess water is not wasted, but returns to the system for reuse within the project, further downstream, or to the ground water where it is recovered for irrigation as needed by the crops. Besides these factors, the *failure risk* associated with various systems under local operating conditions must be considered.

3.4. CONJUNCTIVE USE

Conjunctive use is coordinating the management of ground and surface waters. There are many advantages of conjunctive use (Coe, 1990). Some advantages include stabilizing water supplies, reducing the need for large dams and reservoirs, and providing greater flexibility in delivering water as needed by crops. Major conjunctive use problems include decreasing ground water quality and potential increases in soil salinity.

4. The Research Network

4.1. PROJECT INFORMATION SYSTEMS

Several networks exist that enable researchers to find out what and where irrigation and water conservation research are being conducted and by whom. One system is the USDA Current Research Information System (CRIS). Information on essentially all agricultural related research projects in the USA is available including summaries of research progress and publications. Similarly, several electronic databases provide information on almost all research articles that have been published in established scientific or technical journals. Every researcher planning a new project can save much time and make better use of research resources if one or more of these databases are checked before planning and initiating a research project.

4.2. DISTRIBUTING RESEARCH RESULTS

All researchers that have completed a research project resulting in good, usable data, whether positive or negative, should publish the results in national journals. If the results are generic, or have potentially broad applications, the researcher should also consider publishing the results in an international journal or a national journal that has wide distribution. This is a first step in making better use of limited resources for irrigation and water conservation research. Direct costs to researchers in developing countries should not be significant because many journals still do not have page charges. However, most journals require peer reviews and the authors may need to revise their manuscripts in response to reviewers' suggestions and questions before they are accepted for publication by the journals.

4.3. NETWORKING

Networking can produce synergistic effects, i.e., greater benefits can be obtained from limited research resources by establishing either formal or informal research networks. Networking can also reduce the gap between what is known and what is being applied.

Networking between institutions that manage water supplies and delivery systems and agricultural institutions can also produce mutual benefits. More important, such networking can enhance the productivity of irrigated lands. Lack of communications between these two groups remains a major problem in many developing countries.

5. Irrigation Support Infrastructure

A subject not identified in the background materials is the need for an adequate infrastructure to support irrigated agriculture. Such an infrastructure will both: 1) help the successful transfer of improved irrigation technology; and 2) assure sustained use of the new technology by continuing training programs and related support services that are necessary to sustain the use of new technology. Making irrigation software programs available to irrigation technicians is part of the irrigation support infrastructure. Mwendera (1993) recently summarized many available irrigation-related software packages.

5.1. PREPARING FARMERS AND SUPPORT TECHNICIANS

With proper planning, training, management and an adequate and stable support infrastructure, almost any level of technology can be adopted by irrigated agriculture if such technology is necessary to achieve production goals. Failure of a new technology is often attributed to unskilled farmers with low levels of education. However, the real cause can often be traced to missing or inadequate infrastructure required to sustain the technology and insufficient preparation of managers, farmers and advisory specialists in the use of new technology (Jensen, 1993 b).

Wolff and Hübener (1992) suggest that the output of the current agricultural labor force must be increased. This can be accomplished by introducing appropriate technologies, including irrigation technologies, that save labor and ease the workload of irrigation because the agricultural population is not growing as fast as urban populations. This raises the issue of whether the significant increases in agricultural output can be achieved because of a decline in motivation for peasant farmers. In some countries they are being replaced by urban investors (Abernethy, 1992). When transferring irrigation technology, we need to assess who will be the most responsive recipients and what incentives and training requirements will be needed to assure sustained use of the new technology.

5.2. PREPARING PUBLIC AND PRIVATE SECTORS SUPPORT ARRANGEMENTS

Major changes in the management of irrigation in developing countries will be needed in the next decade. These include the restructuring of public sector irrigation, both in terms of rationalizing the scope and operation of irrigation departments and devolving management to farmers' groups and water users associations. Already significant institutional changes are already taking place in many developing countries.

Another major change is the growing awareness of the need to link investment in irrigation with sustainability of schemes being built or rehabilitated. This need relates to the reorganizing of irrigation systems so that they are attuned to the people who live and work on them, i.e., the *farmers*, who are vitally interested in their sustainability (Jensen, 1993 b). Irrigation and drainage systems must also be economically and financially sustainable.

Infrastructure includes more than water storage, distribution, delivery and drainage systems. It also includes institutions and organizations that develop and manage irrigation water supplies and excess water often associated with irrigation, the irrigation industry, and service personnel who keep systems operating. An important irrigation support activity is *training*. The role of training, though important in the past, will become more critical in the future as irrigation technology becomes more complex and as irrigated agriculture produces more per unit of water consumed.

6. Summary and Conclusions

The impact of population growth on sustainable food production cannot be overstated. In the long-term, adequate food production will require both increased production on existing irrigated land and continued expansion of irrigation. In water-scarce areas, water will be diverted from irrigated agriculture to meet domestic and urban needs.

Environmental requirements will also affect the allocation of water supplies. All natural environments *consume* water by evaporation and transpiration. There must and will be tradeoffs in the allocation of limited renewable water supplies. The ability to capture and manage renewable water resources may also decline as watersheds are degraded because of deforestation causing increased reservoir siltation and reduced usable storage space.

Irrigated agriculture *must* be sustained, but not all existing irrigated land can be sustained. In many regions renewable water supplies are scarce, and agriculture must compete with other users for renewable water supplies. Agriculture will be pressured to pay the same price for water as domestic and industrial users. The cost of storing and delivering water in many areas is already too high for irrigating some common crops at current commodity prices. Therefore, production per unit of both rainfall and irrigation water consumed in evapotranspiration must be increased.

Problems such as waterlogging and salinity problems, though severe, generally are reversible. For sustainable development, we must consider whether an acceptable salt balance will be maintained in both the soil and in the receiving water bodies.

Failure of a new technology is often attributed to unskilled farmers with low levels of education. However, the real cause can often be traced to missing or inadequate infrastructure required to sustain the technology and insufficient preparation of managers, farmers and advisory specialists in the use of new technology. An adequate infrastructure is essential to support irrigated agriculture. Such an infrastructure will both: 1) help the successful transfer of improved irrigation technology; and 2) assure sustained use of the new technology by providing continuing education programs and related support services that are necessary to sustain the use of new technology. These long-term issues must be considered in planning the future direction of irrigated agriculture research.

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ECONOMICS OF IRRIGATION

IAN CARRUTHERS
Professor of Agrarian Development
Wye College, University of London
Ashford, Kent, TN25 5AH
U.K.

1. Introduction

This review of economic aspects of irrigation is highly selective. It deliberately focuses on positive aspects of irrigation development although it is of necessity somewhat defensive in tone. It is argued that many of the current debates on irrigation policy have been relatively uninformed and unbalanced, with the critics, notably those coming from an environment perspective, dominating the arguments. The imbalance stems from the neglect of the 'without irrigation' scenario which is a necessary ingredient of any appraisal.

Many of the criticisms of irrigation are valid but the overall impression is negative and wrong. Research is urgently required on the varied contributions of irrigation as well as an accessible digest of the information in the public domain that presents a fair picture of the opportunities and constraints to irrigation development.

An assessment of the benefits of irrigation development should come from an appreciation of the difference between the with and without irrigation scenario and a comparison of the real costs of the resources used with alternative ways of using these resources. This requires complex analysis. If the critics have their way then the without irrigation scene will increasingly become the real situation in the absence of appropriate consideration of options. Insufficient attention and analysis of the implication of the without irrigation scenario results in a massive undervaluing of the economic and social impact of irrigation.

This paper has been prepared in recognition of the fact that for many governments and aid agencies the public sector investment in water development in general and in irrigation in particular has become extremely unpopular. The main purpose of this paper is to set out why this is considered to be an inappropriate stance for those primarily concerned with poverty alleviation and sustainable development.

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 35–46.

2. The Rationale For Irrigation Investments

There are legitimate grounds for calling for an improvement in irrigation investment performance. Certainly there is scope for achieving considerable progress throughout the 250 million hectares presently irrigated worldwide. However, the proper response to an evaluation of what is often disappointing irrigation experience is to improve the workings of irrigation and realise the potential of the technology. This is particularly important given the vision presented later of a depressing future for global food supplies.

Most irrigable areas are already developed and therefore an improvement in the maintenance of the existing infrastructure will inevitably be an important component of any future irrigation development strategy. Aid donors can ill afford to turn their backs on the opportunities furnished by these huge, often incomplete investments in irrigation. Donor supported investments and institutional reforms can transform irrigation projects into genuine and sustainable development assets. To achieve this potential and to avoid the problems highlighted by the critics requires all parties to absorb the lessons of experience some of which are set out below.

There are six major sets of reasons for public and private, national and aid community support for irrigation all of which require elaboration and research before the sub-sector is either subject to investment or abandonment:

* *Food Reasons*

* *Investment Reasons*

* *Environmental Reasons*

* *Social Reasons*

* *Aid Reasons*

* *Sector Specific Reasons*

3. Food Reasons

Critics of irrigation claim that, *inter alia*, food will be cheaper and more reliable if purchased from Chicago today and possibly from Kiev tomorrow. However, the following propositions (3.1 to 3.3) can be regarded as testable hypotheses in future research:

3.1. TODAY MORE THAN ONE THIRD OF WORLD FOOD COMES FROM IRRIGATION, MOSTLY IN LOW INCOME COUNTRIES

This often asserted 'fact' emerges from a set of plausible assertions. It is testable and should be tested. If correct then sustaining irrigation is very important if we are to maintain a large part of the present global food production capacity.

3.2. MORE THAN TWO THIRDS OF ADDITIONAL (MARGINAL) FOOD WILL COME FROM IRRIGATION

This statement, if true, has profound implications for the allocation of research and investment resources. It is certainly the case that population growth continues and rural-urban migration accelerates and therefore growth in local food production is clearly important. This additional food growth has to be of the order of 3 per cent per year to maintain supplies at current prices. Crop area growth is now virtually ended and hence if production rises are to match needs then the additional or incremental returns must come from higher yields. Yield increases will mainly come about with the application of modern agronomic methods on small as well as larger farms using costly purchased inputs. An assured water supply is part of the package of modern inputs. Mention of 'the package' of modern inputs does not imply that there is only one way forward. There are probably as many packages as there are projects and situation-specific solutions must be found. However it is argued that the hardware package will probably include artificial fertilizer and responsive, high quality seeds. Experience suggests that designing and delivering the software package and education of users is likely to be the biggest stumbling block to progress. Research of the locally-specific package to adapt the generic technology produced by the CGIAR international research system and others is an important but neglected area.

Without the assurance of a secure soil moisture supply, which in most areas outside the temperate zone implies irrigation, the risk factors associated with intensification will loom too large for many (especially low income) farmers.

3.3. COMPLACENCY ABOUT WORLD FOOD SUPPLY IS MISPLACED

World food prices are at unprecedented low levels which in part reflects shifts in supply as a result of successful application of modern agronomic advances. Discussed below are several sets of factors that taken overall show that the current secure food supply and low prices may not be as permanent as is clearly desirable.

3.3.1. *Reform of Industrial Country Agricultural Policy will Contribute to an Increase in World Food Prices*

Reform of the industrial countries' agriculture policies stemming from pressures from the GATT as well as their domestic financial authorities who wish to reduce subsidies will over time reduce the supply of food and increase food prices. This price rise will not offset a fall in the overall value added in their agriculture and consequent cut backs in agricultural research investment, first in the public sector and, as farm incomes are squeezed, then in the private sector. Developing countries that import food will be harmed, at least in the short run, by any increase in world food prices.

3.3.2. *Research has Benefitted from Industrial Country Subsidies*

Modern agronomic research has benefitted from an investment climate with product prices distorted upwards by massive industrial country subsidies (for example Japanese farmer rice prices are over six times world levels, and the average European cow gets twice as much as an annual subsidy as the average income of a third world farmer). These subsidies were mainly production increasing and developing countries were able to pick up some spin-off benefits in terms of yield increasing technology. In future subsidies are likely to be reduced overall and/or shifted to low input agriculture or environmental protection. This will not produce research output of much relevance to poor tropical countries that still need to increase their levels of production.

3.3.3. *Crop Area Growth Era is Over*

The relatively uncomplicated method of obtaining increased food supply (the expansion of area cropped) is now practically over as virtually all suitable land is cultivated. From now on we must increase global food supplies by boosting the yield of crops on existing arable land.

3.3.4. *Easy Part of Yield Increases Completed*

Crop yields can still be increased considerably with known technology. Unfortunately much of the easy part of the yield increasing campaign to harness modern agronomic advance has also been completed by achieving the widespread adoption of artificial fertiliser use on stiff-strawed cereals that respond to nitrogen and do not lodge. Future developments to maintain production growth will require a wider range of inputs and much more difficult management improvements and reform of traditional institutions such as land tenure, credit systems and farmer education (especially women) all tailored to local situations.

3.3.5. *Institutional Reform Lessons Need Adopting*

These management and institutional reforms are important but they have and will continue to prove hard to realise in practice. There are few general lessons to be gleaned from development experience but what has been learned should make us cautious about our ability to sustain yield increases above the 2.5% per year and make us more realistic and flexible in project design and in maintaining investments than hitherto. The World Bank summarise the lessons of their area development projects as:

- clear government commitment to rural development objectives (as evidenced by a supportive policy environment especially pricing policies);
- participation of beneficiaries;
- incentives in the form of benefits (including indirect benefits);
- realistic, not too complex and flexible project design;
- institutional capacity of government and others involved (e.g. NGO's) to implement a programme efficiently;
- proven technology and support services to provide the necessary production

growth[1].

3.3.6. *Public Resistance to Biotechnology May Hinder Research Investment*
There are clear signs of public resistance to accepting the products of biotechnology and other promising lines of research. These signs are worrying if, for example, we regard biotechnology as the major future source of crop (and animal) yield growth or for more benign methods of crop protection. If resistance to biotechnology is sustained or grows then more resources will be diverted from agricultural research. If for these or other reasons biotechnology fails to make an impact then yield increases will inevitably slow and given the continued growth in demand then food prices will rise. If however biotechnology has an impact then irrigation is the category of production system that stands to gain most. Either way we can expect irrigation to become a potentially more important production system in the future.

3.3.7. *Aid Commitments are Falling*
Aid resources are generally falling or being spread more thinly (e.g. in the 1995 budget presented to Congress in early 1994 USA aid is scheduled to be cut from the $32 billion spent in 1993 to $17 billion in 1996 and thereafter, with 21 USAID offices closing). Aid for the rural sector is also falling (according to a recent IFPRI report world aid to agriculture fell from $11.7 billion in 1980 to just over 10 billion in 1990)[2]. Although precise data are not available the impression gained is that aid for water development has had a disproportionate share of the cuts just at the time when water has become recognised to be a scarce valuable resource with a consequent political focus at international, national, regional, and village levels. Competition for aid resources comes particularly from new urban priorities. All these cuts in aid can be expected to affect, after a lag, the growth in agricultural production.

3.3.8. *Urban Influences*
Unprecedented and rapid urban growth has created a market for food (and water - releases of water by using irrigation water more efficiently will be an important future source of urban water supplies). This shift in demand for food plus future higher prices will be an incentive for farmers. However in many countries education and other social factors has changed peoples attitude to agricultural work and people, particularly the young and active have permanently moved out of the rural labour force. A less well specified factor affecting production is the large amount of fertile land lost permanently to urban sprawl and far from fully compensated for by the growth of intensive production in and near cities (urban agriculture). Despite the importance of these influences and effects for policy the research base upon which to formulate action is weak particularly in the area of migration.

3.3.9. *Part of Existing Food Supply Systems are Unsustainable*
A proportion of current world food supplies come from what are generally agreed to

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(1) "Area Development Projects" *Lessons and Practices* N° 3 Sept. 1993, OED World Bank, Washington.
(2) Joachim von Braun, Raymond Hopkins, Detlev Puez and Rajul Pandya-Lorch (1993) *Aid to Agriculture: Reversing the Decline* IFPRI, Washington.

be unsustainable production systems in developed and developing countries. For example, in the irrigation field fossil groundwater abstraction, highly subsidised surface and groundwater irrigation, pumping groundwater from great depth or in excess of annual recharge (sometimes causing salt water intrusion and irreversible deterioration in aquifers) are all associated with unsustainable agricultural production systems. Other examples of production systems that are using degrading soil resources, eroding hillsides, deteriorating pastures and so forth abound showing that the present level of production in these circumstances cannot be guaranteed. The effects of the inevitable growing population will be to increase these types of pressures. Irrigation technologies can help provide safety valves to help lower the unsustainable pressures on production systems and livelihoods. Irrigation is sometimes argued to be unsustainable and certainly there are areas that have been abandoned for various reasons. But all irrigation is not unsustainable. The Egyptians who have cultivated the Nile valley for several thousand years indicate that concern for sustainability can be exaggerated. Current worries about physical aspects of the Nile system and about the impact of the Aswan High Dam in particular are real but soluble. There is little doubt that the major influence on Egyptian agriculture over the last 2000 years has been the harmful urban-biassed macroeconomic policy framework of the last 30 years which has done much pervasive damage and changed Egypt from an agricultural exporting country to almost certainly being a permanent importer of more than half its food.

3.3.10. *Pest and Disease Risk*

The final factor that has to be considered is the risk to world food supplies from the increasingly narrow genetic base of much of the improved cereals. The small farmer that grows a wide range of traditional crops and varieties suffers lower yields than if a narrow range of high yielding crops were grown. However, he/she acts as a custodian of biodiversity and thereby creates an external social benefit. This could be an important economic justification for small farmer subsidies were finance ever to be made available for that purpose. The risk is related to the potential breakdown in resistance to virus or fungal disease and widespread loss of production. Whilst it might be argued that it was irrigation that created one of the preconditions for the adoption of the narrow range of high yielding varieties it can also be claimed that the production benefits have been high and are likely to remain so. Furthermore, in the unlikely event of, say, a devastating disease in rice that has a global impact then the irrigated wheat would be invaluable.

3.3.11. *Water Resource Scarcity*

Agriculture is the world's largest user of fresh water. The belated recognition that fresh water resources are finite and valuable and that demands on this finite supply are increasing has thrust irrigation into the limelight. It is acknowledged that water use efficiency can be markedly improved and thereby release water for alternative use in agriculture and elsewhere. Water policy options are reviewed in detail in many official publications but a comprehensive recent account with a strong underlying economic content is the theme chapter of the 1993 FAO Annual Report[3]. Improvement in water use efficiency will require investment in the software (eg farmer education, improved management systems, agency staff training) as well as in the hardware of irrigation development. Unfortunately in hard economic times it is the software investments that are most vulnerable to cuts.

3.4. COSTLY FOOD HARMS THE POOR

The overall influence if some or all of these factors come about will be to affect the security of food supply and lead to an increase in world food prices. We should remember that for the most part the poor buy food and spend a high proportion of their income on it and any increase in food prices will have a particularly hard impact on their welfare. The single most effective anti-poverty instrument is low basic food prices. Efficient irrigation can help bring this about.

These are the main reasons why we have argued that the current complacency about world food security is misplaced. There is much conjecture about many of the elements. If these factors come into play then irrigated agriculture can help compensate for these effects and produce food and fibre in the developing countries close to the rapidly growing numbers of consumers in the cities and the countryside.

4. Investment Reasons

The rate of return to investment in irrigation is widely believed to be low. This perception is wrong. Returns are generally comparable to alternative investments. For example the World Bank portfolio includes 585 irrigation-related projects. The expected economic internal rate of return at appraisal was on average 22 percent. Some years later after construction the projects averaged a lower but acceptable level of 15 percent.

This realised rate of return might be considered quite modest and critics might argue that it will fall further as the schemes age and particularly so if they are not well maintained. However 15 per cent was achieved in an era when the domestic terms of trade were stacked against agriculture with overvalued exchange rates and a variety of indirect taxes or subsidies to competing urban interests. In future these public (and private) irrigation investments and any new schemes promise to provide somewhat higher returns for the reasons discussed below.

4.1. SUNK COSTS IN IRRIGATION ARE HIGH

Billions of dollars of investment are already in place, much of it now free of any financial charge. Incremental investment in modernisation, completion, extension and rehabilitation will benefit from these sunk costs and yield high rates of return. Lessons

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(3) FAO (1994) *The State of Food and Agriculture 1993*, Rome.

from evaluations of irrigation need to be incorporated into new investments in any modernisation or rehabilitation. Important among these lessons (in addition to those mentioned above) are the need to complete projects (including drainage, properly designed field channels and land levelling), to deal with the whole watershed including the non-irrigated upland areas, and to ensure mechanisms are in place that will maintain the scheme over the life of the project.

4.2. ECONOMIC LIBERALISATION WILL INCREASE RETURNS

Economic liberalisation and macroeconomic reform tends to favour the agricultural sector and therefore as the full effects of these changes in many countries begin to bite we should see an improvement in rates of return to rural investment in general and to irrigation in particular. This will be especially so if overvalued exchange rates are adjusted, industry/urban subsidies are removed, and if neglect of O&M through budget squeezes, arbitrary cuts and delayed release of funds is ended. There is comparatively little research on sectoral level 'second round' effects and how they can be assisted or speeded in the sequence of reforms.

4.3. ADVANCES IN COMPLEMENTARY INVESTMENTS

Technological developments in agronomy, even if the pace of their arrival slows down, will improve the returns to irrigation. Indeed the availability of an assured supply of soil moisture is a precondition for much of the pipeline agronomic and biotechnology projects.

4.4. RATE OF RETURN WILL RISE IF FOOD PRICES RISE

As explained above we believe that it is likely that the net effect of various factors will lead to upward shifts in the demand for food in the face of slower supply shifts. This in turn will lead to increases in the price of food which will then increase the rate of return to irrigation.

4.5. HIGH RETURN INVESTMENTS REQUIRE BETTER PLANNING

The main output of the last fifty years of research on how to achieve development is that it is complex and difficult. The main practical effect of this insight is contradictory in that more criteria and tests for plans are set to match the complexity (e.g. environmental, regional impact, gender focus) but the resources available to carry out these investigations are diminishing and hence the growing popularity of rapid appraisal techniques. Poor irrigation performance can have many causes but skimpy investigations are a false economy in the search to eliminate it.

5. Environmental Reasons

The environmental critique of irrigation is an extreme response to real threats and in some cases to actual environmental damage from irrigation. Irrigation is seen by its critics to be unsustainable with problems such as those associated with the salt balance, soil waterlogging, sea water intrusion into estuaries and destruction of important ecological zones and wildlife habitats.

Much of the environmental literature that deals with irrigation can be considered to be unbalanced with an emphasis upon the negative environmental aspects (for example the World Bank 1991 Environmental Assessment Sourcebook)[(4)]. The indirect and direct benefits of irrigation need to be considered simultaneously and a balanced view obtained.

Despite the reservations above there is also plenty of evidence that environmental damage can and does occur and that without reform the threat of further environmental deterioration is inevitable. However, this not a reason for withdrawing from irrigation but rather a reason for engaging in a serious search for solutions. There are certainly technical solutions to each of these problems. But many of the problems require a management rather than an investment approach and where investment is needed (e.g. in the case of drainage) the financial demands are huge.

We would contend that irrigation, far from being an environmental problem area, can be an environmental asset providing that we can follow the following guidelines.

5.1. DISTINGUISH BETWEEN GOOD AND BAD IRRIGATION

Badly planned, constructed or managed irrigation schemes will create an environmental threat. Well-conceived, well-built and soundly managed schemes are a contained risk. The varied lessons of experience, often specific to a particular country or scheme, need to be incorporated into policies and practice.

5.2. COMPARE ENVIRONMENTAL RISKS OF ALTERNATIVE INVESTMENTS

Environmental risks are likely to be even worse in the hills, swamps and in marginal rainfed areas. The growing rural population has to live somewhere and it will be more readily absorbed with a livelihood onto the intensive farming of productive irrigation schemes at a relatively low environmental risk.

If irrigation is not brought up to its potentially productive level to absorb the growing rural population then there will inevitably be greater environmental risk of damage in the more fragile hillsides, streamsides and low rainfall zones that farmers and their families will be forced to occupy. Simply put the population absorptive capacity of irrigation is higher than any other farming system and providing it is well managed

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(4) World Bank (1991) *Environmenta! Assessment Sourcebook*, World Bank, Washington.

and maintained it is likely to be the best option to provide sustainable livelihoods. With population densities continuing to increase research on the absorptive capacity with decent livelihoods of differing farming systems is urgently needed.

6. Social Reasons

Irrigation often disrupts traditional ways of life and patterns of settlement. Resettlement is often poorly planned and badly executed. Once again this is not grounds for not carrying out irrigation settlement but a reason to make greater effort to improve performance.

There is scope in irrigation for increased levels of participation in decision making. In the recent past consultation procedures may have been minimal but in introducing modern irrigation practice an opportunity exists to bring in new institutional forms such as genuine water user groups. Women can benefit if conscious efforts are made to address their special interests and if, for example, new job opportunities and income sources encourage less male migration in search of work.

The scope for more participation has to be incorporated into working procedures. Participation is acknowledged to be an important aspect of development but still procedures to achieve it are not well specified and tested. Some government agencies are rightly sceptical of conventional wisdom in this area. Much more action research and extension of successful experience is needed.

Public investment in irrigation is often condemned because it does not benefit the really poor (except, if successful, through lowering the price of food). It is true that capital gains are often made by the landowning elite and obviously the larger the holding the greater the gain. However, it is unreasonable to blame technology for a social ill and the minimum remedy of making sure there are no subsidies (or they are made transparent), or the more radical one of promoting land reform or betterment levies on capital gains are all in the hands of the government. Furthermore it could be argued that to get the irrigation service working well is one precondition for a land reform. Certainly a land reform or any radical change wrought on a poorly maintained and deteriorating system would appear doomed to failure.

7. Aid Reasons

Critics argue that aid for irrigation is wasted. We have argued that economic returns (at least in the case of the World Bank projects) are equivalent to other sector and project aid. Where failures have occurred they are generally avoidable and even predictable. Success and not failure can be the hallmark of irrigation aid.

Aid for irrigation must be maintained at least at present levels for the following reasons:

7.1. AID POLITICS

The OECD countries have the technology to develop irrigation and voters understand irrigation aid. They can see irrigation on television and for them it has existence value.

7.2. AID TRANSFERABILITY

In principal the technology is not complex and can be maintained by the recipients.

7.3. AID ACCOUNTABILITY

Financial support for irrigation schemes are less fungible than some other forms of aid such as balance of payment support or even programme or sector aid and thus there is a high degree of accountability. Whilst policy based lending, programme or sector aid can be good in principle it does make accountability more difficult which can be an important limitation when aid is striving for political support in donor communities.

7.4. SCOPE FOR PRIVATISATION

There is scope for elements of privatisation or beneficiary management -both elements high on the aid agenda.

7.5. JOB CREATION HELPS REDUCE MIGRATION

In countries where the proportion of the population 16 years of age or less is more than 40 or even 50% only intensive agriculture (and labour intensive catchment protection) offers the prospect of creating jobs and cutting urban drift or intracountry and international migration pressures. Catchment protection also produces externalities in space (downstream - no silt and lower flood peaks) and time (longer life to reservoirs). Here again there may be grounds for subsidies to those undertaking the work to protect the land and water resources. We are in an era when the term subsidy almost automatically meets an initial negative response from governments and the aid community. Where real external social benefits that might otherwise be lost can be realised by subsidy then very careful consideration has to be given to undertaking this action. This is particularly the case if the damage that can be avoided is irreversible. Industry in comparison to rural development has unfavourable capital/labour ratios and employment possibilities are dismal although expectations are high.

7.6. DIRECTS AID TO WHERE MANY OF THE POOR LIVE

Irrigation already exists where many of the poor are living and to that extent it is an appropriate location for aid. There is also a potential for a greater degree of control of the project environment and aid donors can target the inhabitants for health or other forms of development assistance. If the irrigation planning includes the upper watershed catchments as advocated above where poverty is commonly found then aid will be well targeted.

8. Sector Specific Reasons - Continued Dominance of Agriculture in the Poorer Countries

In summary agriculture continues to dominate economic activity in low income countries, providing jobs, and food and raw materials for industry and for export. Irrigation is the sub-sector of agriculture that has most unrealised potential but it also uses most water which is increasingly recognised to have multiple uses and to be scarce and valuable.

Directing development resources to the irrigation potential with a focus upon the poor farmers and landless labourers in the irrigated areas and in the upper catchments would provide an unusual opportunity to link poverty alleviation and environmental protection. It would certainly be a poor strategic move to neglect opportunities for irrigation development at this time because of evident but soluble problems. Far better to accept the acknowledged challenges and to fully test preferred solutions to the areas of difficulty.

For the reasons set out above, it is argued that aid donors and governments should not neglect water development but embark upon a new era working to protect and then allocate efficiently, in a sustainable way to promote development, increasingly scarce and valuable water resources.

INSTITUTIONAL QUESTIONS AND SOCIAL CHALLENGES

HARRY HILL and LAURIE TOLLEFSON
Prairie Farm Rehabilitation Administration
Room 603, CIBC Tower
1800 Hamilton Street
Regina, Saskatchewan, S4P 4L2
Canada

1. Introduction

Irrigated agriculture can be environmentally sustained provided the basic principles of good water management, water conservation, salinity, and erosion control are recognized. This has been practiced in certain regions of the world for over 5,000 years. In addition to the technical side, however, for irrigation to be sustainable, it must be viable socially and economically, as well as environmentally. Institutions must evolve to be compatible with concepts of sustainability if irrigated agriculture is to be successfully practiced in the future.

This paper focuses on institutional questions in relation to the sustainability of irrigation.

2. Irrigation Development Overview

The twentieth century will be characterized as an age of irrigation. Between 1900 and 1950, the world irrigated acreage doubled. The development of new irrigation projects has proceeded, however, at a diminishing rate since that time. The per annum rate of increase since 1980 is estimated at 1.2% (Pallas 1993). The development is no longer keeping pace with the increases in food production necessary to meet the needs of an expanding population. The slow down in irrigation development has occurred for several reasons. Poor commodity prices, higher energy costs, and generally poor economic conditions have discouraged agricultural investment. In addition, the cost of building irrigation capacity i.e. dams, reservoirs, etc., has risen rapidly making it difficult to justify the investment on economic grounds (Postel 1990). Many of the best less expensive projects have been developed leaving the more complex and expensive ones to be done. Also, rapid population increase in both developed and developing countries have resulted in increased pressure on our natural resources. This competition is particularly true for water which is slowly reducing the water

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 47–59.

available for irrigation. Currently, there is approximately 250 million hectares of agricultural land irrigated. This includes 185 million ha (73%) in developing countries with the remaining 65 million ha (27%) in developed countries (Shady 1991).

Environmental and social issues have also played a role in limiting expansion. Irrigation development produces ecosystem changes. It benefits human populations but, when not properly planned, implemented or managed, threatens the long term productivity of the system (Pallas 1993). Closer attention to environmental and social issues have slowed the development process. It is now recognized that appropriate attention must be paid to economic, social and environmental objectives to achieve balanced and sustainable rural development.

Understanding how competition for water will affect irrigation requires an indepth understanding of our institutional setting, i.e. the laws and regulations which apply to it. There is no uniform system in the world in regard to water (Ives 1993). In some countries, it is well documented, while in others, non-existent. Methods for organizing institutions and managing water are well established in some countries. The applicability of these methods in countries lacking formal institutions, however, may be limited by cultural or social factors.

In Canada and many other countries, government has historically covered the capital cost of developing the water supply. Viewed as a key to economic growth, water use has continually expanded as additional supplies and increasing infrastructure were developed to satisfy increasing demands. Governments were satisfied in promoting development and capturing spin-offs to the economy (Ward 1993). The barriers to irrigation development in Canada are primarily economic rather than physical. Irrigation development within the prairie region is estimated by the Prairie Farm Rehabilitation Administration (PFRA) at 543 thousand hectares of which 80% is in Alberta, 18% in Saskatchewan, and the remainder in Manitoba. Approximately 70% has a firm water supply with the remainder relying on runoff and local storage (Hill 1985). An important economic dimension in Western Canada is the fact that irrigation focuses primarily on low valued cereals and forages. The most recent statistics show the percentage of cereals and oilseeds as follows: Saskatchewan (72%), Alberta (83%) and Manitoba (26%). The historical struggle has been to increase the proportion of irrigated cropland to higher valued specialty crops. This has been slow due to many reasons including competition from the dryland regions (Veeman 1985). Irrigation is at an early stage in Canada and it will take time to develop the financial infrastructure and knowledge of crops, markets, etc., required to make it successful. A major institutional challenge is to assist in making irrigation projects sustainable through the diversification and increased intensity of associated crop production along with the development of value added industry.

The new global economy and prolonged recession have realigned government wealth. Many governments understand that deficit financing has reached its limit. In short, public dollars are not available to finance new projects. These realities will make institutions change their approach. In the future, more emphasis will be placed on improving existing projects rather than developing new ones. Institutions will be forced to carefully examine such questions as cost recovery and privatization.

For irrigation projects to be economically sustainable in the long run, they must create enough wealth to operate and rebuild the systems. In turn, the water users must receive enough income from the sale of their products to be able to pay sufficient water charges. However, the price of products is often determined in the international market place or by government food policy, or both. In this way, government food policy becomes part of the institutional framework under which irrigation projects operate. This linkage is fundamental in the sustainability equation.

The relationship between irrigation institutions and other related organizations continue to evolve in many countries. Many of the major irrigation projects developed are part of multipurpose water supply schemes, and as such, the benefits may accrue to many different sectors and take generations to be realized. In addition, irrigation benefits accrue to others as well as irrigators. In Alberta and Saskatchewan, Canada, it has been estimated that 15-20% of the total benefits of irrigation go directly to the farmer with the remainder to society (Hill, 1985). These benefits come from economic activity and employment beyond the farmgate that is derived from irrigation activity. Farm benefits are often a small part of the total benefits, and many projects become feasible only when other beneficiaries contribute to the cost. There has been criticism of the economics of past irrigation development. There is a continuing need to address this issue in a practical, consistent and integrated manner. In turn, the related institutional policies and funding arrangements for construction, rehabilitation and operation are dependent upon this relationship.

However, no matter what this relationship is eventually determined to be by economists, relying on governments for significant funding to help construct, rehabilitate and operate projects may not be sustainable in the long run. Projects would be more sustainable and efficient and contribute more to society if the wealth created directly by the projects was transparent and beneficiaries paid directly for the project. In many cases, this is not now possible because of the low prices typically paid to farmers for their product. However, this situation may change. If methods are found to access the wealth created by indirect beneficiaries, projects would become more viable. Also, as food shortages increase because of increasing populations, the value of food will likely increase and consequently enable water users to pay more for water. There is likely to be a continued search for institutional arrangements that will allow irrigation projects to become self sufficient. This is an area that has received little attention in the irrigation literature.

The institutional arrangements for developing and managing water resources are the transmission gears between policy objectives and field activity (Guggenheim 1992). Institutional arrangements are really an interrelated set of organizations and rules to enable coordinating activities to achieve social goals. Radosevich (1987) states that a good institutional arrangement recognizes that, to have a plan, there must be a policy and to have a policy, there must be a reason. In addition, he states that in many countries, water policies and laws either do not exist, are inadequate or antiquated. The law must be an essential ingredient of effective management.

Institutional factors refer to policies of a local entity, region, state or federal government (Mjelde *et al.*. 1990). These factors encompass local water district's rules, bank's lending policies, state and federal policies, and other laws and regulations. These factors have an enormous impact on water-use decisions.

Institutional framework is established by legislation which provides the operative norm. Legislation is often incomplete, however, and the formal institutions established by law are often supplemented by informal institutions (water users associations) that can either complement the function of the institution or compete with them (Guggenheim 1992).

3. Institutional Questions

3.1. COMPETITION FOR WATER

Competition for water develops when there is not enough to satisfy all demands. This competition occurs between farmers for irrigation water, between farmers and non-agricultural users of water (cities, industry, power plants) and environmental uses (Bouwer 1993).

Social view points are changing. Agriculture was once a major factor in most local economies but as areas diversify, competition between uses for water increase. In addition, there has been a rise of the environmental ethic in the society whereby people now stress the value of preserving biological diversity and aesthetic value for future generations (Bucks *et al.* 1990).

The relative demands for domestic, industrial and agricultural supplies show that for developing countries, agriculture (80%) dominates. Demands will likely increase significantly in all sectors over the next years. All sectors will have to target to improve efficiency, however, inevitably, the main efficiency benefits must come from the dominant user - irrigation (Hennessy 1993).

Pressures are forcing agriculture to compete for water which will have a major impact on food production (Jensen 1993). The cost of storing and delivering water is already extremely high based on the current prices for most crops. As competition forces price increases, growers will discontinue the production of low value crops until commodity prices rise to meet the cost of irrigation. Subsidizing water for agriculture in many countries is a subsidy for food to consumers. Allocating less water for agriculture will reduce crop production and increase the importation of food.

Conflicts and competition among water uses will affect irrigated agriculture in many ways. These pressures will increase as water supplies become better utilized. Conflicts will increase which will require revisions to water laws and allocations. In the future, water use charges will likely be more closely related to its economic cost.

3.2. WATER PRICING

Irrigation systems have traditionally been built, operated and maintained by public agencies which charge little for their services. It is estimated that in the third world, average government revenues from irrigation are 10-20% of the full cost of delivery (Postel 1990), leaving little for operation and maintenance. The same is true in the developed world where water is often allocated to irrigation districts at costs which do not reflect market value (Ives 1993). This results in a reluctance to adopt efficiency measures. When prices reflect water's scarcity, when costs of obtaining water increase or when government regulates its use, then farmers will use it more efficiently.

Changes in water pricing policies aimed at water conservation and facilitating water allocations are under consideration in some countries and being made in others. Urban and industrial water users have a greater payment capacity than agricultural water users (ICID Newsletter 1993).

Various scenarios have been seen as potential solutions to the scarcity situation. Water transfer is a possible solution and involves the sale or leasing of water (Ives 1993). Voluntary transfers enhance the flexibility of water use. Water banking is a means of facilitating this transfer and has been used successfully in California (Bouwer 1993). Here, entities with critical water needs can purchase water from the bank with the proceeds directed to the seller.

It must be remembered that a water pricing scheme requires an institutional structure with well established rules. A market process cannot function without defining the rights and duties, and ensuring one receives what one has paid for. Canadian institutions have been challenged to restructure and reform the system of water rights to facilitate this transfer of water to higher valued areas, in the course of economic development, whether that be within or outside the agricultural sector (Veeman 1985).

3.3. WATER CONSERVATION

Water conservation is recognized by many institutions as a mechanism to solve problems and concerns in irrigation. Policy debates about agricultural water conservation are often confused by the fact there is little agreement on what constitutes water conservation and who benefits from it (Bucks *et al.* 1990). Water savings almost always occur due to an increase in the price of water.

Many technologies exist for improved water management. In Canada and other countries, water management for irrigated agriculture must turn from sole reliance on supply management (increased quantity) to greater emphasis on demand (Ward 1993). This change is due to the fact that the cost of developing new water supplies has increased and demand management is being recognized as a lower cost societal solution. In addition, it seeks to reduce water consumption through promotion of efficient use and elimination of waste.

3.4. IRRIGATION DEVELOPMENT VS. REHABILITATION

It is clear that the development of new irrigation schemes has been increasing at a diminishing rate since the 1950s. Poor commodity prices, increased government debt, reduced spending and limited land and water resources have all played a role in this reduction. Continued development will occur, however, economic conditions are projected to keep it at a minimal rate. These conditions will cause increasing attention to be paid to the rehabilitation of water distribution and control (Jensen 1987).

Irrigation development does cause major changes to social and institutional processes. Walsh (1986) noted that in a program to develop the Senegal River Valley, that farmers had at one time used flood recession technology to supplement rainfall. With the improvements, better agricultural technology was necessary, marketing was required to cope with excess production and better technology transfer was needed. In addition, the social implications were large since women traditionally looked after the small plots but with the change, men now make all the decisions for the larger land area.

Rehabilitation of existing projects is often favoured over construction of new projects since it builds on existing infrastructure, tradition and expertise (Jensen *et al.* 1990). The social changes will not be as widespread. Rehabilitative measures will increase productivity and save capital dollars provided changes in the total water management system are made (Bucks *et al.* 1990). Poor management, however, is often a major cause of the deterioration of the physical system. Major institutional changes must be made to improve management in addition to the overall physical improvement. Greater emphasis must be placed on farm water management.

During the 1980s, Canada, like most other donor countries, assisted in the financing of major infrastructure development and multi-purpose projects in the developing world. The latter part of the 1980s until present, however, have shown a major shift in emphasis toward integrated resource management, rehabilitation and strengthening of institutions (Shady 1991).

3.5. PUBLIC VS. PRIVATE SECTOR

The challenge for irrigation development today is not solely the responsibility of public irrigation development agencies (Barghouti and Hayward 1988). Increased involvement of the private sector has often resulted in higher efficiency and profitability. Private sector involvement is profit motivated and leads to greater sensitivity of market opportunities. These advantages must be balanced against the need for long term environmental safeguards and socioeconomic equity. As irrigation spreads to more marginal farmers, the public sector must be involved to provide services for sociopolitical and equity reasons.

Increasing the privatization of water development places substantial demands on the public sector (Guggenheim 1992). Major institutional restructuring is often required before privatization can occur (Kinnersley 1992).

The role of both the public and private sectors must be fully exploited with the challenge to maintain a balance between profit motivation and socially acceptable and sustainable irrigation schemes. It is likely a blend of the public and private sector activity which will produce most immediate and sustainable results.

Current world economic and financial problems have resulted in a shortage of public funding. Irrigation has traditionally been funded by government. The role of the private sector must be enhanced since, in the longer term, this shortage of public funds will likely prevail (Shady 1991).

3.6. CENTRALIZATION VS. DECENTRALIZATION

Planning, decision making and implementation of many irrigation agencies are centralized. These agencies are often structured top down with a result that policy and procedure governing water supply are not necessarily linked to the needs of the crop and the farmer. Centralized institutions tend to be bureaucratic and slow whereas decentralized institutions are more specialized and flexible. Decentralized institutions are often poorly coordinated and have a tendency to delegate functions to institutions before they have the mandate, skills or resources to effectively manage them (Guggenheim 1992).

Management of irrigation systems is conducted in a variety of settings. A wide variety of institutional framework exists involving various levels of government, water users and private entities (ICID Newsletter 1993). It is essential that the authority and responsibility be placed as close to the end user as possible. Specific socio-cultural characteristics and the history of each country must be accounted for along with the size of the scheme, technology and level of agricultural productivity. Most developing countries have limited money for operation and maintenance. Politically supportable water charge policies must be established for cost recovery, system management, and maintenance. All farmers who benefit must contribute to the cost of providing water. Generally, decentralization of operational and financial responsibilities are encouraged as is the involvement of water users in establishing rates (FAO 1986 b). A major challenge will be for developing countries to promote an institutional and technical framework to realize these decentralization initiatives.

3.7. FARMER PARTICIPATION

Many governments have recognized that the top down approach characteristic of traditional development strategies has failed to reach and aid the farmer. There is a high correlation between farmer participation in managing irrigation systems and sustainability (Pallas 1993). More involvement provides greater accountability, better service and increased crop productivity. This participation is also essential by need of the government to reduce expenditure as part of economic reform. An expectation exists that farmer participation would assist in the beneficiaries bearing more of the operating and maintenance costs creating considerable savings to public expenditures. An institutional challenge is to encourage farmers to initiate planning and action, and to adapt administrative procedures at all levels.

Formation of water users associations that represent the users at all levels of decision making in planning, management, and operation has been a key mechanism in involving the farmers in this process. The development of these associations has helped promote a socially cohesive behaviour in irrigation. This is essential since irrigation tends to constrain the freedom of individuals since irrigation users must follow the rules of the system (Barghouti and Hayward 1988). This involvement of farmers in the process has been found to be critical to the successful operation of a project. User managed schemes should be encouraged along with the decentralization of operational management to the district level. In addition, these farmer groups could be expanded to account for non-water factors essential to production and marketing.

3.8. EDUCATION AND TRAINING

Sound education, training, and technical assistance programs are essential to sustainable irrigation practice. Few irrigation managers are adequately trained and those that are, are often civil engineers with little experience in agricultural science.

Institutions must ensure that good information is developed and provided to the trainer and the end user (Hasan *et al.* 1993). Priorities in each country, state and region must be set on measures best suited to improved water use and management. Government agencies along with universities and private consultants must deliver the required training.

Improved on-farm water management is an essential area requiring additional training. Inefficient water use, poor distribution of water and low farm incomes are related to inadequate education and training (Bucks *et al.* 1990). Considerable attention must be paid to extension, farm credit and marketing. Good design, installation and equipment does not guarantee "per se" optimum yield and economic sustainability, but are essential.

3.9. WATER RESEARCH INSTITUTIONS

In order to respond to sustainable water issues, an institutional framework for research must be in place. Institutions originally evolved to meet problems that were relatively simple, acute, and localized. Today's problems are complex, global and chronic (Smith 1993).

Three implications arise from this. There is a need to develop institutions which encourage long term strategic research that is responsive to national policy needs. Research on water use is often fragmented among different departments and the cooperation is weak. An integrated cooperative approach is essential. There is a need to demonstrate that science is the foundation of good environmental policy and to effectively link the findings of research to policy development. And finally, training is necessary to ensure scientists are available to meet future problems (Smith 1993).

In many developing countries, research and demonstration to develop and improve indigenous capabilities is an area of chronic neglect (Shady 1991). Strengthening the institutions is essential to ensure continuity of improvement, adaptation to socioeconomic factors, inclusion of environmental issues and changes in technology.

3.10. IRRIGATION DELIVERY ORGANIZATIONS

Irrigation sustainability is dependent on the effective interface between crops and water, hence an integrated approach must be taken. It is impossible to divorce water delivery from crop uptake, thus the engineering and biological dimensions must be integrated.

In many countries, the institutions and organizations dealing with water management are numerous and complex (Tollefson 1993). Often, the responsibility for assessment and allocation of water resources along with the planning and construction of irrigation schemes is given to a national water resources institute staffed primarily by engineers. The on-farm management portion is handled by the ministry of agriculture. Lack of cooperation and coordination between these agencies have contributed to poor water use efficiency. It is essential to realize that the overall success of irrigation depends on the effective interface between crop and water. It is impossible to effectively divorce water delivery from crop use. The engineering and biological dimensions of the system must be integrated (Barghouti and Hayward 1988). Continuity must occur from planning through to implementation (Hasan *et al.* 1993).

In addition, institutions today are challenged to look at economic and environmental sustainability far more critically. No longer is their role primarily construction of capital works. This has lead institutionally to a requirement for a different set of disciplines. Rural development and environmental sustainability are now major objectives of these institutions. People involved in the irrigation industry must refocus intellectually to meet these requirements.

This shift is apparent in the U.S. Bureau of Reclamation where organizational changes have changed its emphasis from a construction agency to one which emphasizes more efficient water resource management. In Canada, the Prairie Farm Rehabilitation Administration (PFRA) has also changed its emphasis from a dam building construction based agency to one intent on rural development and environmental sustainability. The institutional challenge is to refocus to meet these needs with generally reduced budget scenarios.

3.11. SOCIAL ISSUES

Irrigation has a complex impact on human and physical environments both within and outside the irrigated area. The social dimension is particularly important to irrigation sustainability (Shady 1991). Three main social themes prevail: a) participation of beneficiaries in all aspects of planning, design and implementation of irrigation systems, b) participation of women in development issues at all levels, and c) equity of distribution of benefits favouring the disadvantaged groups.

It is well recognized that in most developing countries, the status of women ranks well below that of men. In education, health, wealth, etc., women are far worse off. These issues can be resolved by raising public awareness of gender issues. Under irrigated conditions, some countries have adopted policies of women's participation, yet it has been in the hands of individual engineers and planners to ensure these broad policies are carried out. Women are frequently excluded from the planning and implementation of projects. Data from Kenya and Zimbabwe (Grid 1993) reports that 50% of the irrigated labour is provided by women but that the number of women land owners, committee members and extension advisors is far below this. It is essential that the public is informed and that institutions ensure that gender issues are addressed.

To implement these actions requires a clear understanding of the value system of the society involved. These systems cannot be imposed. Finally, it is imperative that the social dimension be an integral part of irrigation research. Sociologists must be included along with engineers, agronomists, etc., to properly assess the impacts of irrigation.

3.12. ENVIRONMENTAL IMPACT

Agriculture development and irrigation schemes produce ecosystem changes. When poorly planned and implemented, sustainability is threatened. Many projects are deteriorating due to waterlogging, salinity, pollution and the spread of vector borne diseases (Pallas 1993).

Developing background information on a project's environmental impact early in the process assists decision makers with economic and engineering criteria. Identification of environmental issues early in the process can also allow them to be handled in a timely and cost effective manner.

An essential institutional challenge is the establishment of environmental agencies with regulations and support that results in a reasonable balance between conservation of the environment and development programs (Hennessy 1993). Finally, irrigators must become environmentally friendly through a better understanding of the total ecological system and by developing mitigating practices to reduce the negative effects (Shady 1991). Education and awareness are essential.

4. Summary and Conclusions

Irrigation development has played an important role in world food production. Despite its important role, it faces serious challenges in several dimensions. These dimensions include technical concerns, but in addition, also include institutional and social challenges.

Appropriate irrigation design does not guarantee sustainable irrigated production. An institutional framework must be in place which is capable of adapting to a rapidly evolving operational environment. One of the primary factors that will affect operations in the future is the need to connect national irrigation policies with food and water management policies more effectively. Food policies continue to change as food demands increase with increasing population and as increased food demands affect international markets. Social issues are also bringing about demands for change in irrigation institutions as people see irrigation as part of the equation for balanced rural development, and as gender issues and women's roles gain prominence. The social dimension must be an integral part of any irrigated research.

The benefits derived from irrigation come from economic activity and employment often derived beyond the farmgate. Farm benefits are often a small part of the total benefit and many projects become feasible only when other beneficiaries contribute to the cost. There has often been criticism of the economics of past irrigation development. This issue must be addressed in a consistent and integrated fashion with related institutional policies and funding arrangements for construction, rehabilitation and operation being dependent upon this relationship.

Irrigation projects have a better chance of long term sustainability if the water users can afford to pay for the operation and rehabilitation of projects. This change will likely become essential because of a need of governments to reduce expenditures as part of economic reform. Water users ability to pay depends, in turn, upon the price they receive for their products, which is greatly influenced by international market prices and government policies, especially food policies. As populations increase and food shortages occur, it is likely that food prices will increase, which in turn would tend to increase the sustainability of irrigation projects. There will likely be greater attention paid to the relationship of these factors as governments seek ways to limit expenditures on projects and when food shortages create domestic problems.

Decision makers have become reluctant to invest limited resources in new irrigation projects if there are alternate ways to increase food production, such as increasing the performance of existing projects. This has caused institutions to restructure and change their emphasis to wealth creation through more valuable crops, value added processing and rural development rather than focusing on new construction. Increased emphasis will be placed on diversification, marketing and value added processing.

Irrigation development has a complex interaction on both human and physical environments within and outside the irrigated area. Development of methodology to assess the long term impacts of irrigation on future generations and on ecosystems while maintaining an economically viable agriculture will be critical. It is becoming increasingly clear that environmental sustainability depends upon economically and socially viable projects.

Institutions are likely to include changes to the private vs. public sector mix, more decentralized decision making, and more participation of farmers in all levels of decision making. Other institutional options that may increase sustainability include water pricing, water conservation, education and training.

The operational environment which is forcing these changes is becoming clear. Irrigation institutions have often been sheltered from market forces in the past which has, to various degrees, ultimately caused trends toward non sustainability. The challenge to institutions is to analyze themselves within their operating environment and make changes that will lead to sustainability. This will likely mean adopting many of the institutional trends cited herein.

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HEALTH IMPACTS OF AGRICULTURAL DEVELOPMENT

IVANILDO HESPANHOL
World Health Organization, Division of Environmental Health
CH-1211 Geneva
Switzerland

1. Health, the Environment and Sustainable Agriculture

Every socio-economic development imposed by the modern society has direct or indirect effect on health and on the environment. Urbanization and provision of basic services, improvement of transportation and communication systems, industrial expansion, energy generation and agricultural development, while providing the basis for economic growth and improved quality of life, impose a heavy burden on natural resources and on the populations at risks.

Agriculture, forestry and fishing provide not only the food and natural resources on which human society depends, but also the livelihood of about half the world's population. Their output can only be sustained if the ecological systems on which they draw are not overexploited (WHO 1992). Water demand for irrigation represents a critical aspect in this respect: agriculture is dependent on water supplies to such an extent that food sustainability cannot be attained without appropriate water resources development and management. In contrast to the last two decades, increases in agricultural production can no longer occur through the expansion of cultivated land. With few exceptions such as North-East Brazil, where large areas of land are now being reclaimed for agricultural use, arable land is approaching limits to expansion. India has exploited practically 100% of its land resources for agriculture, while only 3% is left for further lateral expansion in Bangladesh. Pakistan, the Philippines and Thailand still have a potential for expansion of about 20%. The global rate of increase of arable land and permanent crops has declined from 0.4% during the decade 1970-1979 to 0.2% during the period 1980-1987. In the developing countries as a whole, the rate of increase also declined from 0.7 to 0.4%. If irrigation represents the only prospect for food security, a worldwide commitment to the protection and management of water resources will be mandatory in maintaining water quality, and in coping with the extraordinary volumes needed in the near future. The misuse of agricultural chemicals, particularly in developing countries, are damaging water resources. Drainage water often contains high levels of pesticides, salts and nutrients, leading to increasing toxicity, salinity and eutrophication of lakes, reservoirs and coastal waters, and groundwater pollution.

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 61–83.

The interactions of environment, food, water and health are complex. The production of food affects health by way of nutritional status and by diseases related to agriculture, fishing and the contamination of food and water. Changes in food production and those in the environment resulting from them may influence human health directly, or indirectly when they affect the disposable income of members of the community. On the other hand, in view of trends in population growth, the demands likely to be placed upon the food and agriculture sectors in the future, and the associated potential for adverse environmental change such as deforestation, soil degradation and water pollution, call for the urgent need to address the problem in an adequate and timely manner to avoid irreversible damage to the environment and serious consequences to human health on a global scale.

Figure 1 illustrates how the changes in the environment and in the community's vulnerability affects the health status of populations exposed to major water development projects (Birley 1989).

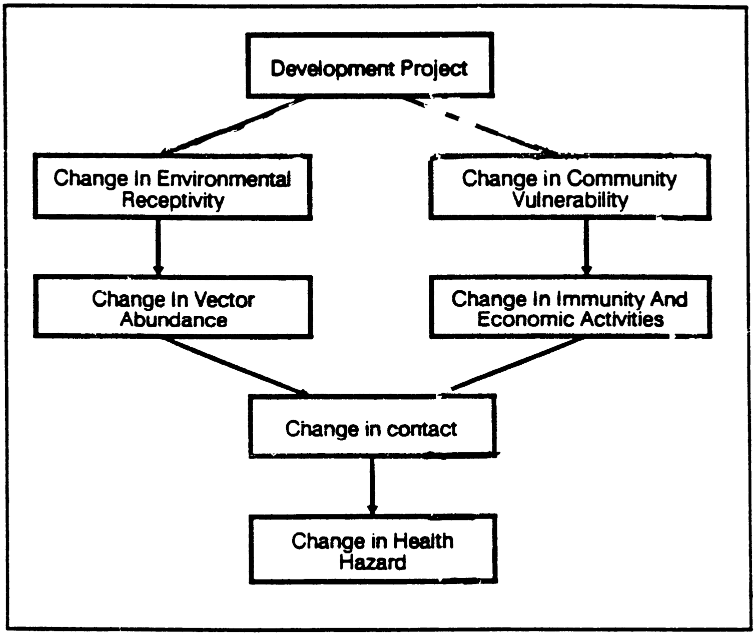


Figure 1. Health changes in association with water development projects (Birley 1989)

2. Health Hazards in Agriculture

Human health is threatened by most agricultural developments both in the industrialized as well as in developing countries. Basic health risks are occupational diseases, particularly among primary producers. These are basically vector-borne diseases (such as malaria, schistosomiasis, filariasis, etc.), zoonoses, (infectious diseases, naturally transmitted between animals and men such as anthrax, rabies, tuberculosis, toxoplasmosis, tularaemia, brucellosis, etc.), chemical exposure, particularly in relation to excessive application of fertilizers, and accidents associated with machinery and unguarded equipment, falls and poisoning.

The socio-economic structures and agricultural policies, particularly the ones related to land tenure and land acquisition and distribution are also important factors affecting the health of the poor in agricultural development.

2.1. VECTOR-BORNE DISEASES

Irrigation schemes, especially in the tropics, carry a high risk of introducing or increasing the risk of transmission of water-borne diseases (cholera, typhoid fever, etc.), water-based infections (schistosomiasis, dracunculiasis, fascioliasis, etc.) and water-related vector-borne diseases (yellow fever, African trypanosomiasis, etc.). More than 30 diseases have been linked to irrigation, the major being schistosomiasis, malaria, onchocerciasis, and Japanese encephalitis. Figure 2 indicates the principal habitats of the vectors or intermediate hosts associated with each of the principal diseases.

It must be pointed out that a development project will alter the environment and may create a habitat which was not previously present. If a disease occurs within the region and a habitat is created for the vector then, sooner or later, the habitat will be invaded and transmission may occur.

Six environmental changes brought about by irrigation practices that may affect health are: simplification of the habitat; increase in the area of the habitat; increase in the area of surface water; a rise in the water table; changes in the rate of water flow; a modification of the microclimate; and urban development (Surtees 1975). Different types of irrigation systems (surface, subsurface, sprinkling, permanent flooding, trickle and drip irrigation) and different water distribution cycles have different effects on the transmission of vector-borne diseases (Goonasekere and Amerasinghe 1987).

The irrigation schemes that appear to present the greatest risk of increased transmission of vector-borne diseases are those located where: soils present drainage problems, rice is cultivated, reservoirs are constructed, canals are unlined, there is compacted settlement or resettlement. Rice production, for example, which continues to expand in most of Southeast Asia, the Western Pacific and in many countries of Africa and South America brought a substantial increase in vector-borne disease incidence and prevalence. Recent estimates indicate that rice areas that are flooded for various periods cover 0.44% of the total West African cultivated land and exposed at least 7.2% of the rural population to the associated risks of vector-borne diseases, in particular, malaria and schistosomiasis (Verhoef and Slooff 1994).

Another aspect which determine substantial health problems in agricultural development is human migration. The *settlement phase* is usually accompanied by an intensification of communicable diseases and health problems related to physical stress (fatigue, undernutrition, malnutrition) or psychological stress associated with the adjustment to different conditions and situations. The morbidity and mortality from vector-borne diseases will be determined by the enhanced risks of transmission and, in the case of malaria, the spread of drug-resistant parasite strains. In the long term, during the *post-settlement phase*, new settlers will be faced with the high risks of vector-borne diseases that are associated with the ecological conditions of river valleys as compared with the upland areas where they, in many instances, came from.

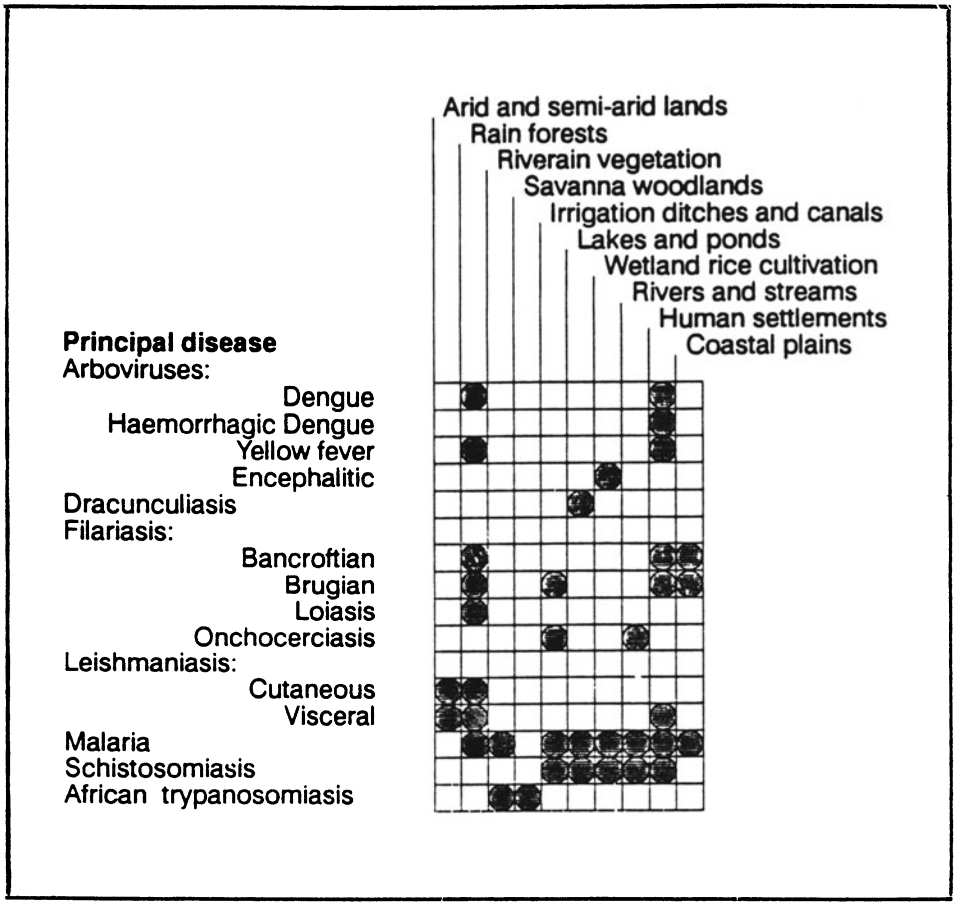


Figure 2. The principal diseases associated with water in relation to the principal habitats of the vectors (Birley 1989)

2.2. CHEMICAL HAZARDS

Agrochemicals are one of the main farm inputs affecting the health of agricultural workers and their families and the environment, particularly surface and groundwaters. These are: naturally occurring soil chemicals; organic additives (mainly animal and vegetable manures and composts); and inorganic compounds (mainly nitrogen, phosphorus and potassium-based fertilizers, herbicides, insecticides, and fungicides). With exception of insecticides, very little is know about the direct and indirect effects of these chemicals. Yet on the farms of poor and vulnerable groups, particularly in Africa, the available nitrogen, phosphorus and potassium comes overwhelmingly from the soil, secondly from organic additives, and least from inorganic compounds. The use of herbicides and pesticides by such groups is very limited. Only in a few countries in the developing world, such as north-east Mexico, the Punjab, Taiwan and Central Luzon, are inorganic fertilizers and pesticides intensively used by small farms. For most poor people, the threats to food production and hence health in this respect are the vulnerability of plants to nitrogen and phosphorus deficiency, weeds and insects, fungi and viruses and shortfalls of output due to inaccurate use of manures and composts.

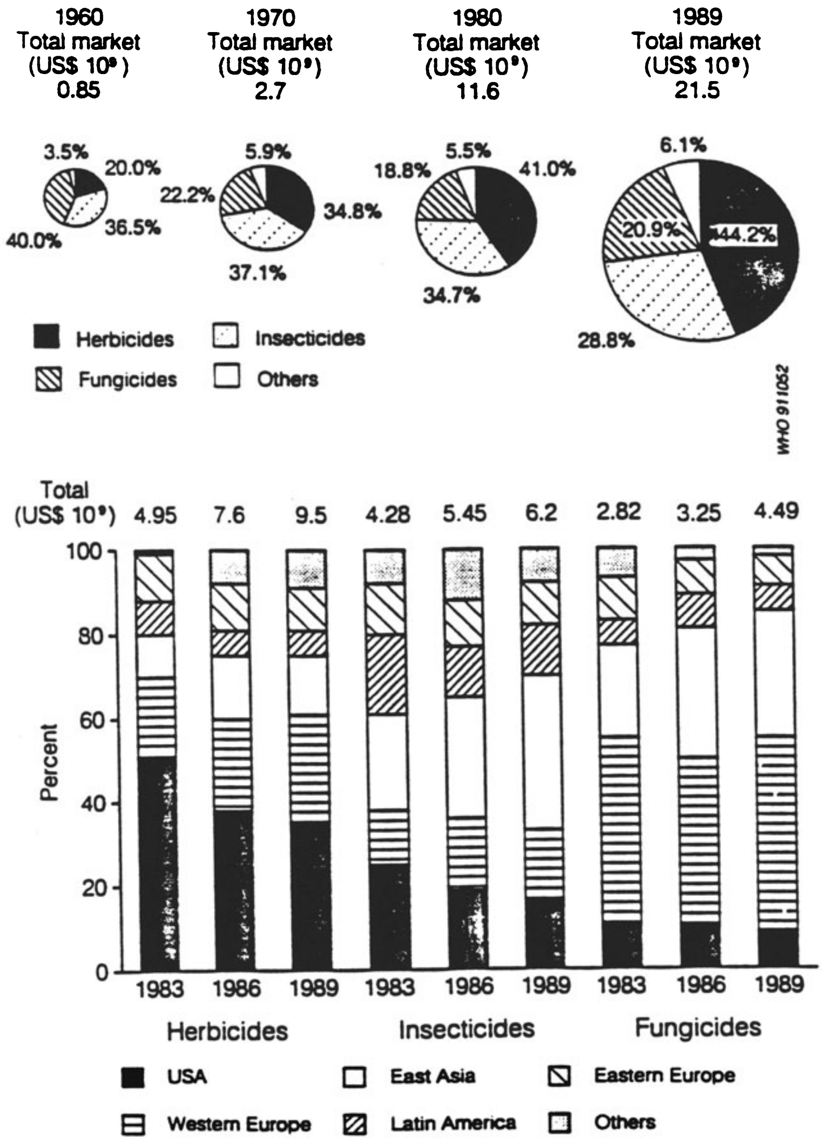
Insecticides save tens of millions of tons per year of staple foodstuffs for human use, and greatly increase the employment income of poor people, and hence nutrition and health, from non-food and food crops alike. However, the vectors of diseases develop resistance to an ever broader spectrum of insecticides, so that, over the years a wider variety of chemicals and increasing amounts and strengths of insecticide must be used to achieve the same level of plant protection. With some crops, notably cotton and tobacco, pesticides destroy natural pest predators together with disease vectors, reducing ultimately, the overall plant protection.

Pesticides are used throughout the world, the intensity of use depending on a number of factors, such as the dominant crops, stage of development of the country, climatic conditions, and the prevalence of pests. Since the years between the First and Second World Wars when the number and complexity of chemicals for crop protection increased, and since the 30's, when Dinitro-orthocresol and Thiram, the first dithiocarbamate fungicide were patented, respectively in France and in the United States, the production and use of pesticides has continuously increased all over the world. Box 1 shows the growth of the worldwide pesticide market and the percentile markets in regions of significant consumption. The largest consumers of pesticides are the United States, although on per hectare basis, European countries utilize higher levels.

Different groups and segments of a population are exposed to pesticides in different ways and in different degrees. As indicated in Figure 3 some exposures are unintentional and some are intentional.

Intentional exposure (mainly attempted or successful suicides) make up a large proportion of the poisonings by pesticides of high toxicity in certain developing countries. In Indonesia, Malaysia and Thailand, for example, the proportion of acute pesticide poisonings that are suicide attempts has been reported to be 62.6%, 67.9% and 61.4%, respectively. When such compounds are easily available in many households, they may become "the method of choice" for individuals with suicidal intent. No systematic population-based data on the role of pesticides in homicides are available, but it is likely that highly toxic pesticides would be used by people with homicidal intent in countries where they are easily available (WHO/UNEP 1990).

Box 1 - The growth in the world pesticide market, 1960-1989



Source: International Group of National Associations of Manufacturers of Agrochemical Products.

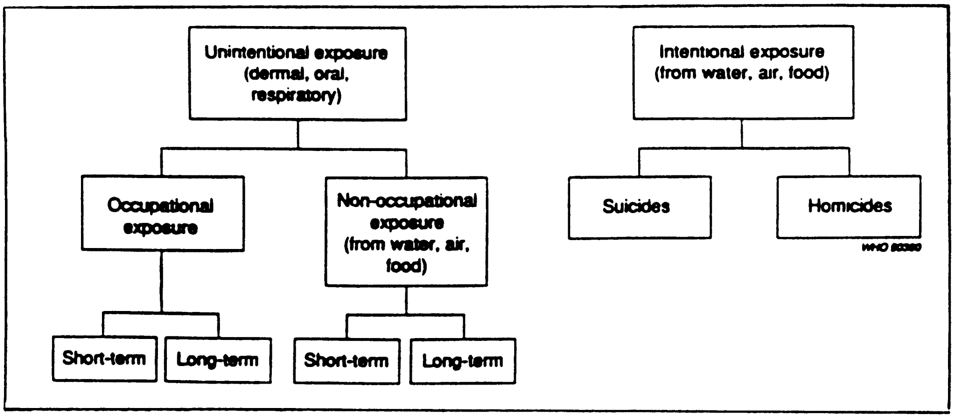
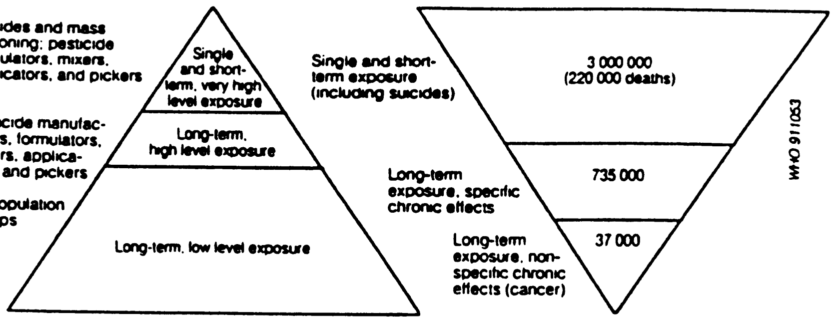


Figure 3. Types of exposure to pesticides

The majority of cases of unintentional exposure are of occupational origin, occurring largely among plantation workers and farmers mixing or using pesticides. Occupational exposure may lead to short-term (acute) or long-term (chronic) effects. A large number of reports are available on acute effects relating particularly to chemical burns of the eye, skin damage, neurological, and liver effects. Chronic effects associated with occupational exposure may lead to bone marrow effects; cancer linked to the use of arsenical and organochloride pesticides; reproductive effects such as male infertility in association with exposure to the nematocide dibromochloropropane; cytogenetic effects such as increased chromosomal damage, and neurotoxicity in association with phenoxy herbicides, arsenicals, methyl bromide, and rodenticides containing thallium. Some behavioural changes have been noted in several cross-sectional epidemiological studies among pest control workers, farmers, and manufacturing workers, and behavioural impairments have been associated with pesticide exposure in serious accidents among agricultural workers.

Acute non-occupational exposure are associated with accidents resulting from unsafe packing and leakage of pesticides during storage or transport. Other accidents have occurred where insecticides that have been found to be effective against one type of pest have been incorrectly and dangerously used against other pests, such as bed bugs or body lice, and have resulted in poisoning. Improper use of pesticides has resulted in serious outbreaks of poisoning. For example, 1350 cases and eight deaths occurred in California among people who consumed water melons that have been treated with aldicarb, a systemic pesticide not registered for such use. Chronic non-occupational diseases can produce: (a) reproductive effects - exposure to phenoxyacid herbicides (e.g., "Orange Agent") is associated with an increased risk of abortions and malformations in offsprings. A similar association has also been suspected in general population exposure to chlorinated hydrocarbons, but so far no satisfactory investigation has been carried out; (b) immunological effects - associations were found between the amount of pesticide used in the area, and both the occurrence of immunological imbalance, and the incidence of infectious disease in children; (c) respiratory effects - some cases of asthma have been reported to be linked to exposure to organophosphorus pesticides, but it is uncertain whether it was the active ingredient or another component in the formulation that produced the effects. The possibility has been studied that paraquat may have been the cause of chronic fibrotic changes seen in the survivors of suicide attempts, and (d) ophthalmological and neuro-ophthalmological effects - optic nerve atrophy has been noted in case reports following exposure to methyl bromide. Box 2 illustrates the population groups at risk and the estimated overall annual public health effect of pesticide use.

Box 2 - Population groups at risk from pesticides and the overall annual public health impact



Source. *Public health impact of pesticides used in agriculture* Geneva. World Health Organization. 1990

The use of pesticides in agriculture may also have long-term effects on the general environment, particularly in water and soil, leading to potential threats to sources of drinking water, crops, and food.

Water - Many human diseases vectors are controlled through the spraying or treating of surface water with insecticides. Herbicides are often applied to water in tropical areas to control aquatic weeds. In addition, water may be polluted by: discharges of surplus pesticide, after spraying operations; water used for washing spraying equipment being poured into rivers, ponds, or lakes; crops to be sprayed being planted right up to the water's edge; accidental spillage of pesticide formulations; run-off, leakage, and erosion from treated soils; fall-out of pesticides from polluted air; application of pesticides to rivers or ponds to kill fishes, which are then removed and eaten. According to data provided by the GEMS/WATER Programme (WHO/UNEP 1989), on a global level, three chlorinated insecticides were found in natural waters namely DDT and its metabolites, aldrin and dieldrin. However some countries have also reported the occurrence of other insecticides such as the isomers of hexachlorocyclohexane (HCH), as shown in Table 1.

TABLE 1. Levels of pesticides measured in natural waters at global level (WHO/UNEP 1989)

Levels of contamination	< 10 ng l^{-1}	10 - 50 ng l^{-1}	100 - 1,000 ng l^{-1}	> 1,000 ng l^{-1}
Africa				Tanzania (1) dieldrin
Americas	Canada (5) USA (12)			Colombia (1). dieldrin DDT
Asia	Thailand (3) Japan (5) Malaysia (5)		China (4) HCH Thailand (1): DDE	Malaysia (1): dieldrin
Europe	Finland (5) Netherlands (6) UK (7)	Belgium (1) DDE Finland (1): DDT Spain (6): DDT UK (1): DDT, aldrin, dieldrin, HCH		
Oceania		Australia (1)		

The numbers in brackets indicate the number of monitoring stations

Soil - Soil may be deliberately treated with pesticides to control insects, nematodes, or diseases. In addition, it has been calculated that as much as 50% of the pesticides sprayed on crops or used as herbicide miss their targets and fall on to the soil surface. Some pesticides, notably organochlorines, may persist for years, even though a large proportion evaporates.

Pesticides may be taken up from the soils by crops, especially root vegetables, such as carrots. If grass is grown, the residues in the grass may be ingested by herbivores such as cattle, and eventually find their way into meat or milk. Fortunately, some pesticides become adsorbed on clay particles and organic matter in soils in a form which is not readily taken up by plants. There is still however, a danger of their polluting groundwater supplies.

Crops - The concentration of pesticide on a crop directly after spraying needs to be high enough to be effective against the pest. The ratio between the effective concentration and the concentration that will affect human health if the crop is consumed is of major importance in assessing the hazard associated with exposure. Pesticides on crops will evaporate, be washed off, break down, or become absorbed into the plant material. The concentration also drops as a result of dilution as the plant grows. Because the concentration of the pesticide in and on the crop decreases, a pesticide application that was initially very toxic to human subjects may, with time become harmless. For this reason farmers are advised not to spray just before harvest, and in many developing countries, the "waiting periods" are formally established, and are part of good agricultural practice.

Food and human milk - Apart from direct contamination caused by spraying, there are various other ways in which food stuffs can be contaminated. For example, meat may contain high levels of pesticides because they become concentrated in certain tissues, following cattle dipping or vector treatment. Fish caught in pesticide treated rice paddies may also contain significant levels of pesticide residues.

Treatment with pesticides to prevent losses of food during storage or bulk transport also creates a hazard. The losses caused by arthropod pests and rodents can be extremely heavy and it is a common practice to treat food and grain with pesticides, more or less indiscriminately, to avoid such losses. Food treated in this way may contain high concentrations of pesticide.

In times of shortage, there have been many instances of pesticide-treated seed grains being eaten by people or domestic animals, either accidentally or intentionally and producing mass poisoning.

The contaminants found most frequently in human milk have been DDT, its main metabolite DDD, hexachlorobenzene, hexachlorocyclohexane, dieldrin, heptachlor epoxide, and the non-pesticide polychlorinated byphenyls. Data on pesticide residues in human milk have been recently collected and evaluated by the Joint UNEP/FAO/WHO Food Contamination Monitoring and Assessment Programme - GEMS/FOOD, (UNEP/FAO/WHO 1993). A summary of the data and estimations of intake for certain pesticides are given in Table 2 (GEMS/FOOD, 1986).

TABLE 2. Estimates of intake of selected pesticides from human milk (GEMS/FOOD 1986)

Pesticide	Estimated intake
aldrin and dieldrin	Data from 11 countries indicate that, in all cases, the 90th percentile exceeds the maximum ADI of 0.1 µg/kg of body weight by up to ten times. Most median values also exceed the ADI
DDT complex	On the basis of an "acceptable level" for DDT in milk (see text) of 167 µg/kg, the ADI was exceeded at the 90th percentile level in recent years only in Guatemala. The 90th percentile intake amounted to approximately 70% of the ADI in the USA in 1979
lindane	Data submitted on median and 90th percentile levels of lindane in human milk indicate that in all cases the estimated intakes were well below the maximum ADI of 10 µg/kg of body weight, never exceeding 10% of the ADI even at the 90th percentile level
heptachlor and heptachlor epoxide	At the 90th percentile level, the calculated intake at times constituted an appreciable percentage of the ADI; in the USA (1975 and 1979) and Switzerland (1974) this calculated intake amounted to approximately 85% of the ADI. Calculated 90th percentile intakes in Guatemala (1974) and Japan (1978) were at approximately the 75% level, but decreased in subsequent years

2.3. LAND TENURE AND DISTRIBUTION

Lack of or insufficient land for agriculture is also a major negative influence on health and nutritional status. Several studies confirm that the size of a rural family's operational landholding (from zero upwards) is strongly and positively related to its income, consumption, and hence health status and risks (Cooper Weil *et al.* 1990). The nature of land tenure also influences the level of production, income, and investment. However, if tenants are not really poor or less well-off than owner-farmers, then it should not be expected, in general, major health gains from a tenancy reform. On the other hand, land redistribution, involving the subdivision of large farms into small family-farmed holdings, would not only increase many poor people's access to income and hence to food and health, it would also usually raise agricultural output in the medium term (Lipton and de Kadt 1988). Box 3 depicts a situation in north-east Brazil, a region long associated with high levels of poverty and emigration.

Box 3 - The links between poverty and ownership

A World Bank study shows that the main cause of poverty and emigration from north-east Brazil is not lack of land but a land-owning structure that keeps large amounts of high-quality land unused or underused. The study states that nearly one million farms or share-cropped plots in the north-east provide an acceptable standard of living for farmers. There are also "nearly 30 million hectares of under-utilized land of similar if not superior quality on the estates" on which "nearly another million families could achieve comparable living standards". Most of this land is unused or underused and is the property of large landowners; just 4% of landowners own more than half the agricultural land and only one in four households dependent on agriculture owns the land it works.

Transfer of this land to those with no land or too little land could provide adequate incomes for perhaps another million families. The smallest farmers in the region "employ 25 times more labour per hectare on their land than do the largest farms and obtain vastly higher productivity levels. The smaller farms (less than 50 hectares) cover only 10% of the agricultural land, produce over 25% of the region's sugar, cotton, and rice and 40% of the beans, corn, and manioc. Yet two million agriculturally dependent families own no land at all, while an area of land the size of France is unutilized or underutilized."

Such a land transfer would bring a major stimulus to agricultural production (which would help feed city populations) and also to small urban centres.

Source: Kutcher G P & Scandizzo, P L. *The agricultural economy of north-east Brazil.* Baltimore, MD, Johns Hopkins University Press, 1981.

A reallocation of land currently unused or underused by large landowners to small farms would mean a large number of additional households with adequate incomes and a large increase in food supplies. It must be stressed that the most immediate impact of land reform distribution policies on health may, in some instances, be a negative one, quite apart from any effects it may have on income. Land distribution schemes and policies promoting the colonization of new lands, especially forested areas, may directly increase the risk of major vector-borne diseases such as malaria and leishmaniasis. A well documented example is that of the Brazilian Amazon, where the opening of the roads (such as the "Trans-Amazonica") and the distribution of parcels of land to landless farming families have encouraged an enormous flux of farms, farm labourers, miners, loggers, and others. The major effect on health has been a serious resurgence in malaria, which is concentrated in settlements, mining, and periurban areas across the region.

3. The Use of Wastewater for Irrigation

In the arid and semi-arid regions of the world, water has become a limiting factor to agricultural and industrial development. Governments are searching for unexploited sources of water which can be economically and effectively used to supplement scarce water resources. Many Eastern Mediterranean countries, where rainfall is about only 100 millimetres per year, rely on a few perennial rivers, wadis and groundwater reservoirs usually located in mountainous regions. Drinking water is usually supplied through expensive and difficult-to-operate desalination systems and more than 50% of the food demand is supplied through importation. In these regions, low quality waters such as drainage water, brackish waters, and, particularly wastewater, represent a valuable resource which can be reclaimed and used for irrigation of crops, aquaculture or other beneficial uses such as industrial processes or groundwater recharge. The city of Muscat, in the Sultanate of Oman, with a population of 350 000, an average consumption of 250 litres per day and per capita, and a return flow of 80%, will produce about 70,000 cubic meters of wastewater per day or 25 million cubic meters per year. At an application rate of 2 meters per year, this water could be enough to irrigate about 1,250 hectares (Hespanhol 1993).

Following the increasing use of wastewater for irrigation since the 20's, many directives and codes of practice were produced in many parts of the world, aiming at the protection of the soil, crops, and the health of the groups at risk. In 1918, the California State Department of Health set a criteria for irrigation (California State Department of Public Health 1968). Several revisions made over the years have turned this legislation into one of the most complete and restrictive in use today. In 1971, the WHO Meeting of Experts on the Reuse of Effluents (WHO 1973) recognized that the extremely strict California standards for reuse were not justified by the available epidemiological evidence, and recommended a microbiological guideline for the unrestricted irrigation of vegetables eaten cooked of no more than 100 total coliforms per 100 ml. The meeting also felt that there was a need for wastewater irrigation guidelines to be given a sounder epidemiological basis, and recommended that this matter be fully investigated. Since then, major efforts have been made by WHO, the World Bank, the United Nations Environment Programme, the United Nations Development Programme, the Food and Agriculture Organization, and many academic institutions throughout the world to provide a more rational epidemiological basis for wastewater irrigation guidelines. Extensive new epidemiological evidence has been accumulated, and earlier studies and reports have been evaluated. The findings of these studies have been carefully reviewed by leading public health experts at many national and international meetings and consultations. The consensus view of the epidemiologists and public health experts who have revised these data agreed that the actual risk associated with treated wastewater is much lower than previously estimated, and that the early microbial standards and guidelines for effluent to be used for unrestricted irrigation of vegetables and salad crops normally consumed uncooked were unjustifiably restrictive, particularly in respect to bacterial pathogens. On the other hand, they considered it unjustified to disregard parasitic diseases which were, according to epidemiological evidence, the main risk for individual and public health associated with the use of insufficiently treated wastewater in agriculture. On the basis of this evidence, the Scientific Group on Health Guidelines for the use of wastewater in agriculture and aquaculture held in Geneva in 1987 (WHO 1989), supported by this preparatory work and the epidemiological evidence currently available established the basic criteria for health protection of the groups at risk in reuse systems, and recommended the guidelines shown in Table 3.

TABLE 3. Recommended microbiological quality guidelines for wastewater use in agriculture (WHO 1989)

Category	Reuse conditions	Exposed group	Intestinal nematodes[b] (arithmetic mean no. of eggs per litre[c])	Faecal coliforms (geometric mean no. per 100 ml[c])	Wastewater treatment expected to achieve the required microbiological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[a]	Workers, consumers, public	⩽1	⩽1000[d]	A series of stabilization ponds designed to achieve the microbiological quality indicated, or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees[e]	Workers	⩽1	No standard recommended	Retention in stabilization ponds for 8–10 days or equivalent helminth and faecal coliform removal
C	Localized irrigation of crops in category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary sedimentation

[a] In specific cases, local epidemiological, sociocultural and environmental factors should be taken into account, and the guidelines modified accordingly.

[b] *Ascaris* and *Trichuris* species and hookworms.

[c] During the irrigation period.

[d] A more stringent guideline (⩽200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.

[e] In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

These are related to the category of crops, reuse conditions, exposed groups and appropriate treatment systems, to achieve microbiological quality. The guideline values are supported by epidemiological evidence rather than being based on microbiological criteria as had been the practice in the past. This involves the concept of "real" or "attributable" risk which introduces in the epidemiological chain physical and social factors, such as acquired immunity and the susceptible/immune population ratio, which affect the probability of developing disease as a result of exposure to reuse. For the first time, a guideline value on intestinal nematodes has been recommended, supported by epidemiological evidence from studies made in Germany, India and Israel on the incidence of ascariasis on field workers and consumers of crops irrigated with wastewater (Shuval *et al.* 1986). In fact, intestinal nematodes present the highest risks of wastewater related disease transmission, due to their long survival periods in soil, long persistence in the environment, a low infective dose, practically no host immunity and the limited possibility of concurrent infection in the home.

Countries utilizing wastewater for agriculture, or planning the implementation of reuse systems should consider the development of national standards and codes of practice for reuse, by adapting the WHO guidelines to their national priorities and taking into account their technical, economical, social, cultural and political characteristics and constraints (Hespanhol and Prost 1994).

Due to the short period of time which elapsed since the publication of the WHO guidelines for reuse, there is still not enough data available to identify the level of health protection provided by irrigation with treated wastewater which comply with the proposed guideline values indicated in Table 3. However, a cross-sectional epidemiological study made in the Mesquital Valley, Mexico, indicated, based on the preliminary analysis of the wet season data, that the increased risks of Ascaris infection and diarrhoeal disease from the use of raw wastewater are removed when wastewater of WHO guideline for reuse quality from storage reservoirs is used (Blumenthal *et al.* 1991/1992). On the other hand, the use of raw wastewater for irrigation has been associated with the prevalence of many diseases such as ascariasis, typhoid fever and cholera. Figure 4 shows the relation of cases of cholera which occurred in Jerusalem in 1970 and the irrigation of vegetables and salad crops with untreated wastewater. The outbreak of cholera which occurred in Chile in April 1991 was associated with raw wastewater used to irrigate 13,500 hectares of vegetables and salad crops. The outbreak occurred during the irrigation season and 68% of the 41 cases identified had consumed wastewater irrigated salads crops eaten uncooked (Shuval 1993).

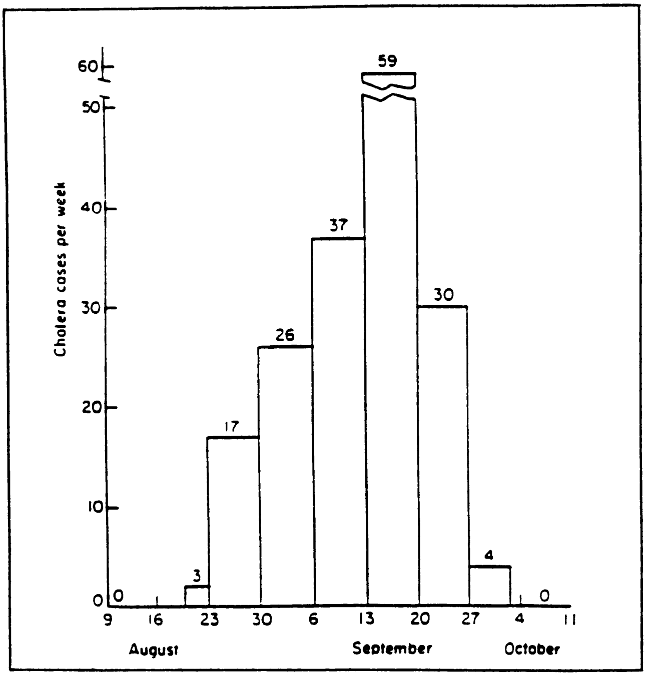


Figure 4. Weekly distribution of cholera cases in Jerusalem duringAugust-September 1970 (n=176). Irrigation was stopped during the week beginning 13 September (Shuval *et al.* 1986)

4. Health and Environmental Safeguards

Sustainable development lies in two basic fundamental factors: control of population growth and the adequate use of non-renewable resources. The pressures of growing populations on demand, particularly in the developing world, and the increasing consumption of rich countries will exploit natural resources and increase the generation of wastes to such a level that the environmental base on which health and survival depend will be definitely lost. Agriculture is one of the developmental sectors mostly affected by these tendencies: the ecological base for feeding the world's population is under stress owing to the increasing food demand and the rapid degradation of land and water resources.

Although both environmental degradation and agricultural development affect health in the short run, increasing food demands on agriculture may produce cumulative and long-term environmental changes that may themselves endanger human health. However, certain strategic principles can promote health and more sustainable patterns of food production. They include the implementation of adequate policies, utilization of adequate technology and strategies, and reduction of food losses before and after harvesting. The health and environmental aspects associated with these strategic principles are presented below.

4.1. AGRICULTURAL POLICIES

Governments should integrate health goals in their agricultural policies. Health promotion and disease control considerations should be included as basic directives for the planning, construction, management and operation of agricultural systems, including management and operation of water resources and land developments.

In many regions, particularly in the developing world, where the legal relationship of farmers to the land have an important influence on income, consumption, nutrition and health status, adequate policies for land tenure and land distribution, as well for population resettlement should be established and implemented.

The development and effective implementation of health and environmentally sound policies can only be achieved through integrated action of correlated ministries (planning, environment, health, water resources, agriculture), non-governmental organizations, and with the cooperation of major international development agencies.

4.2. APPROPRIATE TECHNOLOGY AND STRATEGIES

Appropriate technology and strategies for incorporating health safeguards in agricultural projects are basically associated with the prevention and control of vector-borne diseases, the prevention of pesticide poisoning and provision of adequate schemes for the safe use of wastewater for irrigation, where the practice is adopted. Other relevant aspects such as appropriate technology for design, construction and operation of irrigation canals systems, drainage, wastewater treatment for reuse, supply of safe drinking water and basic sanitation facilities will not be in included in this paper.

4.2.1. *Integrated Control of Vector-borne Diseases*

The effective control of vector-borne diseases can be achieved by integrating three basic strategies:

a. Chemical vector control, aimed at reducing vector densities or vector lifespan to interrupt or decrease disease transmission. It can be achieved through the use of pesticides, repellents, chemosterilants, etc. The concept of pest control based solely on the use of chemical products is being abandoned in most countries, particularly in the industrialized world.

b. Biological vector control is also aimed at reducing vector densities or vector lifespan to interrupt or decrease disease transmission, but based on natural predators, microbial insecticides and genetic manipulations. These are naturally occurring, or introduced, biological agents that can help to limit the abundance of vectors and the incidence of plant or animal diseases. Whenever possible, biological control measures should be used, although the extent that these can provide the necessary control may be limited. However there have been a number of successes, particularly in relation to pests introduced from other countries. Pheromones are becoming increasingly useful, especially for lepidopterous control, and considerable progress has been made with control of cut worms. One of the main problems with pheromones is their high degree of specificity and the need for a different pheromone for every pest. The release of sterile males is very effective for certain vectors such as the tsetse fly.

c. Environmental management, means the management of environmental determinants with the objective of achieving an optimal health status for a target population (Bos 1993). In terms of vector control, it is aimed at the reduction of breeding sites. Environmental control includes three types of basic measures which can be implemented individually or in combination (WHO 1982):

- Environmental modifications are permanent or long-term physical alterations of land, water and vegetation, aimed at preventing, eliminating or reducing vector habitats. To be effective in the long run, such works will require proper operation and maintenance;

- Environmental manipulations consist of any planned recurrent activity aimed at producing temporary conditions unfavourable to vector breeding sites or habitats.

  A good example of environmental manipulation is the alternate wetting and drying irrigation system modernly utilized in rice fields. The primary concern with water in rice fields relates to its abundance and long duration which are favourable to the breeding of mosquitoes. It takes about 9-14 days to complete the reproductive cycle of a mosquito from the ovulation to the adult mosquito stage. Since rice fields are most often kept flooded with a shallow depth of water for almost the entire duration of the plant growth, many life cycles could be completed during a growing season. Fields grown to a second or a third crop of rice could become almost a perennial ground for multiplication of mosquitoes. The wetting and drying method is highly effective provided the drying cycle is long enough to destroy the larvae and the wetting cycle short enough not to allow mosquitoes to multiply (Bhuiyan and Sheppard 1987).

- Modification or manipulation of human habitation or behaviour is intended to reduce contact with vectors or unsafe water. Measures are aimed at reducing man/vector or man/pathogen contact, such as mosquito proofing of houses, personal protection measures and health education. In some circumstances other additional actions must be taken to avoid excessive disease proliferation. This is the case, for example, where local populations utilize small impoundments for a variety of purposes, including water supply, bathing, fishing, animal watering, irrigation and flood control. The aggregate impact can be much higher, since the human and animal contact with water are more frequent.

Figure 5 illustrates some examples of specific environmental management measures and the groups of vectors on which they may have beneficial impacts.

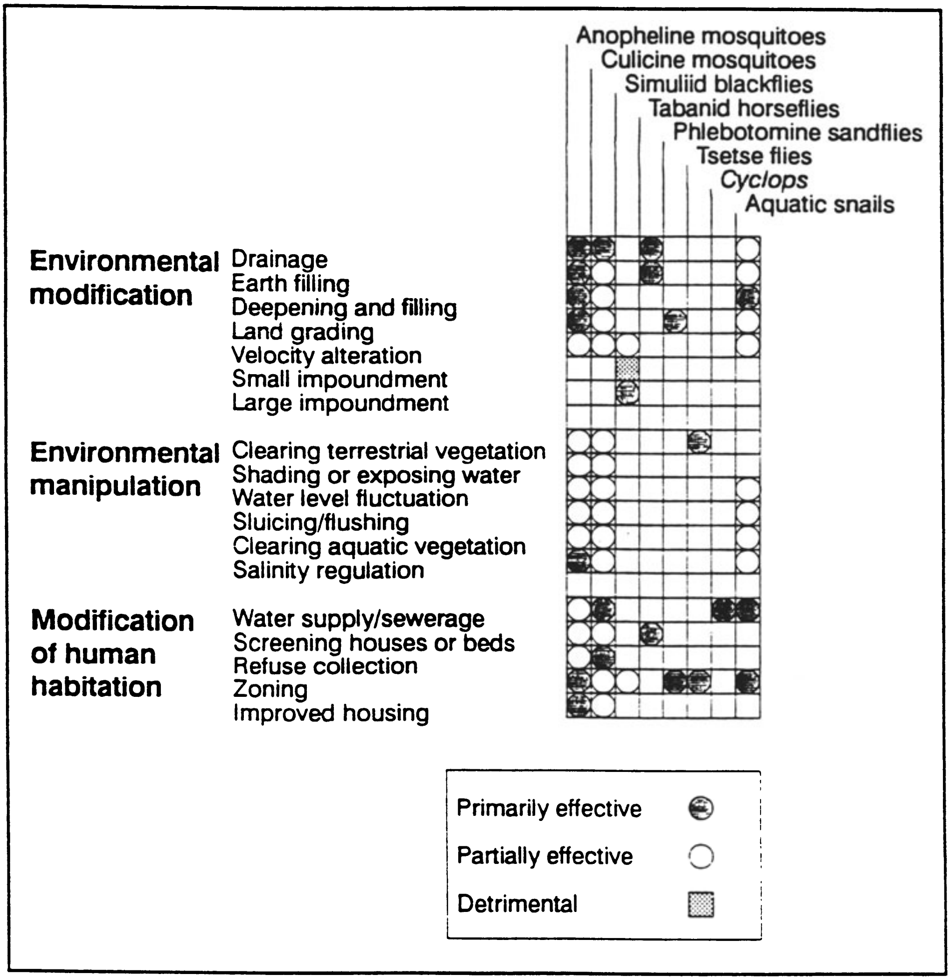


Figure 5. Examples of environmental management measures for vector-control and the vector groups which may be affected (Birley 1989)

Adequate planning is required to establish the most adequate combination of the above strategies for effective vector-control achievement. It is important to note that some environmental management measures, for example control structures provided for channels, steepness of water channel banks, or sites and layout of new settlements, can only be selected at the design stage. On the other hand, the choice of adequate technologies and strategies at the planning level may reduce the costs of maintaining acceptable levels of health during the operational phase.

As a last consideration for the overall planning, it should be taken into account that although biological control methods are sometimes not fully adequate to control major pests, they can be incorporated into integrated control and pest management programmes to provide satisfactory control with minimal environmental problems.

4.2.2. *Prevention of Pesticide Poisoning*

Owing to its extensive health impact, as shown in Box 2, a major effort is required to prevent the millions of cases of pesticide poisoning that occur every year. Intentional poisoning such as suicides, homicides and mass poisoning may be reduced only by prevention, by making highly toxic pesticides less available to people not actually engaged in their application.

Unintentional poisoning, particularly in developing countries, occur mainly during the handling and application of pesticides. The occurrence of health hazards are normally due to lack of information, knowledge, and awareness, poor supervision during spraying, absence of proper legislation or of enforcement of legislation, and sale on the open market of highly toxic pesticides. Actions to improve safety are associated with:

a. Technical guidance
FAO, in consultation with WHO and other UN Organizations, has prepared a Code of Conduct on the Distribution and Use of Pesticides, based on internationally agreed technical guidelines. It defines the responsibilities of, and establishes voluntary standards of conduct for the various sectors of the society, including government and industry, in order to reduce the hazards associated with the introduction, distribution and use of pesticides. The Code also defines the conditions under which different pesticides may be used efficiently while minimizing risks to human health and to the environment.

b. Legislation
Both developed and developing countries should have adequate standards for all activities associated with pesticides. In developing countries, one of most effective single regulation to reduce poisoning is to restrict the use of the most hazard compounds to teams, governmental or private, who have been specially trained in application and whose work, practices and applications can be regularly checked. Agencies in charge of approving the use of pesticides at national levels should have legal support to request that the manufacturer provides data from standard animal toxicity tests and from field studies of ecological effects and environmental transfer.

c. Education and training
Education and training can be provided to health and agricultural workers who have leadership roles in their community, through radio broadcasts, farmers' groups or cooperatives, retailers or other community leaders. Training courses on pesticides for trainees are available from WHO, FAO, UNEP, the International Group of National Associations of Manufacturers of Agrochemical Products, and the International Organization of Consumers Union.

d. Information
The manufacturer, formulator, or person responsible for labelling and registering a pesticide with the appropriate national authority, should ensure that the product offered for sale, or otherwise distributed, bears a label written in the language of the region, giving comprehensive instructions for safe use, warning of possible hazards, specifying the active ingredients, as well as other ingredients, and giving guidelines for first aid in case of poisoning, including antidotes.

4.2.3. *The Safe Use of Wastewater for Irrigation*
Health protection in wastewater use systems can be achieved through the integration of four major measures: wastewater treatment, crop restriction, wastewater irrigation methods, and human exposure control and personal hygiene.

Wastewater treatment is aimed at the attainment of the quality guideline values shown in Table 3, keeping at the same time some of the nutrients and organic matter originally available in the raw wastewater. Many countries which are not able to fully treat their wastewater may adopt crop restriction policies, allowing the use of wastewater only for the irrigation of crops included in classe B (industrial crops, cereal crops, fodder crops, etc.). Irrigation methods providing higher health protection are normally more expensive. Subsurface and localized irrigation, for example, will provide higher safety to consumers of crops but has high cost and requires a better treated wastewater to avoid clogging of distribution orifices. Human exposure control, while not highly effective as a single measure, can be achieved through immunization, use of appropriate footwear and gloves by field workers and crop handlers, health education and the provision of adequate medical facilities to treat diarrhoeal diseases and to provide chemotherapic treatment.

To planners and decision makers, wastewater treatment appears to be the most straightforward and "visible" measure for health protection, followed by crop restriction. Both measures, however are relatively difficult to implement fully; the first one is limited by costs and problems of operation and maintenance, and the second, by lack of markets for specific products, or by legal and institutional constraints that hinder its effective implementation.

It must be considered that the application of isolated measures, while not economical, may have only partial effects in terms of health protection. In order to analyze the various measures in an integrated fashion, and aim at the optimization of the health protection scheme, it is necessary to develop a cost/benefit analysis to define which measures should be adopted, and at which level, in consonance with the local economical, technical and cultural conditions as well as the related national policies, characteristics and constraints.

5. Conclusions and Recommendations

Human beings are deeply concerned about their own health, and that of their relatives and close acquaintances. However, when placed in the position of policy maker for the implementation of developmental activities involving major environmental modifications, these same people do not often take into account the health implications, either direct or indirect, of their actions.

Agricultural development is one such developmental activity, where the technical, financial, institutional and regulatory aspects are fully considered from the early planning stages and throughout the implementation, but where no consideration has been given to the potential health consequences.

This paper has shown the health and environmental hazards associated with agriculture, particularly irrigated agriculture, such as the increased risk of transmission of water borne diseases, the indiscriminated use of agrochemicals, particularly pesticides, the unsafe use of low quality waters, land tenure and distribution and human settlements and resettlements.

In order to protect the health of the groups at risk associated with agricultural development it is strongly recommended that:

a. Agricultural policies
   Governments consider to integrate health goals in their agricultural policies. Health promotion and disease control considerations should be included as basic directives for the planning, construction, management and operation of agricultural systems, including management and operation of water resources and land development.

   In many regions, particularly in the developing world, where the legal relationship of farmers to the land have an important influence on income, consumption, nutrition and health status, adequate policies for land tenure and land distribution, as well for population resettlement should be established and implemented.

   The development and effective implementation of health and environmentally sound policies can only be achieved through integrated action of correlated ministries (planning, environment, health, water resources, agriculture), non-governmental organizations, and with the cooperation of major international development agencies.

b. Appropriate technologies and strategies
   Governments enforce the use of appropriate technology and strategies for incorporating health safeguards in agricultural projects. This should include particularly: (i) the use of integrated control of vector-borne diseases (chemical vector control associated with biological vector control and environmental management); (ii) prevention of pesticide poising trought technical guidance, adequate legislation, education and training, and provision of information; and (iii) the safe use of low quality waters, particularly wastewater by providing wastewater

treatment, crop restriction, health protective irrigation methods, human exposure control and health education.

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VULNERABILITY OF SOILS UNDER IRRIGATION

J. PORTA* and J. HERRERO**
**Department of Environment and Soil Science*
ETSEA. Avgda. Rovira Roure, 177.
Universitat de Lleida
25006. Lleida. Spain
*** Department of Soils and Irrigation*
Servicio de Investigación Agraria (SIA)
Diputación General de Aragón (DGA)
Carretera de Montañana, s/n, 50016 Zaragoza. Spain.

1. Introduction

The vulnerability of soils under irrigation is a classic topic. Nevertheless, the problem of salinity and sodicity in irrigated agriculture becomes more severe every year. Salinization appeared early in some 20 historic districts in which the problem exists. Worldwide, it is projected that, by the year 2000, 50% to 65% of currently irrigated cropland will suffer reduced productivity due to excess soil salinity (Buras 1992). Soil salinization is also related to land desertification processes.

The sustainability of irrigated lands is sometimes questioned. For example, Heathcote (Heathcote 1983) stated that, owing to the salinity hazard, in arid zones financial budgets would be better employed in the development of industries than in the irrigation of lands. More to the point, given that these arid areas of the world need to produce food, the vulnerability of soil under irrigation must be taken into account in order to avoid land degradation.

Moreover, in many countries, the growth of cities occurs at the expense of the irrigated lands which surround them, in which long-established and working irrigation systems exist. Consequently, agricultural expansion must consider the use of new lands where irrigation systems will be required, even though mismanagement of such systems frequently induces land degradation.

Therefore, with regard to land usage, it is of fundamental importance to establish the reason for the perception, which persists even today, that soil irrigation poses a major problem in terms of sustainability. The nature of the damage must be analyzed with a view "to learning from the past".

This paper will attempt to present a general overview of the topic, considering previous questions relating to our knowledge of soil characteristics in dry conditions,

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the impact of land systematization for irrigation, impacts of water application on soils and of drainage systems, and the hazard of further land degradation.

Soil behaviour might constitute a cause of the non-sustainability of the system, but irrigation mismanagement could also account for soil degradation.

Properly constructed irrigation systems, designed on the basis of a sound knowledge of the soils to be irrigated, followed up by effective management which takes into account soil behaviour, generally prevent possible adverse effects. The numerous technical solutions available for irrigation and drainage systems have to be adapted to prevailing soil conditions. However, all too often this kind of adaptation is carried out after the construction phase is completed and the irrigation system is in operation, rendering the process excessively empiric (Herrero 1992). Furthermore, while information on soils is essential, sociological and economic conditions cannot be ignored, hence the only viable approach is a holistic one (Rennes Workshop 1992).

2. Irrigation Impacts and Sustainability

Loomis and Connor (1992) state that today's anxieties will give way to strong pressures for expanded land use and the intensification of production.

Irrigation changes land productivity in absolute terms, normally bringing about a general improvement. However, in some cases the arrival of water affects soils and the system becomes non-sustainable. The main impacts identified are due to the following causes.

2.1. LANDFORMING WITHOUT CONSERVING TOPSOIL MATERIAL

Topsoil horizons are the most beneficial for growing crops. In arid and semi-arid lands, the A-horizons are thin and fragile. Their formation has been very slow and frequently they are remnants of an old natural vegetation, disappeared since long times, sometimes formed in a more humid climate. These horizons have been ripened by soil fauna so that their structure, organic matter content, and other features allow us to anticipate positive soil behaviour when irrigated.

2.2. CHANGES IN THE HYDROLOGIC CONDITIONS

These changes include:

- water tables elevation
- seepage in slopes and waterponding in bottoms and in plains.

Saline groundwater can be a source of Na^+ and other deleterious ions in irrigated soils. For this reason, if irrigation induces an elevation of the water table, the soil salination hazard will be increased.

2.3. SALINIZATION

Changes in land use due to irrigation have led to secondary soil salinization in many countries (Szabolcs 1992). The main effects can be:

- poor plant emergence
- limitation in the number of feasible crops
- ion-specific toxicity
- nutrients absorption problems
- water availability shortage by osmotic effects
- degradation of irrigation channels and drainage networks

2.4. SODIFICATION

Sodic soils are not very extent, but sodification is sometimes induced by irrigation. Reclamation of highly sodic soils is very difficult or impossible in practice, when the soil becomes impervious. The main effects of sodification can be:

- degradation of the topsoil structure
- crusting and sealing,
- decrease in hydraulic conductivity,
- lack of root hair development,
- toxicity by exchangeable sodium
- clay sodification,
- sodic clay translocation,
- clogging of subsurface pipe-drains,
- piping and other erosion phenomena

3. Landforming: a Requirement in Surface Irrigation Systems which Can Be a Hazard for Sustainability

Surface irrigation is the traditional irrigation system in Spain, as in most places around the world. Sprinkling systems have become more and more popular for extensive crops, but from a sustainability point of view, flooding has several advantages such as simplicity, the absence of energy inputs to operate the system, the avoidance of water losses by wind and low contact of water with leaves.

The volume of materials removed per hectare through landforming for irrigation has increased in the last century owing to the extension of irrigation over less plane areas, the substitution of manual work by powerful machinery, and the need for larger plots. The construction of a flat land surface having the slight and continuous slope needed for irrigation can produce an important impact on soils when soil horizon characteristics are not taken into account.

When landforming is carried out without consideration for the vertical anisotropy of the profile, the topsoil is removed and mixed with other materials.

The main impact is due to unfavourable subsurface material left on the surface. In some cases, a calcic horizon or a petrocalcic horizon appears as, for example, is the case in Villanueva de Campana, Spain. Even though the coarser fragments of this cemented material are exported, a lot of calcium carbonate remains in the topsoil and iron chlorosis problems can appear in orchards and other crops. In other cases, coarse fragments are crushed *in situ* with tractor-towed stone mills.

In the Plan Badajoz irrigation system (Badajoz, Spain), argilic horizons were left as topsoil in some places. The poor hydraulic conductivity of this clay horizon does not favour sustainable irrigation because infiltration of rain and irrigation water becomes too low.

In the Ebro Valley (north eastern Spain), landforming left as topsoil a C horizon with a platy structure, as will be described in 4.1. In other areas, saline and sodic fresh marls were put on the surface by landforming.

Detailed soil maps are needed in order to avoid these problems. Landforming must be planned according to soil information. As a general rule, the A-horizon material must be kept and protected during landforming operations. The subsequent restoration of the topsoil material improves water infiltration, providing a favourable material for plant growth and favouring the sustainability of the system.

4. Irrigation with Drainage: a Key for Sustainability.

To avoid salinization, a downward flux of water must be maintained through and beyond the root zone. By achieving this with an appropriate leaching fraction (LF), salts concentration of the soil solution will be avoided in the root zone.

Leaching water must be collected in drains in order to eliminate salts from the soil system and to avoid resalinization. Irrigation projects must always be associated with drainage. Adequate natural or artificial drainage can be a critical element in the success or failure of any irrigation project (Ochs 1992).

4.1. DRAINAGE DESIGN CRITERIA: A CRITICISM

In some regions, like the Ebro Valley (Spain), quaternary soil parent materials of large areas present a platy structure (Martinez-Beltràn 1978; Herrero 1992). This structure is inherited by soils and preserved in subsurface horizons. These soils have a profile AC, and in some cases A2C. The C-horizons have a platy structure from fine to very fine, and a silty loam texture.

This platy structure can be identified in the field. When a thin soil section is observed, the microscope shows alternative clay and silty loam layers. Classic sampling methods for granulometry analysis do not take into account this alternation of millimetric layers of clay and silt. Granulometric analysis in the laboratory masks this microarchitecture of the soil. For this reason, infering soil behaviour from these results does not correspond to the real behaviour of the soil in the field.

Under dry farming, these materials have a low level of salts: ESP is higher than 15% and pH is higher than 9.5. However, the A-horizon has not got these sodic characteristics.

With respect to these soils, the general theory for the design of parallel open or closed drains based on the Dupuit-Forchheimer expression or other assumptions, (van Schilfgaarde 1984) which consider a steady-state position of the water table between drains, is not applicable.

In soils with a micro-layered structure, water flows to the pipe drain from the soil surface only through drain trench material in which the hydraulic conductivity is much higher due to voids remaining from drain trench filling, with the result that the flow of water is not uniformly distributed over the field. When this factor has not been taken into account, the drainage system fails.

4.2. SILTATION

For irrigation system sustainability, associated drainage systems must be put into practice. Subsurface pipe networks are needed to control groundwater level and to allow soil desalinization by leaching. The hazard for pipe drain clogging must be considered. In some cases, visual observations show sediment deposits in pipes. In general, no chemical deposits are present in pipe drains in soils of arid and semi-arid regions where calcium carbonate is a common soil component.

Deposition of sediments in drain pipes has been studied in humid temperate climates for soils with an excess of water (aquic characteristics) being non-saline and non-sodic. Some indexes to evaluate siltation risk have been proposed (Cestre 1985; Stuyt and Cestre 1986). These indexes are based on classical granulometry parameters such as D_{10}, D_{50}, D_{60}, $C_u = D_{60}/D_{10}$ (uniformity index).

When trying to use these indexes on soils from the Monegros-Flumen irrigation system (Ebro Valley, Spain), some adaptations are needed in order to improve the index performance. These soils have a high content of silt and sodic characteristics. The silt particles are unable to aggregate, and the sodic clays disperse after wetting.

The study of sediment deposit material from drain pipes shows that siltation has affected silt size particles from 5 to 20μm and from 20 to 50μm (Rodriguez *et al.* 1990). These results contrast with Nelson (1960) for other soils. According to the latter author, soil particles of a size less than 50μm do not move to the pipe, or else they are easily transported out of the pipe by water flowing in the pipe.

In the drainage systems studied in Ebro Valley, clogging material in the pipes never belongs to the fraction 50 to 100 μm, as would be the case according to the criteria proposed by Broughton *et al.* (1982). The parameter D_{10} is not suitable in siltation risk evaluation in these soils. The D_{50} parameter seems to be more suitable than D_{10}.

The differences between these soils and hydromorphic soils can be interpreted due to the high silt content and sodic clays (Herrero *et al.* 1989).

Another important point is the kind of pipe material used. Comparing ceramic pipe and corrugated PVC pipe efficiency, after ten years of installation of a drainage system, complete clogging of the ceramic pipes due to sediments has been observed, while clogging varied from 25% to 75% of the pipe capacity for PVC drains. This suggests that sediment deposits increase due to the space existing between ceramic pieces (Rodriguez *et al.* 1990). The sediment deposits increased with decreasing drain spacing suggesting that sediment deposits were related to drainage rate (Gupta *et al.* 1991).

The material used for drain pipe envelopes is instrumental in the avoidance of pipe siltation. The study of water flow patterns inside drain pipes and the effect of envelopes on the development of such patterns show that water flow and mineral envelope clogging are heterogeneous and largely determined by soil structural features (Stuyt 1992). The study of the efficiency of different envelopes to protect different types of pipes is important for system sustainability, but efficiency must be investigated taking into account soil characteristics in every case. Unfortunately, this kind of information is not always available nor even considered.

While drain pipe envelope materials made of organic-fibre (wheat, rye and rice straw) have sufficient porosity, their filtering ability is low and their lifetime (2 to 3 years) short (Rodriguez *et al.* 1990; Wagner 1992). However, coconut fibre has medium filtering ability and its lifetime is long (10 years). Synthetic fibrous material with volume mass of 0.08 to 0.15g cm^{-3} and a porosity of 80% to 93% were found to be most suitable to retain soil particles larger than 50μm (Wagner 1992). Synthetic non-woven geotextile may be too expensive for agricultural purposes but, on examination after being installed from four to fifteen years in silt and sand soils in Canada (Bonnel *et al.* 1992), the fabric continued to perform its design function very well. No measurable amount of sediment deposition was noted in any drain. The fabrics exhibited inconsequential amounts of internal clogging by soil particles. A fibreglass fabric was easily torn and was brittle upon drying.

Another aspect for the sustainability of the system concerns the effect of sub-surface drain spacing on soil salinity. In a Camborthid saline phase, from India, three spacings (25, 5O and 75 m) were compared. As the distance between drains increases, so does salinity and residual soil water content, while root penetration and root development at lower depths decrease (Sharma *et al.* 1992).

The pedological investigations suggest that a careful management of the machinery used for landforming, trenching and pipe setting is needed, as a consequence of the fragility of soils with low structural stability. A specific recommendation is to establish a covering of local salt-tolerant grass previous to starting work with machinery.

5. Salinization and Sodification

5.1. SOIL SALINITY AND CROP PRODUCTION

The effect of salinity in agriculture and on plant life has been largely studied and reviewed (Ayers and Westcott 1987; Bhati 1989; Bresler *et al.* 1982; Shainberg and Shalhevet 1984; Breckle 1990; Gupta and Abrol 1990).

Secondary soil salinization and waterlogging are significant problems in irrigated areas. Salinization can be due to a low irrigation water quality or to the initial salt contents of the soil being redistributed by irrigation water and by seepage. Waterlogging results from a lack of drainage, when farmers apply large amounts of irrigation water to leach the accumulating salts from the root zone. Seepage of irrigation water adds salt to soil from canals or from upslope to downslope plains soils.

The most serious salinity problems in irrigated areas are caused by over-irrigation (Suarez 1992). Technical advances in irrigation delivery systems enable accurate irrigation scheduling and water billing, thereby improving water application control.

Crop yields and land use patterns for an irrigated district may be significantly affected by secondary soil salinization induced by irrigation. Worldwide, it has been estimated that in the late 1980s there were probably around 91 million hectare of irrigated land, a third to a half of which was in a poor state due to salinization (Table 1), that is, approximately 30 to 46 million hectare (Barrow 1987).

TABLE 1. Global distribution of salt-affected irrigated areas (Middleton 1998; Lal *et al.* 1989)

Country	% irrigated area salinized
Egypt	30-40 %
USA	30-25 %
China	15 %
Iraq	50 %
Pakistan	35 %
Australia	15-20 %

Sustainability in irrigated land use systems in many developing countries depends on problems which originate from salinity and drainage as a result of the improper use of water and a rising ground water table. Health effects, displacement of populations, soil erosion and deforestation are among those problems associated with soil salinization (Teferi 1992).

In many coastal regions, salinization can be due to intensive exploitation of coastal aquifers for irrigation. Continued pumping from an unconfined fresh-water aquifer depresses the water table and sea water intrudes into the aquifer. Wells become contaminated by salt water and secondary salinization is induced in the soils when irrigated.

5.2. SODIFICATION: THE DEGRADATION OF PHYSICAL PROPERTIES

Soil sodification can be induced when irrigating with water with a low ion content, such as water from the Pyrenees (Spain), or by irrigation mismanagement. In general, sodification is avoided in large irrigation projects where advice is adhered to.

Several combinations of salinity and sodicity occur under natural conditions in each of the continents (Szabolcs 1979). These soils are often in broad, plane areas where there is a ready supply of water. Farmers and local managers assume that soil sodicity precludes irrigation because these soils are impervious, therefore probably rendering its reclamation unfeasible. Problems arise when slightly sodic soils, often saline-sodic, are irrigated.

The application of high quality waters, with low calcium content, can change saline or saline-sodic soils into sodic soils.

A good example of this process is reported from the Ebro valley (Spain) where winter cereals were produced under dry farming. Following irrigation project implementation, fruit trees were planted. After a few years the trees died and the soils became impervious. A rice crop was made possible only by permanent irrigation (Porta *et al.* 1986). Other examples have been reported worldwide as, for example, from the inland Niger river delta.

6. Soil Surface Sealing and Crusting

In the arid and semi-arid regions of the world, soil surface sealing and crusting due both to rainfall impact on the soil surface and, in irrigated areas, to different irrigation methods such as flooding, sprinkler or centre pivot systems, are well-known. In traditional agricultural systems, farmers try to solve the problem by using mechanical tools in order to crack the crust or by adopting supplementary irrigation systems. In such cases, the profit of the crop is decreased.

In the new irrigated districts of Spain, sprinkler irrigation and centre pivot systems are commonly used for extensive crops of corn, onions and other crops. Some problems appear when irrigation equipment is selected without taking into account the risk of soil surface sealing or crusting. A seal is usually 1-5mm thick and does not crack. However, a crust does crack, peels-off and may be moderately thick (O.5-2cm).

The nozzle-regulated water droplet size defines the sprinkler droplet impact on the soil surface. This impact can destroy the unstable aggregates which make up the loose, fine material infilling surface vughs, thereby inducing soil surface sealing or crusting.

The effects of sealing or crusting are mostly negative. The main effects (Sombroek 1985) are the mechanical impedance of seedling emergence, lack of aeration just below the crust retarding root development, reduced infiltration and loss of irrigation water as runoff, which can induce erosion.

Management of irrigated soils with a high risk of crusting or sealing is difficult. Any excess of water must be avoided because some plants can be affected during emergence. But it is also necessary to avoid drying of the soil surface since the crust is very compact when dry. If a centre pivot method is used, the nozzle must be appropriate to obtain very fine droplets.

Advisers must recommend low application rates since sprayers may produce a rain which is either too intense or, alternatively, drops which are too large due to insufficient pressure. Low pressure sprinklers (2-6 bars) might perform better, together with a relatively high irrigation frequency.

The FAO (1983) has developed an empirical crusting index to measure the risk of physical degradation. The selection of suitable irrigation equipment and the improvement of the surface horizon structure are necessary if the problem is to be diminished.

7. Sociological and Economic Aspects: an Holistic Approach

Soil behaviour controls the sustainability of irrigation systems, but other aspects must also be taken into account for sustainability.

Significant investments are being made in irrigation and drainage of irrigated lands for salinity and waterlogging control. It is imperative that these investments be protected, and that systems are sustainable in the long-term (Madramootoo 1992). In Spain, the economic analysis of the impact of salinity on agriculture was carried out for the Ebro valley by Albisu *et al.* (1988) for irrigation water and by Zekri and Albisu (1993) for soil salinity. The Ebro region provides a good example of competition over water use.

Limited success of some irrigation projects and their sustainability are due to centralized government control with little farmer support or knowledge, and a lack of trained personnel (Shyam 1992). Sometimes, planners are exclusively concerned with the irrigation project in hand, and the technical, sociological and institutional aspects of sustainable operation are often neglected (Huppert 1993).

The major concerns in future irrigation training and research are focused on social, economic and political issues which affect the basic tenets of efficiency and quality in irrigation allocation and management (Feyen and Mwendera 1992). Irrigation scheme design for sustainability requires an holistic approach to management (Keller 1992).

Such a holistic approach should include (Kirpich 1993) the application of management principles to improve inter-agency coordination, the adoption of performance incentives for staff and individual irrigators, the use of indigenous knowledge and the assurance of effective local participation for concurrent activities. These activities include the supply of information on soils, inputs, agricultural extension, processing and marketing, farm credit and operation and the maintenance of the distribution system.

8. Sustainability Challenges

Planning irrigation development for sustainability must take into account both short- and long-term processes. Lack of recognition of the processes of irrigation degradation or the lack of expertise needed to address the problem, is not the primary constraint to successfully preventing or arresting land degradation under irrigation. Soil information can be obtained and soil vulnerability can be evaluated. Constraints limiting the effective response to land degradation (Sheehy 1992) under irrigation include:

a. Scale
   Land degradation under irrigation has occurred on such a large scale throughout the world that the mobilization of the resources necessary for reclaiming salt-affected soils under irrigation to a higher agronomical condition is difficult.

b. Politics
   Scientists', researchers' and educators' knowledge about land degradation under irrigation, its causes and control, is not effectively incorporated into government policy-making on agricultural development. Sometimes irrigation is a political target, not a sustainable development target. Soils cannot be studied sufficiently because it is a time-consuming task. In some countries governments have created an artificial gap between "agriculture" and "environment".

c. Cooperation
   Cooperation within and between different research and scientific institutions, and between these institutions and management agencies and the extension services that implement policy, is inadequate.

d. Attitudes
   There is a pervasive attitude that the exploitation of lands for short-term economic returns is allowable and even necessary to develop a country.

e. Ethics
   There is a lack of a sustainable use ethic in resource development and the focus on cropping agriculture regardless of ecological sustainability.

Management agencies currently supporting short-term, non-sustainable exploitation of resources to meet current social and economic needs will then be forced to address policy-making within an environment characterized by rapidly decreasing options.

9. Conclusion

A broad knowledge is available about the natural laws governing the soil behaviour. The same applies to the rules to select the adequate soil behaviour for irrigation. When a new irrigation district is being planned, or when an old irrigation district is to be improved, this knowledge has to adapted to the specific case. To do so requires investments that are negligible if compared with the total budget.

The experience of areas having both successful and unsuccesful irrigation districts can be very valuable. Most of the failures in recent years can be attributed to populations, or perharps the fast establishment of hungry populations or the fast establishment of spectacular systems. Another basical reason is the performance of agriculture under a commercial viewpoint, looking for short term benefits.

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SUSTAINABILITY CONCERNS OF IRRIGATED AGRICULTURE

L.K. SMEDEMA
International Program for Technology Research in Irrigation and Drainage
Program Office, The World Bank, Room N-7023
1818 H Street, N.W.
Washington D.C. 20433
USA

1. Introduction

The introduction of irrigation generally constitutes a significant intervention in the prevailing physical,environmental and socio-economic conditions of the area. In the process, existing equilibria are disturbed and in the course of time new ones are established. The underlying premise of irrigation development, of course, is that the new conditions satisfy mankind's objectives better than the old ones. In many respects this premise has proven to be true. Irrigation has been a major development force in many ancient civilizations and it continues to play this role in today's world. While only one sixth of the world's cropped land is irrigated, this irrigated part accounts for about one third of the world's food harvest. Over one half of the increase in food production over the last 25 years has come from irrigated land and irrigation undoubtedly will continue to play a critically important role in assuring the food security of the world's ever growing population. Irrigation also contributes significantly to the poverty alleviation and general improvement of the quality of rural life. All this applies especially to the developing countries many of which rely heavily on irrigation for their further development and experience the highest population growth rates.

Although there should be no doubt that the introduction of irrigation is generally a desirable development, it is equally true that irrigation development has also been shown to have negative effects. While many of these negative effects can have been avoided by better planning and/or can easily be mitigated by appropriate measures, some seem to raise the question whether irrigation development is sustainable. This question is addressed in this paper. Sustainability is taken in the rather narrow sense of assurance that the irrigation technology is not causing undue damage to the environment and is capable of maintaining high levels of agricultural production of irrigated land in the long run.

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2. Main Sustainability Concerns

The world's irrigated area is far from uniform. Different areas are affected by quite different sustainability problems. Many of the sustainability concerns of irrigated agriculture in developed countries are the general ones of modern high input agriculture which heavily taxes the natural resources and often excessively burdens the environmental assimilation capacities. At the other hand, many of the sustainability concerns of irrigated agriculture in the developing countries derive from the general development problems faced by these countries such as lack of public resources, macro-economic dependance on agricultural commodity export, wide spread poverty, population pressure, inadequate management and human resources development, institutional and regulatory shortcomings, etc. (DGIS 1992). Still another group of concerns are not unique to irrigated agriculture but are related to general or specific agricultural policies of the concerned countries. The discussion here will focus mainly on problems which are intrinsically related to irrigation technology. More attention shall be given to concerns affecting irrigated agriculture in the developing countries than in the developed countries.

2.1. WATER RESOURCES

In many countries but especially in those in the arid climatic zone with high rates of population growth, urbanization and industrialization, water is rapidly becoming a scarce resource (The World Bank 1993). The increasing competition for water shall greatly affect the water supply for irrigated agriculture in these countries. Generally, available quantities will be reduced and costs will increase. While these trends will as a rule promote the proper use and allocation of water and often will have a positive environmental impact, they clearly will put much strain on an irrigation sector which so far could depend on abundant, low cost water supply and was allowed to operate on low water use efficiencies. The sector will have to make considerable adjustments and investments for its survival under these changing conditions. The pressure on more efficient water use in most countries will increase gradually however, giving the irrigation sector ample time to prepare and adjust. Moreover, in most countries water requirements of the competing sectors will always remain a relatively small percentage of the naturally available supplies and the extra requirements of these sectors could generally be met by a gradual marginal improvement in irrigation water use efficiency.

Groundwater deserves special mentioning. The use of this water resource for all sectors,including irrigation, has increased considerably during the last decennia and in many areas abstraction is greatly exceeding the recharge. Although such water use is clearly unsustainable, it may be a conscious decision, justified on grounds of national macro-economic considerations. Most cases of groundwater mining, however, are due to a lack of adequate regulation and enforcement as well as neglect or ignorance about the environmental consequences.

In addition to the pressure on reducing water usage, the irrigation sector may be expected to face increasing pressure to reduce its degrading impact on the quality of downstream water resources. While much of water quality degradation caused by irrigated agriculture is similar to the degradation caused by rainfed agriculture, the former has some very specific aspects which are inherent to the irrigation technology (see discussion below on drainage water disposal).

2.2. LAND RESOURCES

The degradation of land resources due to the use of the land for agriculture is of great worldwide concern (ISRIC 1991). Irrigation development in some cases has contributed to this concern by creating conditions which often inadvertently led to deforestation and soil erosion. This applies especially to land degradation in upstream catchment areas of river diversion schemes. Apart from the loss of productive capacity in the affected areas, this catchment degradation has also created tremendous siltation problems in constructed reservoirs and in the actual command areas. In most bifurcating alluvial irrigation canal systems, the silt carrying capacity varies considerably, generally declining in downstream direction. Canal siltation not only constitutes a major maintenance burden but also adversely affects the equity and reliability of the water distribution and delivery. In some cases, the silt deposits by the irrigation water are of such a magnitude that they have brought about significant geomorphological changes (such topographic inversions) in the command area. Of major concern also are the enormous silt accumulations in some reservoirs that have become a threat to the safety of the impounding structures.

The most serious irrigation induced land degradation in the command area is undoubtedly the wide spread waterlogging and salinization of the soil (see discussion below). Another hazard is soil erosion caused by poorly designed field irrigation systems. While irrigated land, just as rainfed land, under poor soil management is liable to loss of soil fertility, there seem to be no other specific irrigation induced threats to the long term productivity of irrigated land.

2.3. WATERLOGGING AND SALINITY

Due to the combination of low water use efficiencies and inadequate drainage, irrigation has led to large scale waterlogging and salinization of the irrigated land. The occurrence of this twin-problem is mostly restricted to the arid zone as here the impact of the new water source on the water balance is relatively the largest; natural drainage conditions are often poorly developed and due to large evaporation surplus, the natural propensity for salt accumulation is greatest. The problem is often aggravated by the typical setting of most large irrigation schemes in geomorphological bottom areas which constitute natural sink areas for accumulation of excess water and salts (Smedema 1993). It is estimated that of the world's currently irrigated area of 270 million ha, about half is located in the arid zone. The waterlogging and salinity problems severely affect at least 20-30 million ha while another 60-80 million ha are estimated to be slightly to moderately affected. The affected area is estimated to increase annually by 1-2 million ha (FAO 1990).

Irrigation development has also affected the hydrology of much irrigated land in the semi-humid climatic zone by reducing the natural storage for excess monsoon rain and blocking the natural drainage paths by infrastructural works. As a result, many of these areas now suffer badly from flooding and waterlogging during the monsoon season.

Although the direct causes of irrigation induced waterlogging and salinity are basically of a technical nature, various non-technical factors have also contributed to or have aggravated the problem. A major factor has been the government policies which condone inefficienct use of irrigation water (underpricing, subsidies, etc.). Other important factors are the institutional arrangements in the irrigation sector which do not reward performance, do not instil a sense of ownership of facilities and do not promote the participation and awareness of all stakeholders. These factors have permitted situations where funds initially reserved for deferred drainage, were used for other purposes (e.g. for politically more expedient expansion of the irrigated area).

Water and salinity management of irrigated land is a complex problem as many underlying causes and remedial measures have to be considered in all their time and space variable interrelationships. Many of the irrigation induced waterlogging and salinity problems are due to shortcomings of the applied conventional analysis and planning methodology which was inadequate to fully predict the impacts of the import of irrigation water on the prevailing (geo)hydrolological, geochemical and environmental conditions of the area. With the progress made in modelling, much better predictions can now be made. These models can also be used to plan optimal packages of remedial measures involving, for example, a judicious combination of canal lining, groundwater drainage and adapted crop management practices. Efforts are also underway to extend this new planning methodology into a fully comprehensive approach covering both technical and non-technical interventions.

2.4. DRAINAGE WATER DISPOSAL

For sustainable irrigation, it is essential that salt balances be maintained both at field level and at basin level. In most irrigated areas, the most practical and economical way to maintain these salt balances is by discharging drainage water from the fields and the basin which is more saline than the applied irrigation water. The higher salinity of the drainage water from irrigated land is an intrinsic characteristic of the irrigation process which is designed to promote evapotranspirative consumption of water for crop production and inevitably leads to solute concentration of the non-consumed drainage water. Part of this saline drainage water may be generated by natural drainage but where the natural drainage is inadequate to maintain the water balance, as is often the case, artificial measures must be taken to enhance the drainage discharge.

The salinity of this drainage water depends on many factors but the most important ones are generally the salinity of the applied irrigation water, the proportion of this applied water which evaporates/evapotranspires and the pick-up of fossil salts by the drainage water. In humid climates, the salinity of the drainage water generated by an irrigation scheme is often of such low salinity that it can readily be reused or be disposed off in a receiving river or lake. As a rule however, this is not the case with drainage water generated by an arid zone irrigation scheme. Finding economically, environmentally and politically acceptable solutions for the disposal of drainage water is rapidly becoming a major problem for many of these schemes (Smedema 1993). This applies especially to schemes which are far from sea, schemes in inland basins, schemes upstream of major intakes for drinking water and schemes naturally draining towards international rivers. Of special environmental concern are the reported cases where highly toxic minor elements are picked up by the drainage water.

2.5. PUBLIC HEALTH

Major interventions in the hydrology of an area as involved in most large scale irrigation developments, are likely to have a significant impact on the area's ecology. This applies especially to impounding and diversion schemes in tropical flood plains. The changes in the ecology and in the land use in such plains may not only adversely affect existing natural values and former production functions such as spawning grounds, fishery and grazing but also create conditions which favor the spread of waterborne parasitic diseases. The spreading of these diseases is much more rapid under the high temperature regimes of the tropics as compared to temperate zone conditions.

Irrigation facilities like reservoirs, low velocity alluvial canal systems and surface type field application systems offer many habitat opportunities for the involved vectors and their intermediate hosts. However, with proper planning and design and taking of the necessary precautionary and mitigative measures, the spread of diseases from irrigation development can be avoided. Enough experiences and research results are now available to prepare effective disease control plans (ILRI 1990). Unfortunately, few such plans have yet been implemented.

The spread of diseases in irrigation schemes is further increased by poor maintenance of the hydraulic systems and by the low irrigation efficiencies and inadequate drainage which result in the emergence of stagnant water. Low levels of technology requiring unhygienic contact for the operation of the systems also promote the spreading of these diseases. Since all these conditions are more prevalent in the developing countries, it is these countries which are especially affected.

2.6. MAINTENANCE

Inadequate maintenance of installed irrigation and drainage facilities is a well known feature of many irrigation schemes in developing countries. Although most of the maintenance problems are related to the general development problems faced by these countries, some are inherent to the irrigation sector. For example, several problems are related to the silt carried by the irrigation water and to the favorable environment created by the reservoirs and open canals for the development of aquatic plants. In most cases, however, these inherent problems can be reduced to manageable size by proper design and operation and should not constitute real sustainability problems. The key causes of the inadequate maintenance in most irrigation schemes in the developing countries are the low levels of available resources and scheme management.

3. Sustainability Enhancement

The above discussion of the main sustainability concerns of the irrigation technology makes it clear that there are no major shortcomings of this technology which makes irrigation development fundamentally unsustainable.The only two sustainability problems intrinsically related to the irrigation technology are salt accumulation/mobilization and the related downstream water degradation, and the spreading of waterborne diseases. Although there may be cases where concern about these problems may pose limits on irrigation development, in most cases they can be overcome by carefully planning and the taking of mitigative measures.

There is, however, a rather widespread appearance of unsustainability of irrigation development, especially in developing countries. This is based on the poor and often declining performance of the irrigation sector in these countries and on the abundant signs of problems faced by the operating agencies which are testimony of this low performance. Further analysis generally reveals a complex set of interrelated causal factors, the three basic factors typically being: inadequate planning, low irrigation efficiency and general development problems of the concerned countries.

The planning factor has usually two components. First, past experiences and available research results are not effectively used because experiences are not thoroughly diagnosed and research results are not made operational. Second, the complex interrelationships of irrigation development were not always fully understood and planning methodologies were unable to taken them all into account. With the development of comprehensive model based planning and design methodologies, impacts of planned interventions can be better predicted. This will be of benefit in the fight against waterlogging and salinity.

The improvement of the irrigation efficiencies is a necessity which shall, willingly or unwillingly, be forced upon the irrigation sector, mostly for the good of the sector. Many of the apparent sustainability problems discussed heretofore are directly or indirectly related to the currently allowed waste of irrigation water and these problems will, to a large extent, be solved by measures which reduce this waste. It is now widely understood and accepted that the improvement of the irrigation efficiency cannot be achieved solely by technical measures but also require changes in the domain of government policy, institutional arrangements, incentives and behavior of the different stakeholders. This could include:

- government policy reforms to improve cost recovery and regulatory and legal frameworks;
- institutional reforms of the irrigation departments to make them more performance and water conservation minded and more accountable to the end-users;
- incentive water pricing to reduce over-irrigation;
- more decentralized water management and increased participation of (groups of) end users in the system design and in the actual water management to improve reliable and equitable water delivery;
- upgrading the skills of operating personnel and extension to farmers to improve understanding and decision making.

This new approach is now being followed in a number of countries. Although the first results are promising, final judgement on its success must await further test results.

The most apparent effects of the general developmental problems of the developing countries on the irrigation sector performance are the underfunding and shortage of skilled personnel. The underfunding especially affects the maintenance of the installed systems and to a lesser extent the inadequacy of drainage. Underfunding will remain a problem but indications are that the above discussed reform measures (cost recovery, decentralization, farmer participation, etc) will improve the awareness of the maintenance needs and the financial resources and discipline of the operating agencies. The shortage of skilled personnel affects almost all aspects of the management of the irrigation sector and of the different schemes. Therefore, upgrading of skills through training will remain an important component of the irrigation development programs of the developing countries.

4. Concluding Remarks

Clearly, the basic problem of the irrigation sector is performance and the attention given by the national and international irrigation community to performance improvement is timely and appropriate. Almost all sustainability concerns would largely disappear when performance of the sector and of the different schemes would be up to standard. The International Program for Technology Research in Irrigation and Drainage (IPTRID) was established to contribute to performance improvement in the irrigation sector by providing a framework for international collaborative R&D work. Under this program, a wide range of R&D activities, with focus on technology, have been launched. The three thematic trust areas of the program are : Modernization of Irrigation Systems, Improved Maintenance and Sustainable Land and Water Use through Drainage. The R&D work in these trust areas is supported by a networking program while human resources development is an integrated part of almost all IPTRID projects (IPTRID 1993). All of these IPTRID activities are at the core of the irrigation sector performance improvement and, as argued in this paper, eventually also of the sector's sustainability improvement.

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PART II

SOIL AND WATER CONSERVATION AND WATER HARVESTING

SUSTAINABILITY OF SOIL AND WATER CONSERVATION IN SUB-SAHARAN AFRICA

C. REIJ and W. CRITCHLEY
Natural Resource Management Unit
Centre for Development Cooperation Services
Vrije Universiteit Amsterdam
The Netherlands

1. Introduction

Many soil and water conservation (SWC) projects have been implemented in sub-Saharan Africa during the last fifty years, but their results have been fairly disappointing. Failure in SWC can be defined in two ways. (1) It means that due to **lack of maintenance** or even due to **deliberate destruction** by the "beneficiaries", conservation works do no longer control erosion or have even disappeared completely. (2) At the end of a project, when external funding is no longer available, all SWC activities usually come to a grinding halt. The **replicability** of many of the SWC techniques promoted by projects **is limited or sometimes even nil.**

When breaches in earth bunds are not repaired, water tends to concentrate in those spots and as a result erosion can be accelerated rather than reduced. Cases of deliberate destruction of conservation works can be found, for instance, in parts of the Highlands of Ethiopia where large-scale SWC programmes were implemented in the 1980's. These programmes were largely based on top-down planning, coercion and systematic use of food-for-work rations. Already in the 1980's some of these conservation works were destroyed in order to rebuild them later and therefore to get food-for-work again.

In 1986, an IFAD document on SWC in sub-Saharan Africa emphasized the need to use **replicability** as a key criterium in the design of SWC programmes (Reij et al. 1986). Replicability means that land users apply SWC techniques on their own fields without the support of a project or continue to apply conservation techniques in the post-project phase.

If adequate maintenance of conservation works by land users and their voluntary adoption of techniques are used as major yardsticks against which the performance of SWC projects is evaluated, the large majority of the SWC projects have failed. Such a judgement, however, would be harsh, mainly because replicability has until now rarely been used as a key project design criterium.

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In a number of cases SWC projects, and in particular projects that have introduced moisture conservation techniques in marginal or semi-arid areas, have had a significant impact on yields. Cases are known where yields have increased by 40 or 50 % in the first year, or where degraded land is restored to productivity. But there is uncertainty with regard to the **sustainability** of yield increases. Are yields high only during the first 2 or 3 years or do yields remain at a higher level ? An answer to this question can not be given, simply because SWC projects, despite investments of millions of dollars, have almost without exceptions not measured the impact of conservation techniques on yields on the same farmers' fields over several years.

Section 2 of this paper will indicate some reasons for lack of replicability and sustainability in SWC in sub-Saharan Africa and improvement of replicability and sustainability in SWC will be the focus of section 3. Assuming for the moment that our current knowledge of reasons for success and failure in SWC enables us to identify which approaches or strategies to SWC are likely to produce better results in terms of replicability and sustainability, it is possible to evaluate SWC projects against a number of indicators. This will be done in sections 4 and 5. Finally, a number of research priorities will be identified in section 6.

2. Major Reasons for Lack of Replicability and Sustainability in SWC

The above-mentioned IFAD policy paper on SWC in sub-Saharan Africa identified 17 reasons for failure. Some major reasons are:

- **A top-down approach**, which means that major decisions about what will be done to tackle land degradation are taken by experts and technicians (outsiders) for land users and not by the land users themselves. Although many SWC policy documents explicitly state the need for land user participation in all phases of the project cycle, much of this remains rhetoric.

- **Inappropriate techniques**, which means techniques not acceptable to land users, often requiring considerable movement of material for construction and maintenance requirements higher than land users are able or willing to spend on them. Where soil conservation and water harvesting works have been constructed by graders and bulldozers, their dimensions are such that they can't be maintained by the land users who only have hand tools at their disposal.

- **High costs per hectare**. Examples can be found where the cost of conservation techniques exceeds 1 500 US $/ha, which implies that such techniques can only be used on a relatively small scale and unless they generate substantial benefits, the use of such techniques can not be justified. Many SWC projects seem totally unconcerned about the cost-effectiveness of the techniques they promote. Some projects deliberately build structures bigger and more closely spaced than necessary, because they want to reduce maintenance needs. The consequences, viz. higher costs per hectare and fewer hectares that can be treated, are disregarded.

- **Low or uncertain benefits**. SWC projects have sometimes promoted techniques without measuring their impact on yields. In some cases where this was done after several years, it became clear that yields on treated fields were sometimes lower than on untreated fields. This explained the lack of maintenance as well as the non-adoption of the techniques by the project's "beneficiaries".

- **Insufficient attention to fertility maintenance and improvement**. Many projects have had a narrow focus on the prevention of soil loss without paying adequate attention to agronomic and fertility management practices which simultaneously increase income, decrease erosion and improve the soil. In other words "**better land husbandry**". In the West African Sahel most SWC projects promote compost pits and for instance in Burkina Faso many families now have one or more compost pits. The new bottleneck has now become the lack of means to transport manure and compost to the fields, some of which are 2 km or more away from the homestead.

- **Neglect of indigenous environmental knowledge**. Projects have often introduced modern SWC techniques and have overlooked or even derided the techniques employed traditionally by the land users.

- **Indiscriminate use of incentives**. Many projects use food-for-work to compensate villagers for their labour spent on the construction of conservation works. Cases can be found where food-for-work was the prime motivating factor rather than conservation of soil and water.

- **Coercion.** The history of SWC has numerous examples of projects coercing land users to undertake SWC. This was not limited to the colonial period. Examples can also be found in recent years (for instance, Ethiopia in the 1980s, during the Mengistu era).

- **Use of heavy machinery**. Many projects have relied (and some do still) for the construction of conservation works on tractors and graders. No example can be found of a SWC project in sub-Saharan Africa, which used heavy machinery, and where land users in the post-project phase have continued to maintain and construct conservation works. There often is no balance between what is constructed with machinery and what local land users can adequately exploit and maintain.

- **Farmer training**. Many projects have neglected training of land users (both men and women) in simple techniques of land surveying and in basic principles of SWC.

- **Scale of intervention**. From a hydrological point of view, the (sub)catchment presents a rational and appropriate scale of intervention. But this is often less a unit of perception and action for land users than his/her own holding, or the village territory.

- **Income earning opportunities outside the agricultural sector**. Land users often do not depend on agriculture alone, but have a range of income-earning activities (trade, handicraft, labour migration to urban and rural areas,etc.). For that reason it is often neither possible, nor economically rational, for land users to undertake labour-intensive forms of SWC.

- **Emphasis on a project rather than on a process approach**. Most donors and governments like to see tangible benefits in the short term. The project format with its short time span and clearly defined inputs and outputs, is the preferred vehicle. No attention is paid to the post-project phase, in which, as experience shows, conservation activities usually come to a grinding halt.

It is clear that many elements have contributed to a disappointing performance of the SWC sector in sub-Saharan Africa (and elsewhere !). At this stage it may be useful to point to three more lessons, which can be drawn from SWC experience and which should influence future design of SWC projects.

a. Many SWC projects have had **a narrow focus on technical aspects**. They have quite successfully promoted a SWC technique or a technical package, but given insufficient attention to the building of local institutions responsible for land management. In recent years SWC in the West African Sahel has sometimes become the starting point for village land use management programmes. In those cases attention is also paid to the management of non-agricultural land, social infrastructure and to local institutions responsible for managing the various activities.

b. SWC projects have rarely paid attention to **equity aspects**. The poorest land users (little land and no access to alternative sources of income) can often not afford to invest in SWC. Unless the poorest are deliberately supported by projects, for example through access to food loans or access to tools and means of transport, economic inequality at village level will tend to increase.

c. **SWC has increased the already heavy workload of women**. Conversely it is usually unclear how women have benefitted.

3. How to Improve Replicability and Sustainability in SWC

Although many SWC projects have promoted techniques, which have subsequently not been maintained and expanded by the "beneficiaries", some projects have been more successful in this respect. An analysis of successful projects shows that these usually have the following characteristics in common:

(a) *They have promoted simple and low-cost techniques:*
Unless techniques are relatively simple and low-cost they can not be adopted by land users. Land users can be trained in setting out contour lines on their fields and in applying certain rules of thumb, but they can not deal with design based on calculating runoff percentages and rainfall intensities. Furthermore the higher the costs per hectare the lower the possibilities for land users to adopt the techniques. In Burkina Faso, Mali and Niger simple planting pits (diameter 30 - 40 cm; depth 15 - 20 cm,

spacing about 80 cm) are a good example of a simple and low-cost technique, which is rapidly adopted by land users. These pitting systems are used to successfully rehabilitate strongly degraded land. Their attractiveness is also that a reasonable yield (300 - 600 kg/ha) of millet and sorghum can be obtained in years of low rainfall (300 - 400 mm) and therefore planting pits contribute substantially to increased food security at household level. In years of good rainfall (700 - 1100 mm) planting pits in the Sahel showed yields of sorghum in the range of 1500 - 2500 kg/ha (Reij 1994b).

(b) *Maintenance requirements are low:*
Practice shows that land users are sensitive to the total workload involved in construction and maintenance of conservation works. On the Central Plateau of Burkina Faso the construction of **earth bunds** requires a relatively modest investment of labour, but annual maintenance requirements are high. Land users in this region prefer to construct **contour stone bunds**, which require much higher initial investment of labour (collection and transport of stones), but their annual maintenance requirements are much lower than for earth bunds (Critchley *et al.* 1992a)

(c) *SWC techniques lead to immediate perceptible yield increases:*
Significant yield increases in the first year are an important stimulus to land users to adopt a SWC technique. These are achieved by an emphasis on **moisture conservation in dry areas**, **and/or emphasis on better agronomic practices, namely better land husbandry** (Hudson 1991).

(d) *Training of land users is a key activity*
Where land users have been trained systematically in simple topographical survey techniques (water tube level, A-frame, spirit level,etc.), in rules of thumb for the spacing and dimensions of SWC works, etc., they have been enabled to expand conservation works without waiting for survey teams and technicians. Examples of projects which have made training of land users a key activity are: the OXFAM-funded Agro-Forestry Project in Burkina Faso and the SIDA-funded National Soil Conservation Programme in Kenya. Currently most projects spend only a fraction of the total project budget on training of land users (less than 1 %). This is wholly inadequate (Critchley *et al.* 1992a).

(e) *Equipment of land users can facilitate and accelerate the adoption and implementation of SWC techniques:*
When land users are given access to adequate quantities of hoes, pick axes, shovels, wheelbarrows and donkey carts, they are in a better position to undertake SWC themselves, when and where they prefer to do so. They also need local means of transport for carting manure and compost to their fields (Reij 1994a).

(f) *The project promotes techniques preferred by the land users:*
Some projects have involved the land users in the evaluation of a number of SWC techniques constructed on farmers' fields. They subsequently promoted the techniques for which the land users had shown a clear preference and not necessarily those favoured by researchers or experts. The *Projet Agro-Forestier* in Burkina Faso is a good example (see section 4, example 1).

(g) *The project relies as much as possible on voluntary participation of land users:* When SWC techniques lead to significant yield increases in the first year after construction, land users tend to adopt these techniques on a voluntarily basis, because they have a clear **economic interest** in doing so. The above-mentioned planting pits are adopted spontaneously by farmers largely through imitation. In Niger's Illela District farmers and traders pay up to 150 000 CFA/ha for one hectare of barren degraded land (Reij 1994 b).

The scale and rate of land degradation is such that in most of sub-Saharan Africa the financial and human resources available to governments cannot cope with the problem. Unless hundreds of thousands of land users are willing to invest their own limited financial resources and their labour in better land management, the battle against land degradation can not be won.

Given that we now know what to do to increase replicability and sustainability in SWC, it is surprising that so many projects continue "business as usual". It is mildly astonishing that new projects continue to be designed on a "conventional" basis, despite considerable rhetoric at the level of donor agencies, governments and experts about people's participation in land management and about the need for simple and replicable techniques.

How to explain the gap between policy and practice ? Administrative procedures and political considerations seem to mitigate against better strategies. Most project or programme design missions spend far more time in the capitals than in the field. Politically and economically it may be more advantageous to donor agencies to export heavy machinery (tractors, lorries or graders) than to support the local production of tools, wheelbarrows and donkey carts. Many donor agencies like to know exactly how much money they will disburse in year x of a project; their procedures can't cope with (unpredictable) processes. In particular donor agencies providing loans for SWC projects continue to attach a high value to calculating internal rates of return, which is an unrealistic ritual, because ex-post evaluation shows that the internal rates of return estimated by all missions in the project design chain usually are consistently well below what was achieved in reality.

4. Examples of Projects Promoting SWC Techniques Showing High Replicability and High Sustainability

The previous section indicates some of what can be done to increase the likelihood of replicability and sustainability in SWC. Projects which promote appropriate, low-cost and efficient techniques, and which systematically train and equip land users to undertake SWC themselves have a better chance of being successful than those which rely on the use of heavy machinery to construct SWC works for the land users. **Based on past and present experience in SWC it is possible to assess what is a good and**

what is a bad project. In other words, **it is possible to become prescriptive.**[1]

EXAMPLE 1. THE OXFAM-FUNDED AGRO-FORESTRY PROJECT IN BURKINA FASO

This project, which is based in the Yatenga province, started with a research phase (1979 -1982). The objective of this research phase was to develop water harvesting techniques capable of stabilizing the degradation of the environment, while increasing the productivity of the soil. It started as a forestry project, but it soon became clear that the villagers were more interested in cultivating food crops than in growing trees. The project therefore tested a number of simple SWC techniques on farmer's fields and evaluated the results with the farmers, who showed a clear preference for contour stone bunds. In 1982 the project tested the use of a water tube level to determine contour lines for contour stone bund construction and it quickly became evident that with some training farmers could easily master this instrument. At the end of 1982 the project was sufficiently confident about the technical package and the associated training programme, that it decided to move into an extension phase (1983 - 1986). During this period about 1750 farmers in 339 villages were trained in the use of the water tube level as well as in basic principles of stone bund construction. The number of hectares treated by farmers increased from 7 ha in 1981 to about 600 ha in 1985. But from the beginning it was clear that a number of farmers realized the usefulness of the contour stone bunds and without being trained they started copying the stone bunds (Wright 1985).

The Agro-Forestry Project has not only promoted contour stone bunds, but its technical package gradually has become more comprehensive. It also promoted improved traditional planting pits (zay), composting methods, voluntary enclosure of livestock as a means to reduce grazing pressure on the vegetation, the creation of fodder banks, among other techniques.

Other projects have adopted contour stone bunding and at present tens of thousands of hectares on the Central Plateau of Burkina Faso have been treated with this technique, which has also spread to neighbouring countries (Mali and Niger) as well as to India (Gujarat State).

EXAMPLE 2. THE IFAD-FUNDED SWC PROGRAMME IN ILLELA DISTRICT OF NIGER'S TAHOUA DEPARTMENT

This project started in 1987. The project staff initially continued doing what several projects in the Tahoua Department had done for two decades: earth bund construction

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(1) It is also urgent to take positions and make clear recommendations to donor agencies and governments about what to do in SWC and what not to do. Aid flows to Africa are under growing pressure, and unless the efficiency and performance of development cooperation can be improved dramatically, aid flows, even for environmental projects, may dwindle in the coming years. The World Association of Soil and Water Conservation (WASWC) is currently undertaking a World Overview of Conservation Approaches and Technologies (WOCAT). In 1994 WOCAT will analyze a number of SWC projects in West, East and Southern Africa, which have the reputation to be successful.
The accent will be on the analysis of approaches and strategies used by successful SWC projects. The ultimate goal is to improve the performance in this sector.

using a grader, deep ploughing and the construction of half moons (demi-lunes). In 1988 the project organized a field trip for a group of farmers to Burkina Faso where they visited the Yatenga region. They were impressed by two things: firstly, the improved traditional planting pits used successfully in the Yatenga region to rehabilitate degraded land, which were larger versions of the traditional planting pits (tassa) the Nigerians sometimes used. Secondly, land users in the Yatenga treated their fields without being given food-for-work.

Upon return some farmers treated 3 hectares of degraded land with improved tassa. From 3 ha in 1988, the number of hectares increased to about 1 000 ha treated in 1992 (Reij 1993). It is now impossible to estimate how many hectares are treated each year by farmers, because many dig planting pits spontaneously without waiting for project staff or extension agents. Sometimes labour is hired to dig the pits or traditional work parties (gaya) are organized. The costs of pitting one hectare was is about 12 500 CFA (about US $ 25 in 1994 after the 50 % devaluation of the CFA in January 1994). The average yields of millet and sorghum on rehabilitated degraded land are in a year of "normal" rainfall in the order of 500 kg/ha (compared to 0 kg/ha in the without situation). Even using conservative estimates, the value of the millet and/or sorghum crop was at least US $ 80/ha (1994 prices). The value of cowpea, which is cultivated in association with the millet and sorghum is not taken into account here. The investment made in one hectare of planting pits is easily earned back the same year. This will change because the prices of barren degraded land are increasing almost by the day (Reij 1994b)

The major focus of the SWC programme in the Illela District is on the promotion of simple, low-cost and replicable techniques. Even if the project stopped its activities today, farmers would continue their efforts to rehabilitate barren, degraded land. The major technical weakness of the project is the lack of fertility maintenance and soil improvement, but also in that field some lessons were drawn from experience in Burkina Faso.

5. Examples of Projects Promoting SWC Techniques Showing Low Replicability and Low Sustainability

EXAMPLE 1. THE KEITA INTEGRATED RURAL DEVELOPMENT PROJECT

This project has the reputation of being a success story. Although this may be true in terms of physical achievements, there are some serious questions about replicability and sustainability. This project started in 1984 in an area with 300 - 400 mm rainfall, and its target was to rehabilitate 11 000 ha. in its first phase of seven years. The project combines the use of machinery for bund construction (tractors) with the use of labour. Between 1984 and 1989 the project mobilized between 2 500 and 3 000 people on a daily basis, not onlyä for bund construction, but also for dam building, tree planting and dune stabilization (Rochette *et al.* 1989). Project documents stress the voluntary participation of local residents in the project's activities. However, all labour was remunerated with food-for-work rations, which greatly facilitates the mobilisation of labour for the construction of conservation works, but at the same time it jeopardizes the spontaneous adoption of the conservation package promoted by the project as well as the continuation of activities in the post-project phase.

From a technical point of view the project has been very innovative. Water harvesting techniques were introduced to rehabilitate degraded plateaus (catchment : cultivated area ratio 2:1) and trenches are used for tree planting on barren hillsides. The estimated costs of bund construction on the plateaus was about US $ 600/ha in 1988 and the costs of tree planting using contour trenches was in the same year about US $ 1 750/ha (Critchley *et al.* 1992b).

There is no evidence of any voluntary adoption of the SWC techniques by the local population, which, given the size and the cost of the structures, is also unlikely in the future. If replicability is low, or even nil, the question of maintenance of conservation works by the land users becomes crucial. One of the major risks of relying on machinery for the construction of SWC works, lies in the fact that there is an imbalance between what can be constructed by machinery and the capacity of the local population to adequately manage the rehabilitated land. They either do not have the labour to cultivate the land, or they do not have sufficient manure to adequately fertilize the soil. The combined effect is that land is inadequately exploited and newly rehabilitated land becomes degraded again.

EXAMPLE 2. THE TURKANA REHABILITATION PROGRAMME

The Turkana Rehabilitation Programme was established in northern Kenya during 1980. TRP managed to alleviate the food shortages caused by drought and livestock deaths, but some of the later rehabilitation projects undertaken did little other than provide a source of food in exchange for construction of earth works of little intrinsic merit. Particularly inappropriate were the attempts, from 1985 onwards, to build "**water spreading schemes**", intended to divert flood flow from ephemeral water courses for crops and pasture. Water spreading had been tested in the District as long ago as the 1950s. These schemes had flopped due both to technical and socio-cultural problems. It was therefore not surprising that the TRP efforts were doomed to failure. The low point of the programme was the construction of a massive and costly scheme at Karubangarok in the north of the District. Food-for-work recipients had to be moved to the isolated site, where they constructed enormous earth bunds by hand in order to divert the "lugga". The first rains after completion caused a flood which tore through the scheme destroying bunds and creating deep gullies. Construction of water spreading schemes in the District provided a means to create labour for food-for-work, but little else. Significantly, where TRP did have some modest successes with water harvesting structures, this was with smaller schemes in locations where land users had a history of opportunist cultivation (Critchley and Erakudi 1992).

6. New Research Priorities in SWC

In the 1970s French scientists carried out considerable research in the West African Sahel on processes of erosion and runoff (Roose 1981). This type of research, which was usually undertaken on research stations or on researcher-controlled farm plots, has contributed significantly to our understanding of these phenomena. In the early 1980s American researchers carried out much research, in particular in Burkina Faso, on tied ridges. Although the research results indicate that investing in tied ridges is economically attractive, this technique has not been adopted by land users. In the second half of the 1980s research has shifted to technical packages that can be used to control erosion, rehabilitate degraded land and improve land management. This shift is part of a trend away from single technical solutions (for example contour stone bunds or permeable rock dams) essentially applied to cultivated fields or to rehabilitate degraded land for crop production, to more comprehensive **village land use management** (including village grazing land).

Much applied research remains to be done to fill up the many gaps in our current knowledge of SWC. The results of this type of research will be of immediate value for the design of more replicable and more sustainable SWC programmes. Six examples will be given of gaps in our current SWC knowledge, which need to be filled.

(a) *Indigenous soil and water conservation techniques*
Experience shows that the chances that land users will adopt conservation techniques increase when these techniques are based on ones which are familiar to them. Some projects have deliberately built on (improved) indigenous SWC techniques and in these cases many land users have spontaneously adopted the techniques and have applied them on their own fields without external support. The first step in the design process of a new SWC programme should be the identification of indigenous farming systems and conservation techniques and the next step should be to determine whether and how these conservation techniques can be used as a starting point for a new programme, and how their efficiency can be improved. In 1993, the Vrije Universiteit, Amsterdam and the London-based International Institute on Environment and Development have launched a two-year research programme which will assess the present state (abandonment, maintenance and/or expansion) of 28 indigenous SWC techniques in Africa.

(b) *The benefits of SWC*
In a large number of cases where moisture generally limits crop growth, the use of soil and water conservation and water harvesting techniques has led to immediate substantial yield increases. However, such yield increases extract larger quantities of nutrients from the soil than can be compensated for by the low application of organic manure or fertilizers (Roose 1994). Therefore critics underline that higher yield levels could not be sustained for more than two or three years. Practice shows that on fields treated with stone bunds and/or improved traditional planting pits higher yields seem to be sustained. When asked farmers often state that yields even continue to

improve over the years. This is probably due to the action of termites, which improve soil structure and soil fertility. When yields decline on treated fields they add more manure. Contour stone bunds and planting pits allow a more rational use of manure. Stone bunds prevent manure to be washed away from the fields by the first big rains and planting pits allow the concentration of water and manure in the same spot. Unfortunately SWC projects have not monitored the evolution of yields and for that reason data are lacking to refute this argument. In particular major (multi-million dollar) SWC projects should build in a systematic monitoring of the impact of SWC techniques on yields on the same fields over a period of at least five years. This type of research is challenging, because yield levels are not determined only by SWC techniques, but there are many other intervening variables, such as the use of fertilizers, the date of sowing and the efforts spent on weeding.

Farmers mention benefits of SWC, which are usually not considered by evaluators, either because they are ignored, or because they are difficult to quantify. On the Central Plateau of Burkina Faso farmers indicate that shortly after the construction of contour stone bunds, the water level in their wells started to rise and trees produced more fruits. It would be useful to develop appropriate evaluation methodologies, which could take such aspects into consideration.

(c) *Testing simple water harvesting techniques*
In recent years the efficiency of a number of simple water harvesting techniques has been proven in the Sahel. Examples are: contour stone bunds, improved traditional pitting techniques for the rehabilitation of degraded land, level permeable rock dams for gully rehabilitation and half moons (demi-lunes) for tree planting, but also for crop and fodder production (Critchley *et al.* 1992b). Two research needs can be identified in relation to water harvesting techniques. (1) Even though rainfall can differ substantially in the regions where water harvesting techniques are used, the tendency is to adhere to the same dimensions and spacing. It would be interesting to test different dimensions and spacing in areas with higher and lower rainfall. (2) East and Southern Africa have had to cope with several years of drought in recent years. It is worthwhile to systematically test water harvesting techniques, which are used in the Sahel, in these regions to explore the possibilities for transfer of technology.

(d) *The impact of different incentives on replicability*
SWC projects usually offer one or more incentives to land users in order to encourage them to spend their labour on the construction of conservation works or the planting of trees. Incentives offered vary from food-for-work, to cash-for-work and tools-for-work. How various types of incentives offered to land users impact on replicability is not clear. It has been argued that paying land users for their labour has had negative effects on SWC. It has encouraged the idea that as government pays for the construction of SWC, conservation works are owned by the government and government is also responsible for their maintenance. The effect of food-for-work and cash-for-work can be that no SWC will be undertaken unless these incentives are made available. The type of incentives provided have a great influence on whether land users are willing to continue SWC in the post-project phase. For that reason it is

urgent to undertake a systematic study of the impact of different types of incentives on replicability. **At present there are no consistent criteria applied to the design of incentive packages for new SWC programmes.**

(e) *SWC and the generation of off-farm employment*
Little attention has been paid so far to backward and forward linkages of SWC. A study on farm - off-farm linkages in sub-Saharan Africa (Haggblade *et al.* 1989) estimated that a 1 US $ increase in the value of agricultural production, generates another 0.5 US $ growth of GDP through backward linkages (increased input) or through forward linkages (trade and agricultural processing). This means that SWC, which produces yield increases of 40 % or more, can have a substantial impact on a local and regional economy. Few projects seem to have made a deliberate effort to strengthen their impact on local and regional off-farm employment. Many SWC projects rely on heavy machinery produced in Europe, Japan or the USA and only few rely on tools and equipment produced in the region and repaired locally. As rural employment generation is increasingly becoming a key issue, a study of the impact of different approaches to SWC on off-farm employment is rapidly becoming more urgent.

(f) *The influence of macro-economic policies on SWC*
Whether land users adopt SWC systems does depend on the acceptability of the techniques, but also the macro-economic situation in a country could play a role. When fertilizers are heavily subsidized, it is less attractive to land users to use manure. Cases are known, for instance in Tanzania, in which traditional fertility management and SWC techniques declined as a result of the introduction of ploughs and subsidized fertilizers. Since the introduction of the structural adjustment programme in Tanzania, which resulted in the reduction of subsidies, traditional fertility management practices are being revived. Little is known about the relationship between macro-economic policies and SWC.

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SOIL AND WATER CONSERVATION IN TUNISIA

H. MISSAOUI
Director of Soil and Water Conservation
Ministry of Agriculture
30, Rue Alain Savary
Tunis
Tunisia

1. Present Situation

Tunisia is located on the North coast of Africa and is limited to the North and the East by the Mediterranean coast, a total of 1300 Km, and to the South-East by Lybia and at the West by Algéria. The total land area is approximately 16.4 million hectares which is divided as follow :

- 7 Million hectares of land not suitable for agricultural production
- 5,4 Million hectares of agricultural land
- 4 Millions hectares of forest and pasture land.

Most of the territory is located within a semi-arid climate which results in a precarious situation for soil erosion control and management.
Studies conducted by the Ministry of Agriculture indicated that, at the present time, over 60 percent of the useful agricultural land is threatened by soil erosion. This is evidenced by the following statistics gathered over the last ten years:

- The loss of top soil estimated to 15000 hectares of agricultural land per year
- The decrease of soil fertility and agriculture yields
- The deposit of 25 Mm3 of sediments per year in reservoirs
- The reduction of the life of reservoirs by prematurely filling with silt
- The increase of 500 Mm3 of water run off per year through infiltration reduction
- The decrease of vegetal cover area due to overgrazing and clearing
- The flooding of plains and low lands resulting in damages estimated to be several million dollars per year.

2. Soil and Water Conservation Programme

To address the erosion phenomenon which has been intensified by different factors during the past few decades, many efforts to control erosion and protect the existing

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soil resources have been undertaken by the Tunisian Government since independence in 1956.

While these efforts have resulted in the treatment of 1.2 million hectares, they remain insufficient to meet the escalating erosion problems facing the country. For this reason, a program of erosion control and watershed management has been developed which integrates the use of appropriate soil and water conservation techniques and watershed and land management according to the land capability. To reach these objectives, the Soil and Water conservation Départment developed a new model based on hilly land treatment measures and integrated watershed management which aim to not only protect and the conserve soil and water resources but also to improve and increase the agricultural production.

This approach is based essentially on:

- The direct use of runoff water by the establishment of spreading structures in different watercourses.
- The improvement of water table level through the construction of structures across stream beds to increase water infiltration and groundwater tables.
- Maintain soil fertility by the use of agronomic and tillage practices in the cereal hillyland to improve agricultural yields.
- Restoration of the vegetal cover by pasture and range management practices and fencing the badlands and the highly eroded areas.
- The protection of dams against sedimentation in order to extend their life use by the construction of silting traps at the upper watershed.
- The preservation of the economical infrastructure against floods.
- The improvement of the life conditions of the rural populations by the creation of employment in the most disadvantaged regions.
- The creation of new agricultural land by the construction of structures across talwegs called "jessours" in the south part of Tunisia.
- The participation of beneficiaries by involving them in all the steps of the soil conservation process, from the initiation of the study to the construction phase.

3. Soil and Water Conservation Technics in Tunisia

The soil and water conservation practices used in Tunisia (see Figure 1) can be divided according to the bioclimatic stages of the country as follow :

**The subhumid region* of the North of the country, which lies between the line linking Bizerte to Gardimaou at the south and the mediteraneen sea at the North, where the yearly rainfall is above 500 mm. The most common soil conservation techniques used in this region are tillage practices, biological treatments, gully stabilization and small earthen dams.

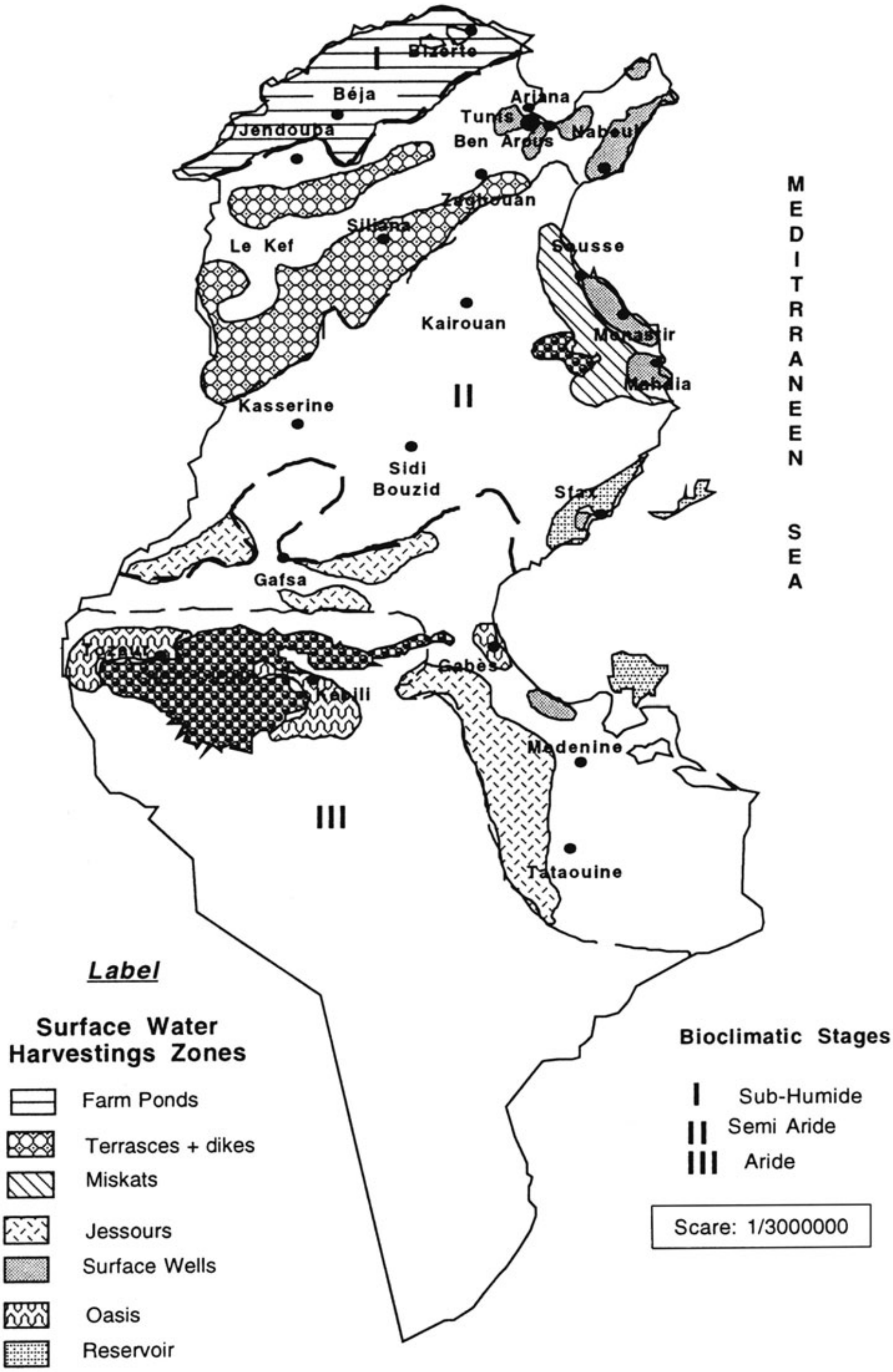

Figure 1. Map of Tunisia indicating main soil and water conservation techniques (El Amami 1984)

**The semi-arid region,* which covers a part of the North and the whole center of the country forming the largest bioclimatic stage of Tunisia, because it is located between the subhumid stage in the North and the line connecting Sfax to Feriana in the South.

The yearly rainfall is between 200 to 350 mm. The soil conservation techniques widely used in this region primarily center around terracing and integrated watershed management.

**The arid region* of the South, which covers the rest of the country and where the mean rainfall is between 100 and 200 mm per year. The soil and water conservation techniques are primarily water harvesting and surface runoff measures.

3.1. THE SOIL AND WATER CONSERVATION TECHNIQUES USED IN THE SUBHUMID REGION OF TUNISIA

3.1.1. *Strip Cropping*

This technique is a relatively easy way to control erosion and consists of a series of grassed strips of uniform width (2 to 5 meters) laid out on the contour line in a hilly crop land where the land slope is between 2.5 to 5% (Figure 2). On fields having larger slopes, a combination of strip cropping and terracing is necessary to control erosion. This technique is one that allows farmers to perform tillage and management practices across the slope or on the contour to reduce soil erosion, to increase water infiltration, to improve the soil water content and thus to increase yields.

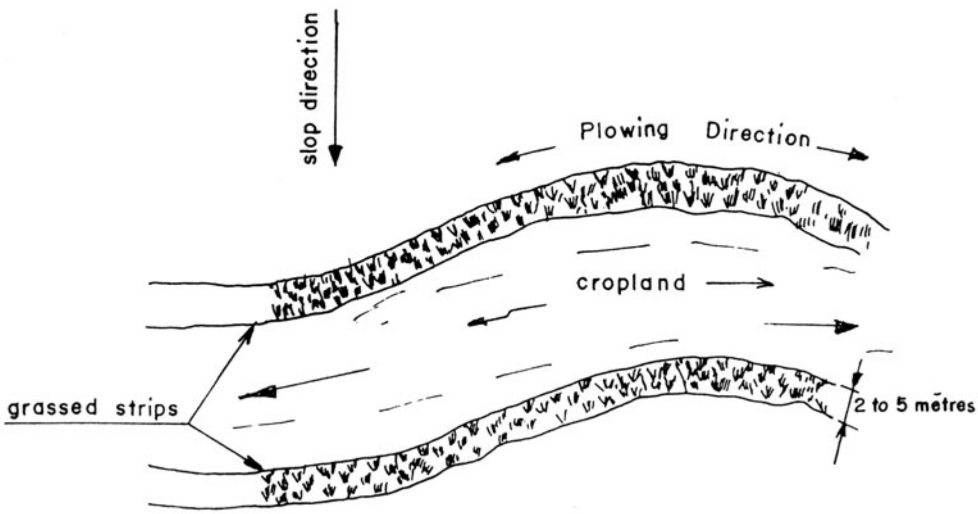

Figure 2. Schematic representation of strip-cropping for soil and water conservation (Laajili and Missaoui, 1988)

3.1.2. *Contouring*
This tillage operation or ploughing is carried out on the contour on hilly land. On gently sloping land, contouring will reduce the velocity of water run off and increase the surface water storage capacity which in turn will increase the infiltration into the soil. When contouring is used alone on steeper slopes or under conditions of high rainfall intensity and soil erodibility, there is an increased hazard of gully erosion because if the contour ridge breaks the stored water may be quickly released, causing damage to the down hill land.

3.1.3. *Biological Stabilization of Gullies*
This operation consists of the establishment of shrub species not eatable by animals to reduce the transport of sediments to the lower part of the watershed to stabilize active ravines. The most used species to fix gullies in Tunisia are: Acacia, Laurier Rose, and Agave.

3.1.4. *Small Earth Dams*
This type of earth embankment is constructed of relatively homogeneous soil material and is keyed into an impervious foundation stratum across the main or adjacent stream bed above the larger dams and are designed to trap sediments and to harvest water run off (Figure 3).

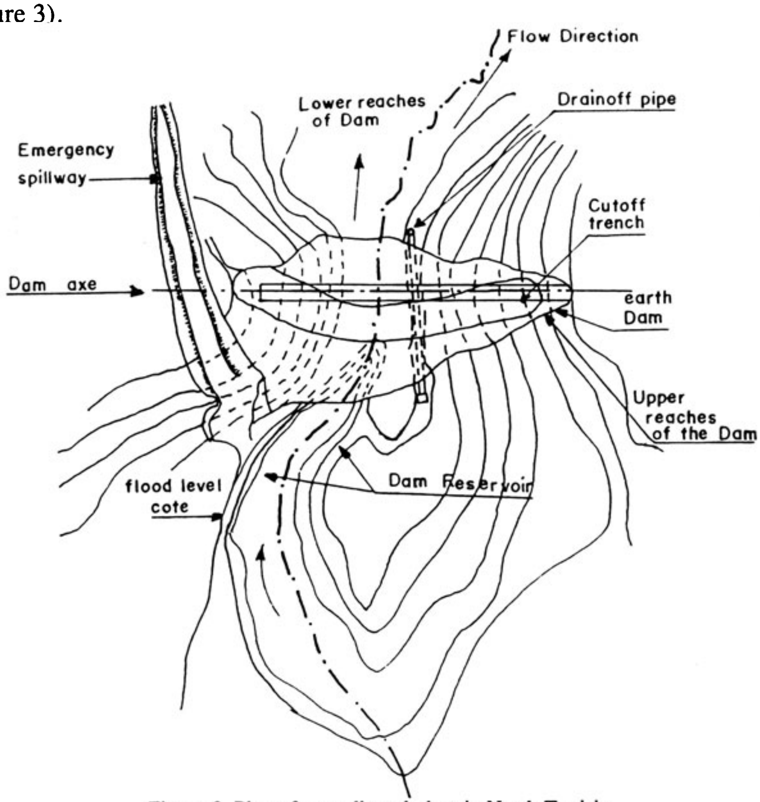

Figure 3. Plan of a small earth dam in North Tunisia

The small earth dams in Tunisia are classified as small hydraulic structures to collect water runoff that can be adjusted to fit domestic use, livestock, kitchen-garden and fruit trees plantation at small scale and eventually recharge the ground water reservoir. The small earth dams built in the framework of soil and water conservation have a water storage capacity from 50 000 to 250 000 m3. They are located in small watersheds having drainage areas from 80 to 1000 hectares in the North and the Central part of the country where the mean yearly rainfall is larger than 250 mm. The total height of this structure above ground level does not exceed 15 meters.

3.2. SOIL AND WATER CONSERVATION TECHNIQUES USED IN SEMI-ARID REGIONS.

These techniques vary from one region to another depending on the traditions of the people, farming systems and the yearly rainfall. The most common soil and water conservation technics are:

3.2.1. *Micro-Catchments, Called "Meskat"*

These are among the ancient water harvesting techniques and date from the Roman Period. They are quite common in the Eastern Tunisian coast (and especially: Sousse, Monastir and Mahdia), called "sahel". El Amami (1984) indicated that this traditional technique has revealed through the years as an efficient device to harvest surface water runoff for arboriculture. It is formed within small catchment areas to divert the water and a parcel to be irrigated in which one or more trees are grown (Figure 4).

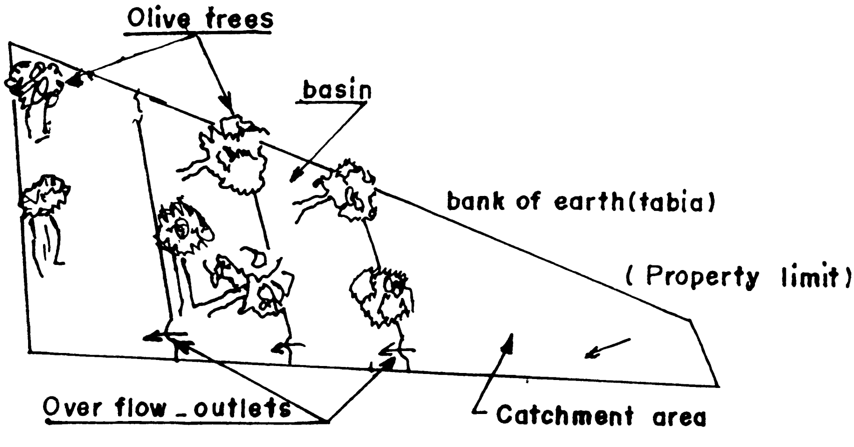

Figure 4. Typical arrangement for a Meskat (El Amani 1984)

Terraces are erected along the contour and spillway outlets allow the excess of water to drain to the next parcel safely. The concept of the Meskat is primarily based on a ratio between the catchment area and the irrigated parcel to be a factor of 2. For the system to function efficiently, the drainage area must be twice the size of the irrigated area. Unfortunately, because of extensive agricultural development and population growth is factor had been widely ignored. Experiments conducted on Meskats by S. El Amami of the Agricultural College of Chott Mariem near Sousse, indicated that Meskats can satisfy the water requirements of olive trees by improving precipitation to 500 mm per year in regions having a normal annual precipitation of 300 mm.

3.2.2. *Terraces*

Terraces of different types (French "banquettes") have been extensively and often successfully used in watershed management for soil and water conservation on hilly land, up to 40% slope (Figure 5). In the central part of Tunisia they are mostly used to collect water runoff and to develop agriculture and pasture land. In the larger precipitation areas the terrace network is usually designed with a slight longitudinal gradient to drain excess surface runoff through a drop structure inlet. In dry regions, they are designed to follow the contour and thereby retain the maximum surface runoff. Long terraces must be broken into separate compartments (cloisonnement) by constructing small berms across the terrace at regular intervals of approximately 20 to 50 meters. It should be emphasized that level terraces should be built on only permeable soils with small slopes.

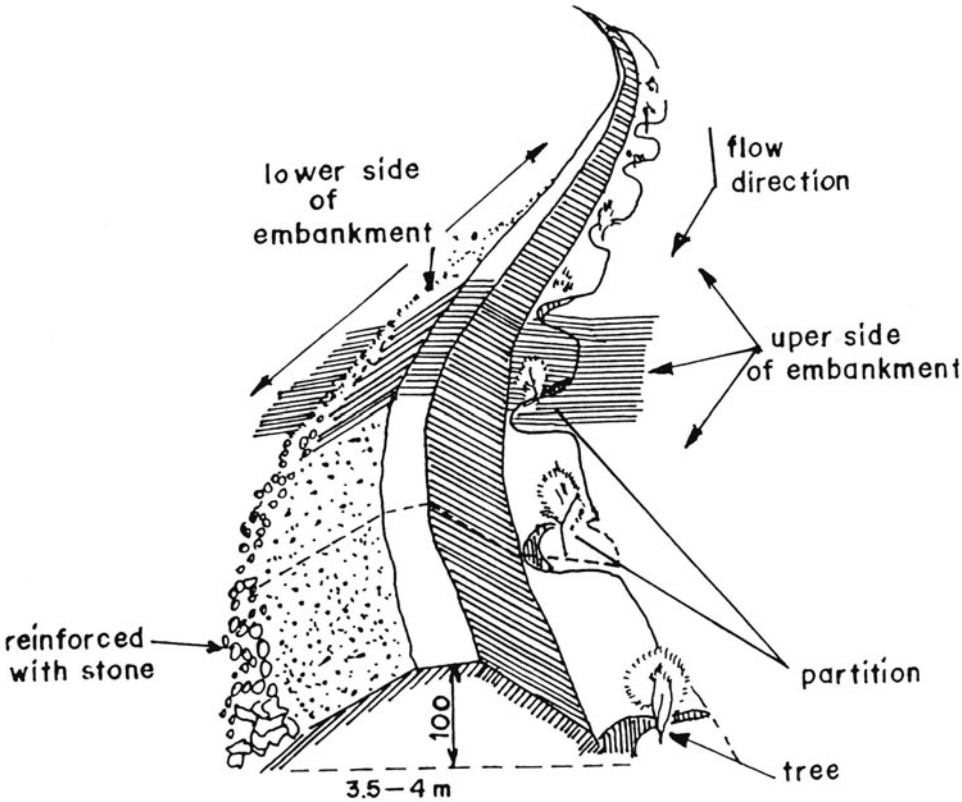

Figure 5. Typical terraces in Tunisia

Diversion terraces are an other kind of technique often used to intercept storm water that would otherwise flow down from higher ground onto the terraced area and cause damage to the lower parcels. These should be designed such that they will effectively control and divert all runoff from the above area.

3.2.3. *Individual Crescent-Shaped Terraces.*
In areas with gentle slopes, individual crescent-shaped terraces are usually most suitable. These are built around trees to harvest surface water runoff, conserve fertilizer and soil water available to the plant, and to increase the yield (Figure 6).

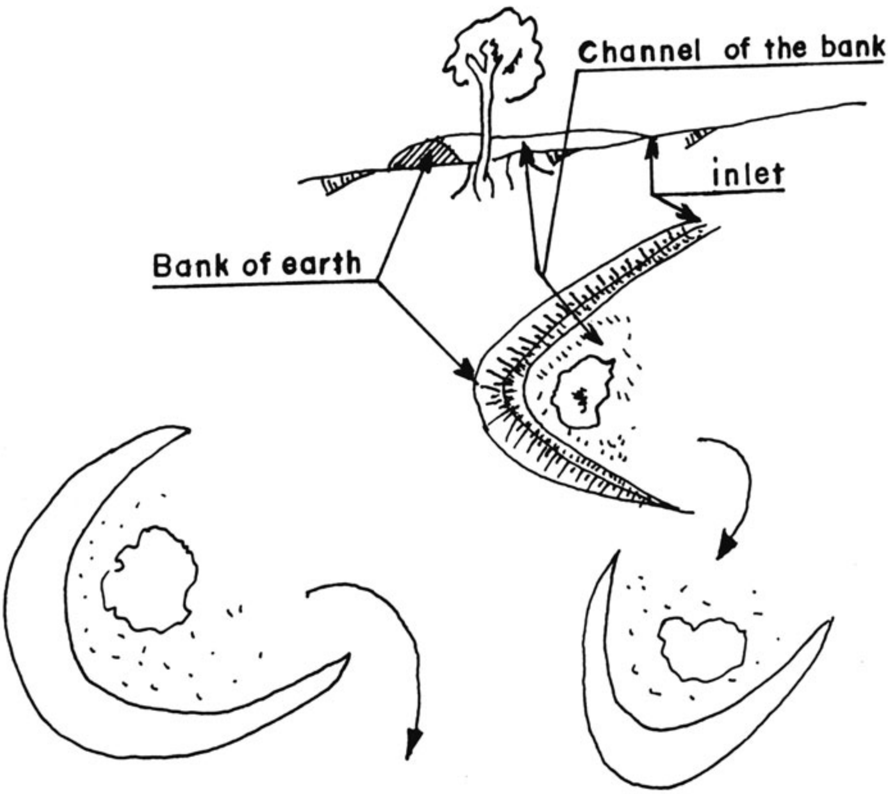

Figure 6. Individual crescent storage basins

3.2.4. *Water Spreading Structures (Traditional Water Spreading, M'goud)*
This technique diverts a portion of stream flow from a river during the rainy season to parcels of land through an opening on the river side slope (locally called "M'goud") (Figure 7). This technique is well developed on the South Center of Tunisia (Gafsa, Sidi Bouzid) and it continues to be used by local farmers because it is simple to instal in the river bed. Care must be taken to reduce the length of the slope and to reduce the runoff velocity. Harvesting surface runoff basically involves a catchment area or

channel prepared in a manner to improve runoff efficiency and a collection area in which crops are grown. This technique is justified in arid regions and it is within the capacity of most farmers.

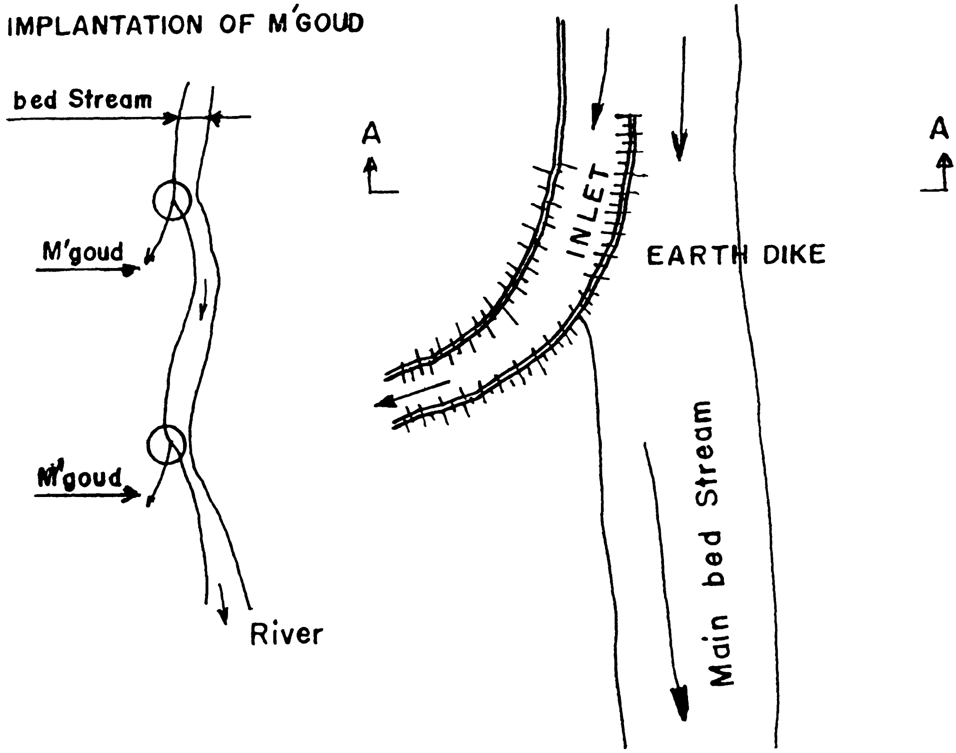

Figure 7. M'Goud method of water spreading (Chekhir 1993)

3.2.5. *New Types of Water Spreading Structures*

The new techniques of water spreading are based on a scientific approach incorporating the computation of river flows and the design of the structures to improve the functioning of the water spreading system. The modern water spreading structures are composed of 3 elements (Figure 8):

* a diversion dike, placed across the stream bed at the upper end of the land to irrigated;
* an inlet structure including the secondary and tertiary canals to divert the water to the projected irrigated land;
* a fusible earth embankment built with stream bed material to raise the water level in order to irrigate the whole perimeter. In case of large storm, this fusible earth dike is broken to protect the whole system from damage.

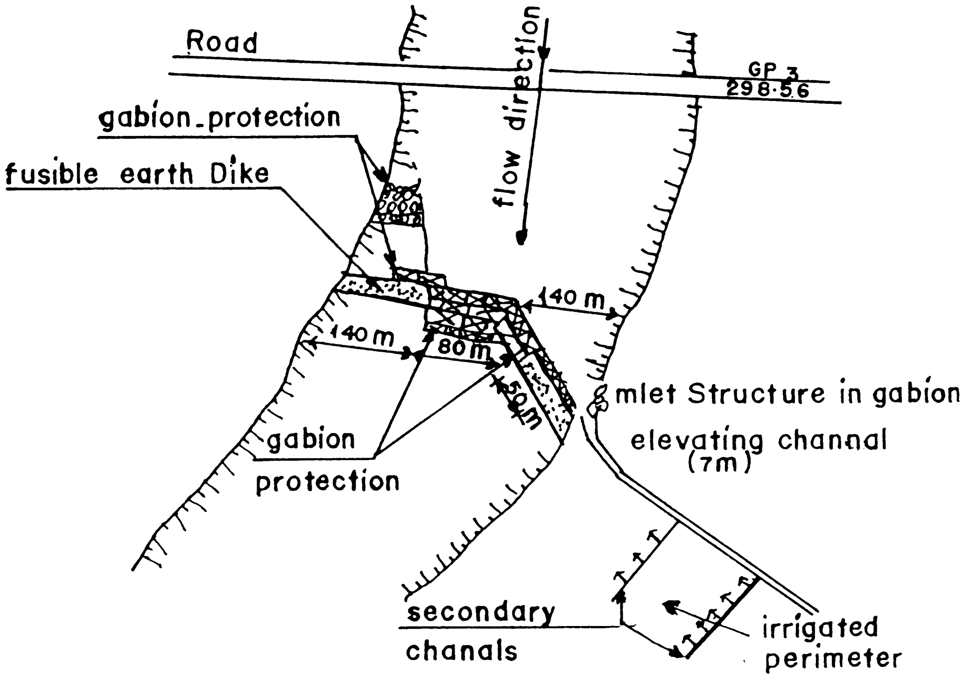

Figure 8. New types of water spreading structures (Laajili and Missaoui 1988)

1)The earth structures. When small inlet structures are used, earth embankments are constructed with material from the gully and established on side slopes of the water course to divert a portion of the run off water to irrigate a small patch of land (Figure 7).

2)The structures in gabions. These structures are built across river beds and in instable layers and pervious materials (wings). They can also be established in fine textured soils. El Ajili and Missaoui (1988) found that in sandy soils, foundations are not necessary because the structure is built on a flooring gabion of 0,50 m thickness which can adapt to the soil surface. A spillway must be provided with an energy dissipation basin to avoid undermining.

3)The structures in masonry. These structures are constructed in the pervious substratum on the main stream bed They can be also erected on rocky foundations or on heavy clay soils. The wings of these structures must be anchored in stable and impervious soils to prevent water run off circumventing the structure. These structures are used for flood control and ground water recharge.

3.2.5. *Bench Terraces (Rock Walls)*
This type of erosion control measure is considered among the most efficient and the most widely used in agriculture for many centuries (Figure 9). Many of them still

exist in the Atlas mountains in Tunisia, Morocco, Algéria and Lybia and are still functioning. They are easy to build and to maintain. In Tunisia, terraces are used for arboriculture and market-gardens. Rock walls are found in eroded and rocky lands. These structures are constructed on steep slope mountains without mortar. With time, sediment is trapped behind the rock walls and eventually agricultural soil is formed. These terraces are built on the contour and their length depends on the availability of material of each farmer, available labor and the area of the property.

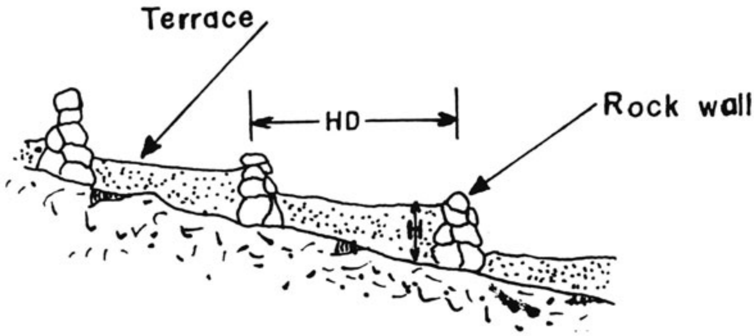

Figure 9. Rock wall terraces (Chammam 1984)

3.2.6. *Loose Rock Belts*

These 15 to 60 cm high terraces are constructed on the contour to reduce runoff velocity, entrap sediment and to clean the hilly land from stones (Figure 10). Once filled with sediments these rock belts form bench terraces for cultivation. They can be raised with rocks until the formation of natural terraces. In order to assure the permanency of these structures, it is necessary to reinforce them with shrub plantations such as, cactus, Agave and Diss. This technique of conservation is often justified in highly eroded and rocky pasture land.

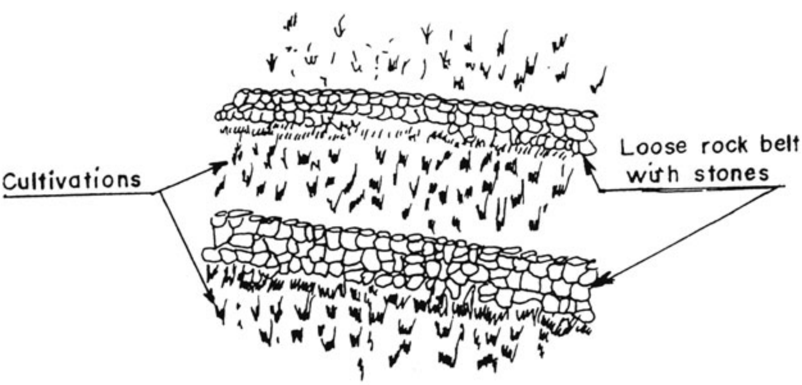

Figure 10. Loose rock belts (Laajili and Missaoui 1988)

3.3. SOIL AND WATER CONSERVATION TECHNIQUES USED IN ARID ZONES

3.3.1. *The Tabias*

This indigenous technique is called "broadbase level terraces" and is often built of soil taken from both sides of the ridge in order to obtain enough material for a sufficiently strong embankment to intercept the maximum amount of run off water and to facilitate infiltration (Figure 11). The end of the terrace can be closed, to store water for plant growth and open at the upper side to collect run off water. Alaya *et al.* (1993) defined the specifications of terraces as follows: the terrace length between 80 and 180 meters, width of 30 meters and height of approximately 1.5 meter. A portion of the water run off is retained and the excess is diverted to the next parcel through an outlet built at the lower part of the embankment. The perimeters managed in these terraces are planted with fruit trees in rows approximately 10 meters apart. This technique allows cultivated land in areas with yearly rainfall less than 200 mm. The Tabias intercept an important volume of run-off water and constitute an appropriate water conservation technique to promote agriculture development in arid zones. The supply of water to the Tabias can be accomplished in two ways:

1) Direct Supply. Tabias are constructed in the zone where the drainage area is located directly under a catchment zone of the upper watershed. The water supply is completed through direct run off during the rainy season (Figure 11).

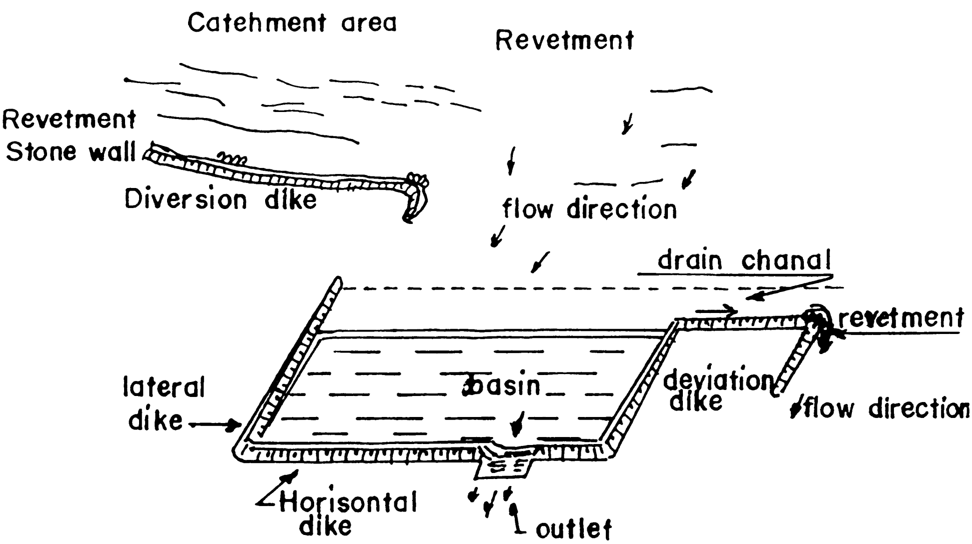

Figure 11. Broadbased level terraces -Tabias- (Alaya *et al.* 1993)

2) Indirect Water Supply. The Tabias are built in a series within a depression area adjacent to stream beds or ravines and are supplied by small earthen channels or diversion embankments constructed for this purpose inside the stream bed. These structures are usually constructed in areas having deep soils and yearly rainfall amounts of less than 200 mm in the central part of the county. Local farmers still rely on these techniques to develop their region and to grow crops, vegetables and fruits needed for their living (Figure 12).

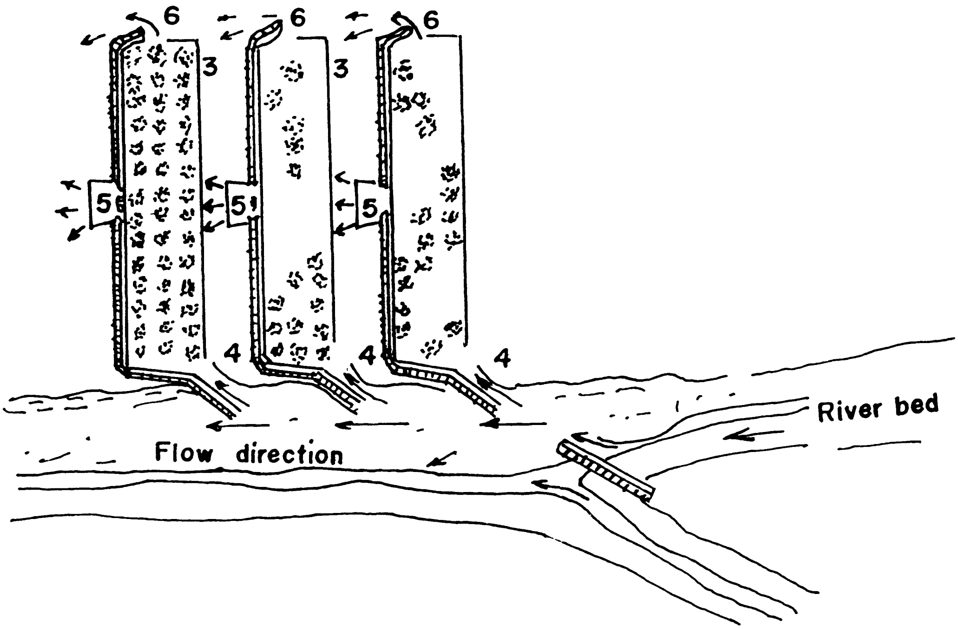

Figure 12. Tabias with indirect water supply (Alaya *et al.* 1993): 1) Affluent of oued hallouf; 2) Diversion fuse dike; 3) Tabia planted with olive trees; 4) Water intets; 5) Outlets; 6) Secondary spillway

3.3.2. *The Jessours or Checkdams*

These traditional hydraulic structures are typical of the mountain regions and arid climates in the Southern part of Tunisia (Figure 13). These structures form a series of small dams erected across gullies or natural talwegs and are made of drystone walls, earth or a mixture. They are especially suited for the mountains of Matmata, Beni Keddache, Tataouine and Sned Gafsa. Sediment delivered by run-off water is built up behind the check dam. Sediment and the accumulation of material form a sort of arable soil favorable for cultivation. That is why cereals, olive trees, palm trees, figs and vineyards have been grown in these areas for centuries. These techniques continue to be utilized in the arid regions for water harvesting to develop agriculture in dry climate where the yearly rainfall does not exceed 150 mm.

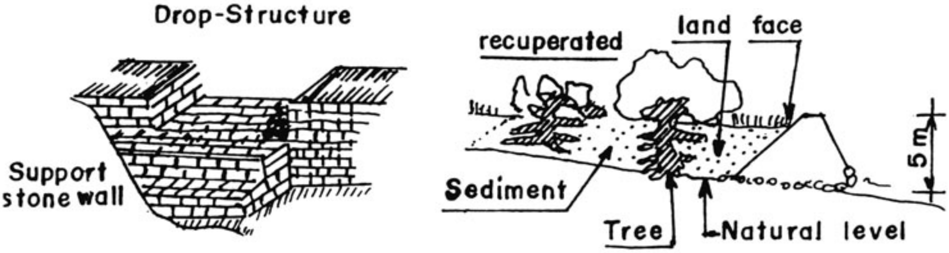

Figure 13. Water harvesting techniques (Jessours)

The Jessours are designed and built in several ways :

1) *The Jessours in earth*. These earth checkdams are built with a broadbase embankment with or without overpass. The earth fill terrace called "Tabia" can be reinforced with stones along the lower bottom of the Tabia to protect it against water pressure. An overflow structure is established on the lower side or on both ends to evacuate the excess of water safely.

2) *The Jessours in drystones*. They are built with drystones across deep gullies in shallow soil, to assure a better retention of water and sediments or silts. These structures are equipped with a bypass located at the middle and an opening to adequate carry the stream flow safely.

3) *The mixture of earth and dry stones Jessours*. These structures are located in the spreading area of rivers and are formed with earth embankments reinforced with a drystone checkdam located either at the depression, at the center or at the end of the earth dike. The size of the bypass is related to the drainage area of the watershed.

4. Conclusion

Soil and water conservation techniques have been used in Tunisia since the Romans. They constitute a rich experience in controlling erosion, protecting soil and contributing to agricultural development. These techniques which are the results of the efforts and the know-how of different civilizations (Berber, Romans, Arabs) who were concerned about food production while preserving agriculture land, continue to play an important role in the agriculture development based on the interception of run off water and its use in cultivation in the region adjacent to the desert.

Most of the techniques described in this document result from farmer experiences to conserve their land from erosion. Soil and water conservation service has provided additional technologies in order to make them more sustainable. These include engineering design, linkage of water runoff use to soil conservation, social acceptability and technical feasibility. These factors have improved the techniques and encouraged their replication by the population. While the cost of the soil and water conservation practices, varing between 350 D (Tunisian dinar) for terracing, 500 D for dry rock belt, 1800 D for the jessours and 700 D for plantation, are quite acceptable by well-off Tunisian farmers, they are still considered expensive for the poor and small farmers who do not have any other income.

To over come this constraint, government programs provide financial support to the small farmers to encourage them to apply soil conservation measures on their land. With this approach, the soil and water conservation program was developed and became a top priority of Tunisia Agriculture since the beginning of the last decade.

Thanks to these techniques agricultural yields are still obtained in areas where the annual precipitation is under 100 mm. Today, these older technologies have been improved through research, design and the selection of appropriate management. They have become an effective tool providing promising results in the conservation of soil and water, and the improvement of agriculture production. A research program must escort the soil and water conservation approach recently adopted by Tunisian ministry of agriculture.

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WATER HARVESTING - PAST AND FUTURE

D. PRINZ
University of Karlsruhe
Institute of Hydraulic Structures and Rural Engineering
D-76128 Karlsruhe
Germany

1. Introduction

As long as mankind has inhabited semi-arid areas and cultivated agricultural crops, it has practiced flood recession farming. Based on "natural water harvesting" the use of the waters of ephemeral streams was already the basis of livelihood in the arid and semi-arid areas many thousands of years ago, allowing the establishment of cities in the desert (Evenari *et al.* 1971).

Presumably millions of hectares of land in the dry parts of the world were once used for water harvesting but a variety of causes has brought about a steady decline.

The European expansion, especially the technological development since 1850, lead to a steady increase in area under "classical" irrigation techniques with preference to large schemes. Small-scale irrigation and traditional irrigation techniques received inadequate attention. The latter include the various techniques of water harvesting and supplementary irrigation.

During recent decades the interest in water harvesting has increased and national as well as international bodies have launched programmes to investigate the potential of water harvesting and to expand its area.

The sustainability of water harvesting systems was in the past based on the 'fitting together' of the basic needs of the farmers, the local natural conditions and theä prevailing economic and political conditions of the region. The preconditions for a positive future development of water harvesting will be the very same (Prinz 1994).

2. Basic Concepts and Characterization of Water Harvesting

2.1. GENERAL CONCEPT

Water harvesting is applied in arid and semi-arid regions where rainfall is either not

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 137–168.

sufficient to sustain a good crop and pasture growth or where, due to the erratic nature of precipitation, the risk of crop failure is very high. Water harvesting can significantly increase plant production in drought prone areas by concentrating the rainfall/runoff in parts of the total area.

The intermittent character of rainfall and runoff and the ephemerality of floodwater flow requires some kind of storage. There might be some kind of interim storage in tanks, cisterns or reservoirs. In the case of rainwater for irrigation, the soil itself serves as a reservoir for a certain period of time (Finkel and Finkel 1986).

Water harvesting is based on the utilisation of surface runoff; therefore it requires runoff producing and runoff receiving areas. In most cases, with the exception of floodwater harvesting from far away catchments, water harvesting utilizes the rainfall from the same location or region. It does not include its conveyance over long distances or its use after enriching the groundwater reservoir. Water harvesting projects are generally local and small scale projects.

2.2. DEFINITION, GOALS AND APPLICATION

There is no generally accepted definition of water harvesting (Reij *et al.* 1988). The definition used in this paper covers "the collection of runoff and its use for the irrigation of crops, pastures and trees, and for livestock consumption" (Finkel and Finkel 1986).

The goals of water harvesting are:

- Restoring the productivity of land which suffers from inadequate rainfall;
- Increasing yields of rainfed farming;
- Minimizing the risk in drought prone areas;
- Combating desertification by tree cultivation;
- Supplying drinking water for animals.

In regions with an annual precipitation between 100 and 700 mm, low cost water harvesting might provide an interesting alternative if irrigation water from other sources is not readily available or too costly. (In summer rainfall areas the minimum precipitation for water harvesting is around 200 mm/year). In areas with more than 600 -700 mm annual rainfall water harvesting techniques can prolong the cropping season. In comparison with pumping water, water harvesting saves energy and maintenance costs. These advantages are countered by the problem of unreliability of rainfall, which can partly be overcome by interim storage (cisterns, small reservoirs). Modern hydrological tools (e.g. calculation of rainfall probability and water yield) allow a more precise determination of the necessary size of the catchment area.

As mentioned before, the central elements of all water harvesting techniques are:

- a runoff area (catchment) with a sufficiently high run-off coefficient (impermeability would be optimal), and
- a "run-on" area, where the accumulated water is stored and/ or utilized. In most

cases the runoff is used for agricultural crops, the water then being stored in the soil profile. A high storage capacity of the soil (i.e. medium textured soils) and a sufficient soil depth (> 1 m) are prerequisites here (Huibers 1985). The water retention capacity has to be high enough to supply the crops with water until the next rainfall event.

The most important parameters to be taken into consideration in practising water harvesting are therefore: rainfall distribution, rainfall intensity, runoff characteristics of the catchment, water storage capacity of soils, cisterns or reservoirs, the agricultural crops and technologies and socio-economic conditions (Tauer and Prinz 1992).

The tools used to identify possible runoff irrigation areas are:

- field visits;
- areal surveys and evaluation of aerial photographs;
- satellite images and their classification and evaluation (Tauer and Humborg 1992).

3. Commonly Applied Forms

As mentioned before, water harvesting has been practiced for millennia and is still applied world-wide. Of the great number of forms in existence with various names, six forms are generally recognized:

a) roof top harvesting
b) water harvesting for animal consumption
c) inter-row water harvesting
d) microcatchment water harvesting
e) medium-sized catchment water harvesting
f) large catchment water harvesting.

Table 1 gives an overview of these forms and their most prominent features. Fig. 1 shows the annual precipitation ranges for various water harvesting (WH) forms.

a) Roof top harvesting
Rain "harvested" from the roofs of buildings including greenhouses is, in many locations, a very valuable resource being used mainly for drinking and domestic purposes (UNEP 1983). However, for the purpose of this paper, roof top harvesting is excluded as its use for agricultural purposes is limited to very few locations only (Papadopoulos 1993).

b) Water harvesting for animal consumption
Ancient dwellers harvested rain water for human and animal consumption by redirecting the water running down hillslopes into cisterns.

TABLE 1. Overview of the main types of water harvesting

WH-type	Kind of flow	Kind of surface	Size of catchment	Catchment: cropping area ratio	Water storage type	Water use
Roof top water harvesting	Sheet flow	Roofs of all kinds	small		Tanks, jars, cisterns	Drinking, domestic, livestock
Water harvesting for animal consumption		Treated ground surfaces	< 3 ha	extreme various	Tanks, cisterns	Livestock
Inter-row WH		Treated ground surfaces	1 - 5 m^2	1:1 - 7:1	Soil profile (reservoirs, cisterns)	Tree, bush, vegetable, and field crops
Micro-catchment WH	Sheet and rill flow	Treated and untreated ground surfaces	2 - 1000 m^2	1:1 - 10:1	Soil profile (reservoirs, cisterns)	
Medium-sized catchment WH	Turbulent runoff/ channel flow	Treated or untreated ground surfaces	1000 m^2 - 200 ha	10:1 - 100:1	Soil profile (reservoirs, cisterns)	
Large catchment WH	Flood water flow	Untreated ground surfaces	200 ha - 50 km^2	100:1 - 10,000:1	Soil profile	

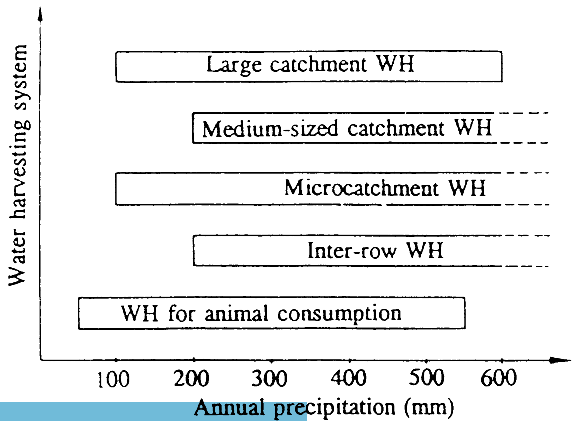


Figure 1. Annual precipitation ranges for different forms of water harvesting

Presently, this tradition is still practiced in many regions, but where the means are available, surfaces used for rainwater collection are usually either physically compacted, chemically treated or covered to increase runoff volume:

I. Clay soils are well suited for compaction. The surfaces are shaped,smoothened and then compacted e.g. by tractor and rubber-tired rollers.
II. Sodium salts, wax, latexes, asphalt, bitumen, fiberglas and silicones can be used as sealants on soils which do not swell with moisture (Frasier 1993). Plots treated with sun-melted granulated paraffin-wax yielded about 90 percent of the rainfall as runoff, compared to 30 percent from untreated plots.
III. Concrete, plastic sheeting, butyl rubber and metal foil can also be used to cover the soil for rainwater harvesting. Gravel may protect the underlying membrane against radiation and wind damage.

The runoff water is collected in lined or unlined pits down the slope of the catchment area (Figure 2), (Frasier and Myers 1983, Dutt *et al.* 1981).

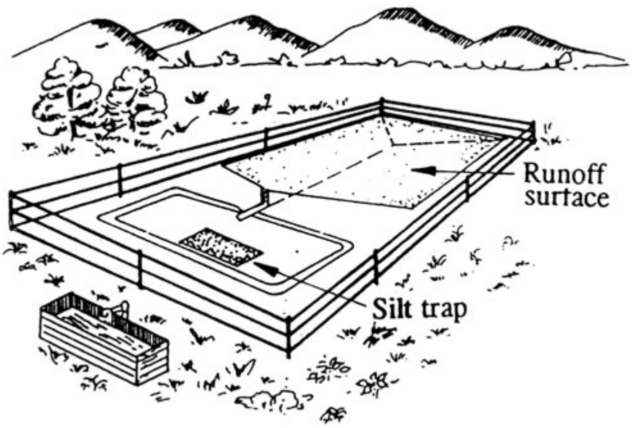


Figure 2. Western Australia rainwater-harvesting system for animal consumption. The runoff-surface is compacted and treated. (FAO 1977)

c) Inter-row water harvesting

Inter-row water harvesting is applied either on flat land or on gentle slopes of up to 5 % having soil at least 1 m deep. The annual rainfall should not be less than 200 mm/year.

On flat terrain (0 - 1 % inclination) bunds are constructed, compacted and, under higher-input conditions, treated with chemicals to increase runoff. The aridity of the location determines the catchment to cropping ratio (CCR), which varies from 1:1 to

5:1 (Fig. 3). Examples are given from India (Vijayalakshmi *et al.* 1982) and the USA (Frasier 1993).

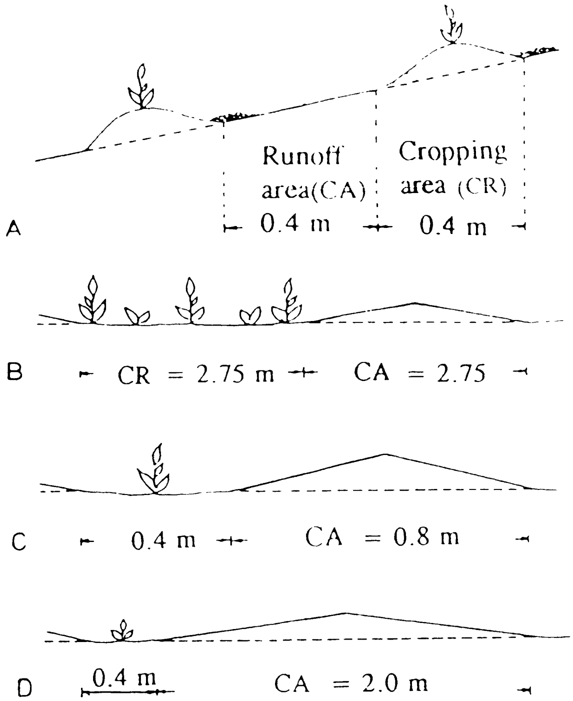


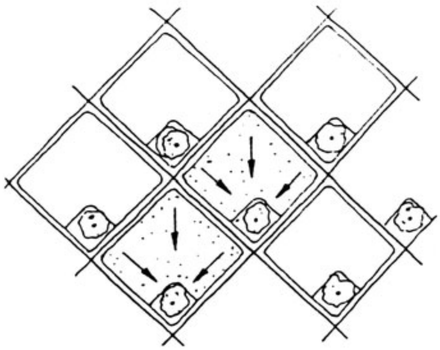
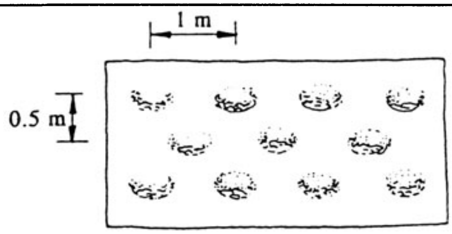
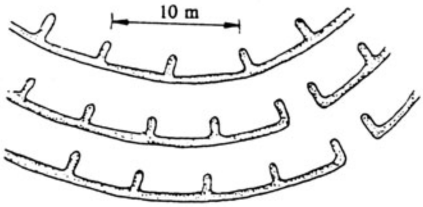
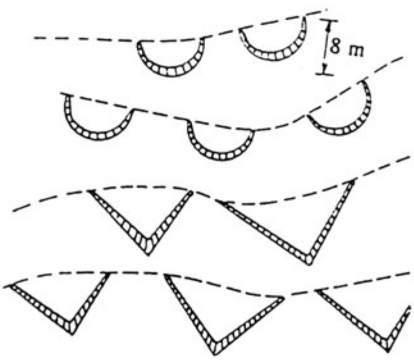
Figure 3. Various forms of inter-row water harvesting; from a - d increasing CCR/aridity of location. (Prinz 1986)

On sloping land these systems are called "contour ridges" (USA) or "Matuta" (East Africa). The ridges of about 0.40 m height are built 2 to 20 m apart, depending on slope, soil surface treatment, general CCR and type of crop to be grown. The catchment area should be weeded and compacted; the crops are either grown in the furrow, along the upper side of the bund or on top of the bund. On sloping land, this system is recommended only for areas with a known regular rainfall pattern; very high rainfall intensities may cause breakages of the bunds. Crops cultivated in row systems water harvesting are maize, beans, millet, rice or (in the USA) grapes and olives (Pacey and Cullis 1986).

The preparation of the land for inter-row water harvesting can be fully mechanized.

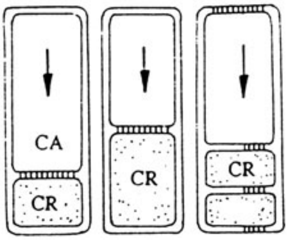
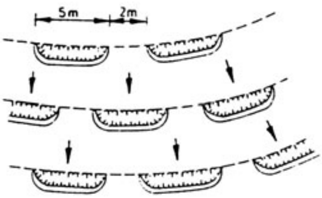
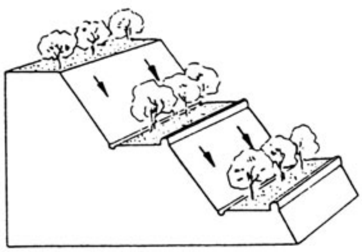
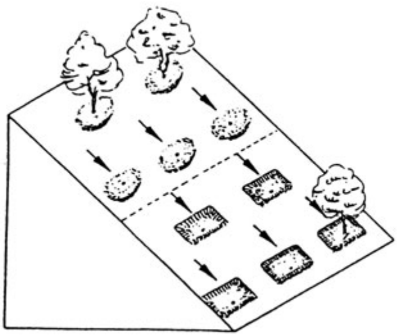
d) Microcatchment systems

Microcatchment water harvesting (MC-WH) is a method of collecting surface runoff from a small catchment area and storing it in the root zone of an adjacent infiltration basin. This infiltration basin may be planted with a single tree, bush or with annual crops (Boers and Ben-Asher 1982). Fig. 4 depicts various microcatchment systems in use.

Type	Illustration	Area (m²)* and ratios**	Regional annual precipitation (mm)	Remarks & References
Negarin		CA= 3-250 CR= 1-10 CCR= 3:1-25:1	100-600	Slope 1-7 %; Ben-Asher 1988
Pitting		CA= 0.25 CR= 0.08 CCR= 3:1	350-600	"Zay system" (West Africa), "Kitui Pitting" "Katumani Pitting" (Kenya) Buritz *et al.* 1986 Gichangi *et al.* 1989
Contour ridges		CA= 100 CR= 20 CCR= 5:1	300-600	Critchley 1987 Chase 1986 Finkel 1986
Semi-circular hoops (demi-lunes); Triangu--lar bunds		CA= 24-226 CR= 6-57 CCR= 4:1	300-600	MoALD 1984 Finkel 1986

* CA = Catchment size (m²) * CR = Cropping area (m²) ** CCR= Catchment: Cropping Ratio

Figure 4. Various types of microcatchment (MC) water harvesting

Type	Illustration	Area (m^2)* and ratios**	Regional annual precipitation (mm)	Remarks & References
Meskat-type		CA= 500 CR= 250 CCR= 2:1	200-400	El Amami 1983 Tobbi 1993
Valleran-type (fully mechanized)		CA= ˜ 15 CR= ˜ 2.4 CCR= 6:1	100-600	400 MC/ha = 960m^2 CR/ha Preparation by "wavy dolphin plough"; Antinori and Vallerani 1993
Contour bench terraces		CA= ˜2-16 CR= 2-8 CCR= 1:1-8:1	100-600	"Conservation bench terraces"
Eye brow terraces; Hillslope microcatchments		CA= 5-50 CR= 1-5 CCR= 3:1 - 20:1	100-600	100,000 trees programme in the Negev/Israel Ben-Asher 1988

* CA = Catchment size (m^2)
* CR = Cropping area (m^2)
** CCR= Catchment: Cropping Ratio

Figure 4. Various types of microcatchment (MC) water harvesting (continuation)

The advantages of MC-WH systems are:

- Simple design and cheap to install, therefore easily replicable and adaptable.
- Higher runoff efficiency than medium or large scale water harvesting systems; no conveyance losses.
- Erosion control function
- Can be constructed on almost any slope, including almost level plains.

The disadvantages of MC-WH systems are:

- The catchment uses potentially arable land (exception: steep slopes)
- The catchment area has to be maintained, i.e. kept free of vegetation which requires a relatively high labour input.
- If overtopping takes place during exceptionally heavy rainstorms, the systems may be irrevocably damaged.
- Low crop density, low yield in comparison with other irrigation methods (e.g. 40 trees per hectare for the Negarim type WH, Figure 4)

e) Medium-sized catchment water harvesting
Water harvesting from medium-sized catchments (1,000 m^2 - 200 ha) is referred to by some authors as "water harvesting from long slopes", as "macro-catchment water harvesting" or as "harvesting from external catchment systems" (Pacey and Cullis 1988, Reij *et al.* 1988) It is characterized by:

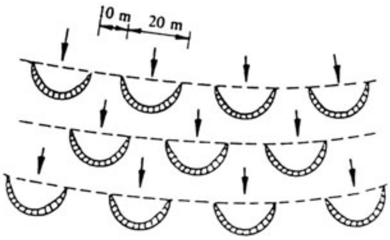
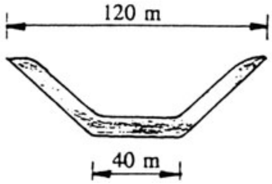
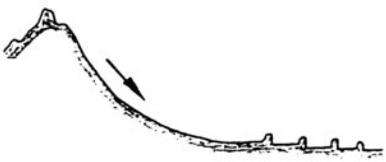
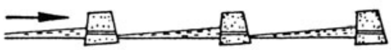
- A CCR of 10:1 to 100:1; the catchment being located outside the arable areas.
- The predominance of turbulent runoff and channel flow of the catchment water in comparison with sheet or rill flow of microcatchments.
- The partial area contribution phenomenon is not relevant for micro catchments.
- The catchment area may have an inclination of 5 to 50 %; the cropping area is either terraced or located in flat terrain.

Fig. 5 shows the most prominent types of this system.

f) Large catchment water harvesting
Large catchment water harvesting comprises systems with catchments being many square kilometres in size, from which runoff water flows through a major wadi (bed of an ephemeral stream), necessitating more complex structures of dams and distribution networks. Two types are mainly distinguished:

"Floodwater harvesting within the stream bed" means blocking the water flow to inundate the valley bottom of the entire flood plain, to force the water to infiltrate and use the wetted area for crop production or pasture improvement (Fig. 6).

"Floodwater diversion" means forcing the wadi water to leave its natural course and conveying it to nearby areas suitable for arable cropping. Floodwater diversion techniques were already applied several thousand years ago (e.g. Marib, North Yemen; Brunner and Haefner 1986) and systems are known from NW Mexico, Pakistan, Tunisia ("Jessour system"), Kenya, China etc. (Reij *et al.* 1988); (Fig. 7). The CCR ranges from 100:1 to 10,000: 1.

Type	Illustration	Area (m^2)* and ratios**	Regional annual precipitation (mm)	Remarks & References
Stone dams		(extreme variations)	300-600	Diguettes or Digues filtrantes: Permeable contour check dams
Large semi-circular hoops		CA= 750-10,000 CR= 50-350 CCR= 15:1-40:1	200-400	Staggered position: used for crops or pasture improvement Reij *et al.* 1988 Finkel 1986
Trape--zoidal bunds		CA= 5 - 3 x 10^5 CR= 3,500 CCR=15:1 - 100:1	200-400	Staggered position: slope 1-3% mainly for crops Reij *et al.* 1988 Critchley 1987
Hillside conduit systems		CA= 10-10^7 CR= 1-10^5 CCR=10:1 - 100:1	100-600	Examples: Avdat and Shifta Experimental Farms, Negev, Israel; For trees and annual crops Evenari *et al.* 1982 Klemm 1990
Liman terraces		CA= 2x10^4-2x10^5 CR= 1,000 - 5,000 CCR=20:1 - 100:1	100-300	In Israel mainly planted to Eucalyptus tree species; sometimes built in succession. Bruins *et al.* 1986, Lövenstein 1993
Cultivated reservoirs		CA= 1,000 - 10,000 CR= 100 - 2,000 CCR=10:1 - 100:1	150 - 600	Khadin, Rajastan (India); Ahar, Bihar (India); Tera, SE Sudan Kolarkar *et al.* 1983, Pacey and Cullis, 1986

* CA = Catchment size (m^2), * CR = Cropping area (m^2), ** CCR = Catchment: Cropping ratio

Figure 5. Types of medium-sized catchment water harvesting

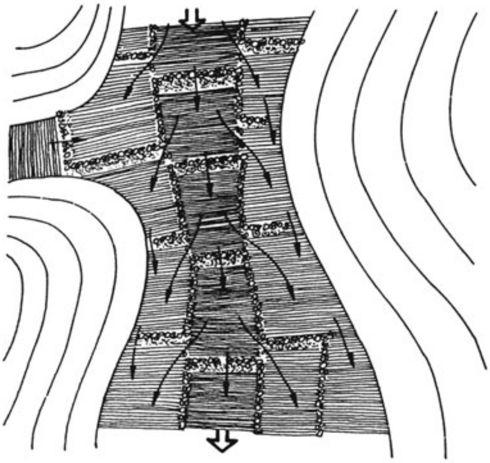


Figure 6. Floodwater harvesting within the stream-bed: Design of rock barriers used to spread the water in large, shallow wadis (Nabatean system) (Evenari and Koller 1956, from Cox and Atkins 1979)

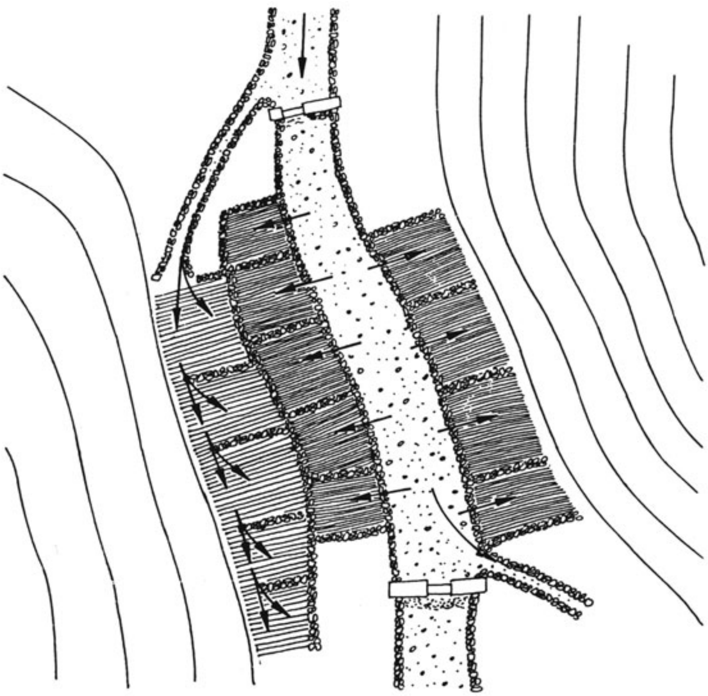


Figure 7. Flood water diversion scheme: Design of water-spreading dams in large, deep wadis, Nabatean system. (Evenari and Koller 1956, from Cox and Atkins 1979)

4. The Past Role of Water Harvesting

4.1. GENERAL ASPECTS

As mentioned before, water harvesting played a more important role in the past for the well-being of people in dry areas than it currently does. The reasons are manyfold:

- Alternative sources of drinking water and water for irrigation were not available:
  - no pumping from groundwater or other deep water sources
  - very few large dams
  - no long distance conveying of water through lined canals, pipes etc.
- The building of structures for water harvesting, the cleaning and smoothing of runoff surfaces, the maintenance of canals and reservoirs are labour demanding. Labour was a cheap resource, or even unpaid as in the case of slaves.
- Agriculture was the backbone of the society and very few other choices to generate income were given. Therefore, relatively more input was invested in agriculture including runoff agriculture.

Various examples are given hereafter to illustrate the past role of water harvesting worldwide. Unfortunately, the extreme importance of certain water harvesting techniques is often not reflected by the number or depth of publications.

Some of the techniques mentioned are still presently practiced.

4.2. ASIA

4.2.1. *The Middle East*

The outstanding importance of the Middle East in the development of ancient water harvesting techniques is unquestioned. Archeological evidence of water harvesting structures appears in Jordan, Syria, Iraq, the Negev and the Arabian Peninsula, especially Yemen.

In Jordan, there is indication of early water harvesting structures believed to have been constructed over 9,000 years ago. Evidence exists that simple water harvesting structures were used in Southern Mesopotamia as early as in 4,500 BC (Bruins *et al.* 1986).

Internationally, the most widely known runoff-irrigation systems have been found in the semi-arid to arid Negev desert region of Israel (Evenari *et al.* 1971). Runoff agriculture in this region can be traced back as far as the 10th century BC when it was introduced by the Israelites of that period (Adato 1987). The Negev's most productive period in history however, began with the arrival of the Nabateans late in the 3rd century B.C. (Fig. 8). Runoff farming continued throughout Roman rule and reached its peak during the Byzantine era.

Figure 8. Reconstruction of an ancient water harvesting system (Hillsite conduit system") in Wadi Avdat/Negev (100 mm annual precipitation, CCR 175:1, 2 ha collecting area) Photo: Prinz

In North Yemen, a system dating back to at least 1,000 B.C. diverted enough floodwater to irrigate 20,000 hectares (50,000 acres) producing agricultural products that may have fed as many as 300,000 people (Adato 1987, Eger 1988). Farmers in this same area are still irrigating with floodwater, making the region perhaps one of the few places on earth where runoff agriculture has been continuously used since the earliest settlement

In the South Tihama of Saudi Arabia, flood irrigation is traditionally used for sorghum production. Today, approximately 35,000 ha land, supporting 8,500 to 10,000 farm holdings, are still being flood irrigated (Wildenhahn 1985).

In Afganistan, composite microcatchments have been in use for a long time. In a survey conducted in the early 1970s, over 70,000 ha of Meskat-type systems used for growing fruit trees were reported.

In Baluchistan two water harvesting techniques were already applied in ancient times: the "Khuskaba" system and the "Sailaba" system. The first one employs bunds being built across the slope of the land to increase infiltration. The latter one utilizes floods in natural water courses which are captured by earthen bunds (Oosterbaan 1983). Figure 9 depicts such a water spreading system in Pakistan.

4.2.2. *India*

In India, the "tank" system is traditionally the backbone of agricultural production in arid and semi-arid areas. The tanks collect rainwater and are constructed either by bunding or by excavating the ground. It is estimated that 4 to 10 hectares of catchment are required to fill one hectare of tank bed.

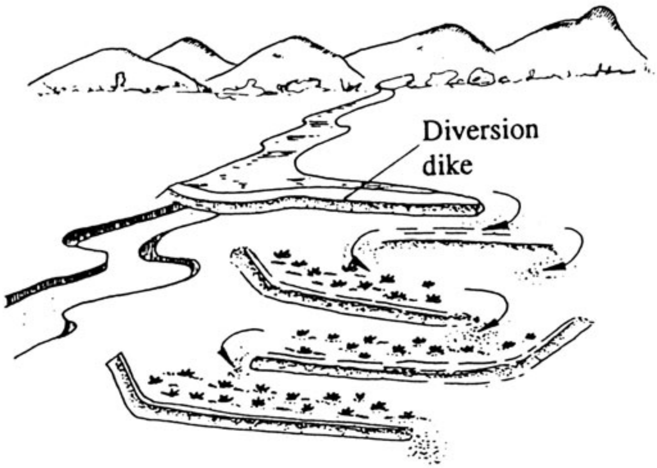


Figure 9. Water spreading system in Pakistan to divert flood water for agricultural use, Sailaba system. (Adapted from French and Hussain 1964)

In West Rajastan, with desert-like conditions having only 167 mm annual precipitation, large bunds were constructed as early as the 15th century to accumulate runoff. These "Khadin" create a reservoir which can be emptied at the end of the monsoon season to cultivate wheat and chickpeas with the remaining moisture (Kolarkar *et al.* 1983). A similar system called "Ahar" developed in the state of Bihar (UNEP 1983, Pacey and Cullis 1986). Ahars are often built in series. It was observed that brackish groundwater in the neighbourhood of "ahars" became potable after the "ahar" was built, due to increased supply of rain water.

4.2.3. *China*

A very old flood diversion technique called "warping" is found in China's loess areas which harvests water as well as sediment (Reij *et al.* 1988).

4.3. AFRICA

4.3.1. *North Africa*

Since at least Roman times water harvesting techniques were applied extensively in North Africa. Archeological research by the UNESCO Libyan Valleys team revealed that the wealth of the "granary of the Roman empire" was largely based on runoff irrigation (Gilbertson 1986). The team excavated structures in an area several hundred kilometres from the coast in the Libyan pre-desert, where the mean annual precipitation is well below fifty millimetres. The farming system here lasted well over 400 years and it sustained a large stationary population, often wealthy, which created enough crops to generate even a surplus. It produced barley, wheat, olive oil, grapes, figs, dates, sheep, cattle and pigs. The precipitation is variable, falling in just one or two rain storms, often separated by droughts several years long. (There isn't any evidence of climatic change since Roman period).

Many other examples of the application of traditional techniques in North Africa can be given. In Morocco's Anti Atlas region, Kutsch (1982) investigated the traditional and partly still practised water harvesting techniques. He found a wealth of experience and a great variety of locally well adapted systems.

In Algeria, the "lacs collinaires", the rainwater storage ponds are traditional means of water harvesting for agriculture. The open ponds are mainly used for watering animals.

In Tunisia, the "Meskat" and the "Jessour" systems have a long tradition, but are also still practiced. The "Meskat" microcatchment system consists of an impluvium called "meskat", of about 500 m^2 in size, and a "manka" or cropping area of about 250 m^2 (Fig.10). Thus, the CCR is 2:1. Both are surrounded by a 20 cm high bund, equipped with spillways to let runoff flow into the "manka" plots.

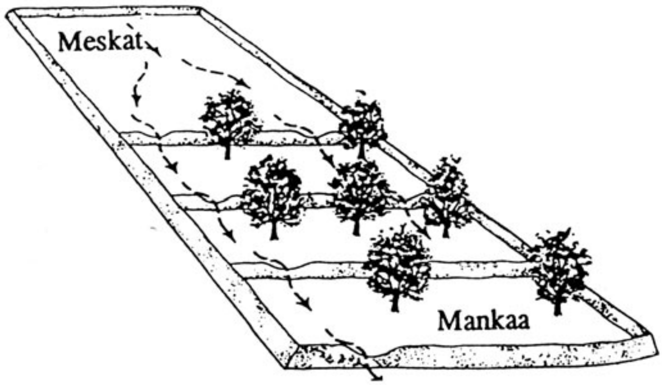


Figure 10. The Tunisian "Meskat" microcatchment system (Adapted from El Amami 1983)

This system can provide the fruit tree plantation with about 2,000 m^3 extra of water during the rainy season from a catchment of about 500 m^2.

Whereas the "Meskats" are mainly found in the Sousse region, the "Jessour" are widespread in the South (Matmata region, in particular).

The "Jessour" system is a terraced wadi system with earth dikes ("tabia") which are often reinforced by dry stone walls ("sirra"). The sediments accumulating behind the dikes are used for cropping (Fig 11). Most "Jessour" have a lateral or central spillway.

The "Mgouds" in Central Tunisia are channel systems used to divert flood water from the wadi to the fields (Tobbi 1993).

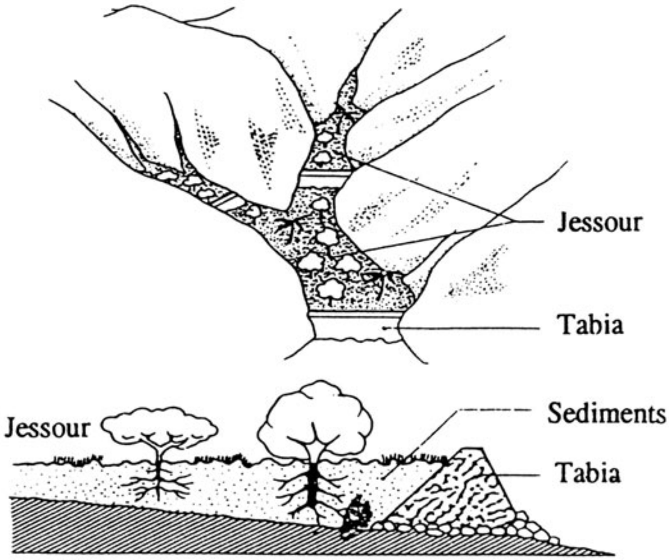


Figure 11. A row of "Jessour" in the South of Tunisia (Adapted from El Amami 1983)

In Lybia, as mentioned before, archeological and historical studies have revealed the development and expansion of a highly successful dry (runoff based) farming agriculture during Roman times. On the slopes of the western and eastern mountain ranges some of these techniques continue to be practiced (Al Ghariani 1993).

In Egypt, the North-West coast and the Northern Sinai areas have a long tradition in water harvesting. Remnants from Roman times are frequently found (El Shafei 1984). Some wadi terracing structures have been in use for over centuries (Fig. 12).

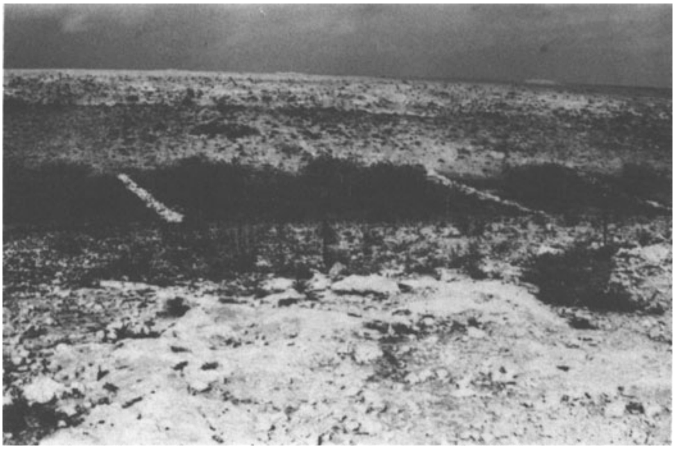


Figure 12. Wadi terraces from Roman times still in use in Marsa Matruh area (NW coast, Egypt)
Photo: Prinz

4.3.2. *Sub Saharan Africa*

Traditional techniques of water harvesting have been reported from many regions of Sub Saharan Africa (Reij *et al.* 1988, Critchley *et al.* 1992a, Critchley *et al.* 1992b, van Dijk and Reij 1993). A few of those systems shall be described here in more detail.

The "Caag" and "Gawans" systems in Somalia: The central rangelands of Somalia are home to a small scale water harvesting system, which has been an important local component of the production system for generations.

The "Caag" system is a technique used to impound runoff from small water courses, gullies or even roadside drains (Fig. 13). Sometimes ditches are dug to direct water into the fields. Runoff is impounded by the use of earth bunds. The entire plot may be a hectare or more in size. The alignment of the bunds is achieved by eye and by experience. In this system, runoff is impounded to a maximum depth of 30 cm. If water stands for more than five days or so, the bunds may be deliberately breached to prevent waterlogging (Reij *et al.* 1988).

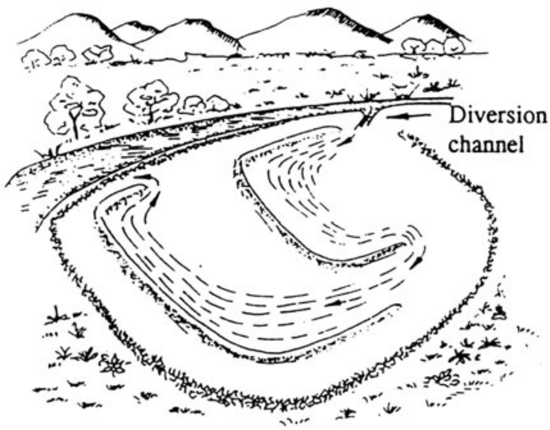


Figure 13. The "Caag" system in Hiraan region, Central Somalia (150-300 mm annual rainfall) (Critchley *et al.* 1992b)

The "Gawan" system is used where the land is almost flat and there is less runoff. Small bunds are made which divide plots into grids of basins. Individual basins are in the order of 500 m^2 or above in size. In both of these systems, sorghum is the usual crop grown, a though cowpeas are also common. If the rains permit, two crops are taken each year (Reij *et al.* 1988).

In Sudan, various types of "Haffirs" have been in use since ancient times. Their water is used for domestic and animal consumption as well as for pasture improvement and paddy cultivation (UNEP 1983).

The Haussa in Niger's Ader Doutchi Maggia have altered a considerable area with rock bunds, stalks and earth to divert water to their fields. The Mossi in Burkina Fasso also constructed rock bunds and stone terraces in the past. Somerhalter (1987) made mention of the existence of various traditional water harvesting techniques (although on a small scale) in the Ouaddai area in Chad.

The "Zay" system in Burkina Faso is a form of pitting which consists of digging holes that have a depth of 5 - 15 cm and a diameter of 10 - 30 cm. The usual spacing is between 50 - 100 cm (Wright 1985). This results in a CCR of about 1 - 3:1. Manure and grasses are mixed with some of the soil and put into the zay (Fig. 14). The rest of the soil is used to form a small dike downslope of the pit. "Zay" are applied in combination with bunds to conserve runoff, which is slowed down by the bunds.

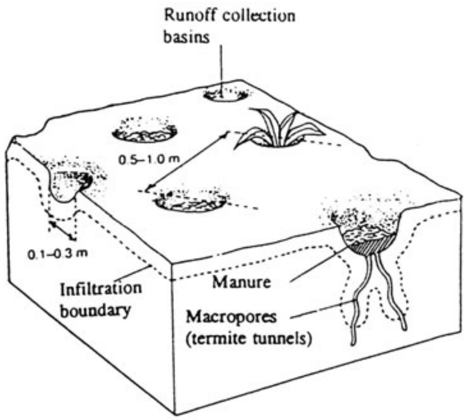


Figure 14. The "zay" microcatchment water harvesting system in Burkina Faso (Reijntjes *et al.* 1992)

Many other traditional water harvesting systems existed or still exist, but the basic problem is that knowledge and information in this zone is extremely limited and fragmentary (Reij *et al.* 1988).

4.4. AMERICA: SOUTHWEST USA AND NORTH MEXICO

Traditional water harvesting was practiced in the Sonoran desert by the Papago Indians and other groups. The Papago fields were located on alluvial flats, fan aprons and fan skirts of ephemeral washes, where large catchments then became concentrated. Brush weirs were used to spread the floodwaters (Nabhan 1984).

Elsewhere, fields were irrigated by gravity-fed channels (arroyos) leading water from earth and stick diversion weirs (Nabhan and Sheridan 1977, Doolittle 1984). For the Eastern Sonora Region of North Mexico, an evolution in techniques took place. Brush water spreaders were gradually replaced by rock bunds as the fields' clearing was increased and the supply of brush was depleted.

A highly sophisticated distribution system was demonstrated by the flood water diversion system of Chaco Canyon, New Mexico (Fig. 15).

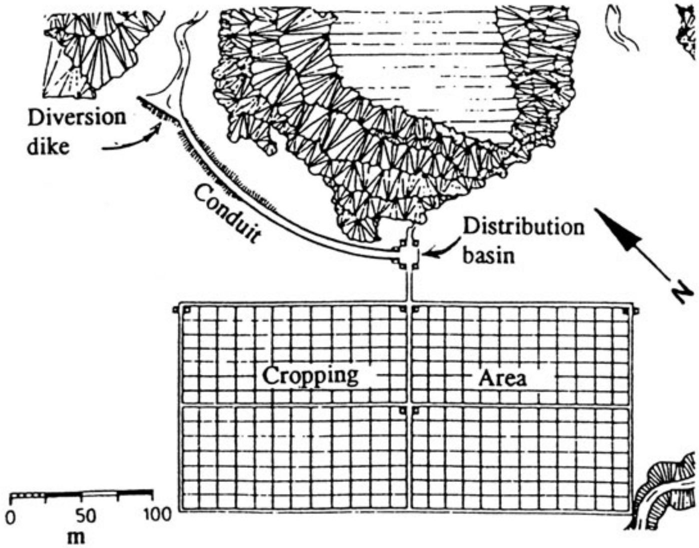


Figure 15. Runoff farming system in Chaco Canyon, New Mexico (175 mm annual precipitation, CCR = 470:1,9 ha horticultural area) (Vivian 1974)

4.5. CONCLUSIONS FROM THE PAST ROLE OF WATER HARVESTING

It is evident from archeological findings and historical descriptions that water harvesting played a dominant role in many arid and semi-arid regions to sustain agricultural production.

Why did its role diminish, why did so many systems fail on the long run?

Why do we see poor land use, and even a desertified landscape, where formerly a flourishing agriculture existed?

There are no simple answers to these questions and we have to admit that the causes are in most instances not fully known or understood. The various causes mentioned are:

- the decline of central powers (e.g. of the Byzantine empire in the Middle East) due to political shifts
- warfare including civil war
- economic changes, e.g. in competitiveness on local or export markets
- social changes, including availability of cheap labour, aspirations or attitudes of the people involved in water harvesting
- climatic change (increasing aridity, change in precipitation regime)
- increasing salinity
- decreasing soil fertility (nutrient status)
- soil erosion (wind and water erosion).

In the case of the successful floodwater farming system in the Libyan pre-desert mentioned above, the explanations for failing focus upon size and competitiveness of the markets in the coastal cities for the agricultural produce which apparently changed after the arrival of the Islamic armies in 642 AD and the conversion to Islam. But there is also some evidence that a slow salinization and soil erosion negatively influenced the agricultural production (Gilbertson 1986).

5. The Development of Water Harvesting Since 1950

5.1. GENERAL

During this century, only very few water harvesting activities in research or implementation were undertaken before 1950. Australian farmers had already started to harvest water for domestic and animal use after World War I. During World War II, some water harvesting activities were carried out on islands with high rainfall (e.g. on the Caribbean island of Antigue). After 1950 water harvesting received renewed interest on the research level as well as in the implementation sector, partly due to the successful reconstruction of ancient water harvesting farms in the Negev by Evenari and colleagues (Evenari *et al.* 1971). Most of the research activities have been carried out in Israel, Australia, the USA and India, but efforts in other countries should not be neglected.

Some institutional or research activities related to water harvesting from recent decades shall be summarized here.

5.2. ASIA

5.2.1. *Israel*

The Israeli experience was reviewed by Ben Asher (1988) within the World Bank Sub-Saharan Water Harvesting Study. Their research work focused on:

- testing of specific water harvesting techniques, especially microcatchments (Fig. 16)
- studying soil surface characteristics, especially crust formation
- studying and modelling runoff behaviour
- analyzing the economics of water harvesting techniques.

Research projects are still going on in Israel. At Avdat farm, two different aspects of the water balance of medium-sized catchment water harvesting are being studied.

The first aspect deals with the water content regime within the planted area, while the other one has to do with the availability of runoff to the planted area. On Mashash farm, a long term project with the aim of developing a model agroforestry system having medium-sized catchment water harvesting was carried out (Zohar *et al.* 1987, Löwenstein 1993). Developing the design criteria of limans (see Figure 5) is also receiving attention and the first steps towards testing at Wadi Mashash Experimental Farm are being taken (Fig. 17).

Figure 16. Microcatchment research at Sede Boker Research Station, Negev, Israel
Photo: Prinz

Figure 17. Sheep grazing a "liman" at Wadi Mashash Experimental Farm, Israel
Photo: Lövenstein

5.2.2. *Jordan*

In Jordan, earth dams have been constructed since 1964 in order for runoff to infiltrate for pasture improvement. At the final stage the total area flooded shall be about 2,500 ha (Al-Labadi 1993). In 1972, a project known as "Jordan Highland Development Project" was initiated. Rock dams, contour stone bunds, trapezoidal bunds and earth contour bunds are used to increase soil moisture around the trees planted on steep lands (Shatanawi 1993). The total area utilized since its inception is estimated to be 6,000 hectares.

Between 1985 and 1988, Jordan's Ministry of Agriculture, in collaboration with ACSAD, used contour terraces and ridges for pasture and range improvement in the Balama district. Better growth of olive, almond and pistachio were recorded (Shatanawi 1993) on the experimental site. In 1987 the Faculty of Agriculture of the University of Jordan initiated the construction of earth dams to impound and store flood waves for irrigation purposes. The catchment area is about 70 km^2 and the annual precipitation is 150 mm. Currently there is a collaborative research project aimed at developing an integrated optimization prediction model for water harvesting, storage and utilization in dry areas in Jordan.

5.2.3. *Other Middle East Countries*

In the Dei-Atiye community of Syria, rainwater harvesting was established in 1987 on an area of 130 ha. The project site was sub-divided into four parts for tree crops, range plants, cereals and runoff research (Ibrahim 1993). The International Center for Agricultural Research in the Dry Areas (ICARDA) in Syria, is currently working on the identification of water-harvesting areas and techniques suitable for various West Asian and North African (WANA) environments.

In the North-West Arabia, a local system known as "Mahafurs" is still in use. This system is simply a shallow excavation of 20 - 100 m in diameter surrounded on three sides by earthen bunds 1 - 4 m high. The open side is pointed in the direction of water flow inside the wadi bed and used to collect water for animal consumption and moisture for plant production (Barrow 1987).

5.2.4. *India*

At the Centre for Arid Zone Studies in Todhpur and at the International Center for Research in the Semi-Arid Tropics (ICRISAT) in Hyderabad, various research projects on water harvesting related programmes have been going on since 1975. One of the findings at these research stations was that alfisols have greater runoff potential than vertisols and therefore the scope of profitable yield responses is greater on alfisols (Ryan *et al.* 1980).

In the eighties, ICRISAT also developed a system, of "broad-beds" and "grassed drains" which collect runoff in storage tanks (Figure 18) during the rainy season to be used for supplementary irrigation during the dry season. To apply the water to the plants, bullock-drawn water casts equipped with sprinklers are used. Research results show that crop yields increased between two and fivefold (Barrow 1987).

ICRISAT also carried out another research work which aimed at adapting a traditional tank irrigation technology to modern socio-economic conditions. The concept of this work was to improve tank management with water control and to find an alternative system of runoff and erosion controlling land management for groundwater recharge and sustained well irrigation (Von Oppen 1985). The concepts above have been found to have great potential and research is still going on.

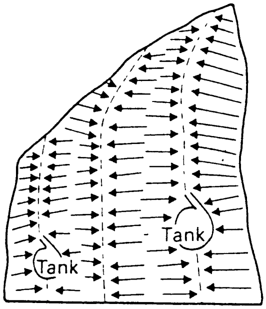


Figure 18. The broad-bed and furrow runoff collection system of ICRISAT, Hyderabad, India (Barrow 1987)

5.2.5. *Other Countries*

In tropical Asia, especially southern India and Sri Lanka, earth bunds and excavated hollows used for runoff retention during the rainy seasons. Tank storage permits farmers to grow a second dry season irrigated crop in addition to rainfed agriculture. Tanks are sited randomly so that any overland flow from one is caught by others downslope. In case of siltation, labourers are hired to remove the silts and spread them on the cropping land during the dry season (Barrow 1987).

5.3. AFRICA

5.3.1. *North Africa*

In different parts of Libya, experimental sites of contour-ridge terracing covering more than 53,000 ha have recently been established (Al-Ghariani 1993).

In 1990, the government of Tunisia started the implementation of the National Strategy of Surface Runoff Mobilization which aims, among other things, at building 21 dams, 203 small earth dams, 1,000 ponds, 2,000 works to recharge water tables and 2,000 works for irrigation through water spreading by the year 2,000 (Achouri 1993). Up to 1984, "Meskats" covered 300,000 ha where 100,000 olive trees were planted; "Jessours" covered 400,000 ha (Tobbi 1993). Modern spate irrigation techniques have been applied in Central Tunisia since 1980, covering an area of 4,250 ha and harvesting about 20 Mm^3 of water annually.

In Wadi El-Arish region of Egypt, stone dykes were used to direct the runoff water flow for irrigation purposes. Also cisterns, which store water meant for animal and human consumption as well as for supplemental irrigation, are common in Egypt. The number of cisterns has increased from less than 3,000 in 1960 to about 15,000 in 1993 with a capacity of about 4 million m^3 (Shata and Attia 1993). In the North-West region of Egypt there is a GTZ/FAO sponsored project on land use planning including water harvesting activities.

In Yemen, small dams storing runoff for later use in irrigation or rural supply have been constructed since the beginning of the eighties; the total storage capacity is between 50,000 to 90,000 m^3 (Bamatraf 1993).

"Matfia" is an old technique of storing water for human and animal consumption in Morocco, which still continues (Tayaa 1993). Expensive modern technology, including the use of reinforced concrete has now been introduced in constructing the cisterns, although the local people are less interested in these large and expensive systems. Since 1984, Morocco has started constructing small dams ("Barrages Collinaires") to harvest flood water. The upstream catchment area under these dams ranges from 500 to 10,000 hectares. As of 1988, thirty five of these dams had been constructed. They provide irrigation water for about 160,000 animals and 3,000 ha of cultivated plots.

5.3.2. *Sub-Saharan Africa*

An agroforestry project (PAF) aimed at improving tree planting using microcatchments was initiated by OXFAM in 1979 at the Yatenga Province of Burkina Faso. In 1982, this was modified to contour stone bunds (aligned along the contour) and used for crop production. Later, it was combined with the traditional "zai" systems which has improved its acceptability by the local farmers. It was reported that by the end of 1989, some 8,000 hectares in over 400 villages had been modified with stone bunds (Critchley *et al.* 1992a).

Various research projects are being carried out on the Central Plateau of Burkina Faso by many research institutes. Emphasis in the region is mainly put on improving stone bund construction, studying the effects of stone bunds on runoff, erosion and yields, rehabilitation of degraded catchment areas and combination of stone bunds with tied ridges (Buritz and Dudeck 1986).

In the Hiraan Region of Somalia the local water harvesting techniques known as "Caag" and "Gawau" still continue (Abdi 1986).

In Ethiopia, the Sudan and Botswana, small check-dams made of earth are used to catch moderate overland flow passing down slight slopes. They are called "haffirs" and support crops planted upslope (Barrow 1987).

In 1985, the Institut für Wasserbau und Kulturtechnik (Institute of Hydraulic Structures and Rural Engineering), University of Karlsruhe, Germany, started a project in Mali with the aim of testing the feasibility of runoff irrigation in the Sahel regions. The total contributing area was 127 ha and the collecting area was 3.3 ha so that the CCR was 40:1. These systems have now being operated for seven years and the harvests for sorghum are three times those for comparable sites using rainfed agriculture (Klemm 1990) (Fig. 19).

In 1989-91 an EC financed study was carried out by the same Institute which aimed at the development of a methodology of identifying areas suitable for runoff irrigation. Maximum use was made of data obtained from satellite systems (Landsat-TM and SPOT) on the basis of site inspections in W-Mali and N Burkina Faso. A methodology was developed which integrates meteorological, pedological, topographic and socio-economic data sets in an user-friendly GIS, distinguishing between the suitability of a site for microcatchments or macrocatschments (Tauer and Humborg 1992; Prinz *et al.* 1994).

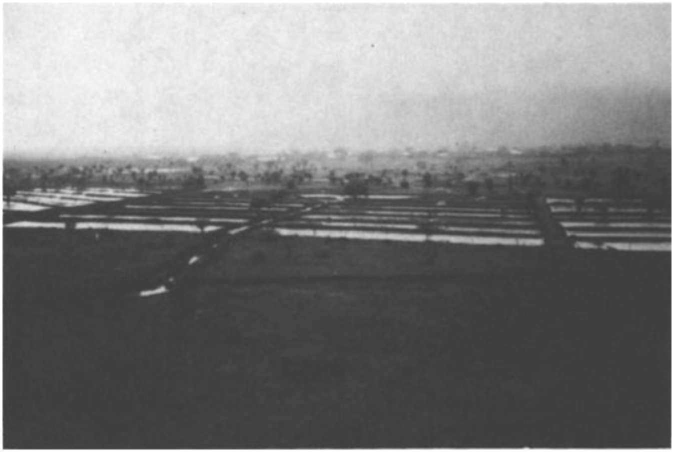


Figure 19. A macrocatchment water harvesting system in Mali, Kayes Province. Photo: Klemm

In 1988, special ploughs developed by Italian scientists were used in Niger for the implementation of (Vallerani type) microcatchments on a large scale. Results from these plots showed excellent rates of tree establishment (Antinori and Vallerani 1993).

A set of test plots on improved trapezoidal bunds in Baringo, Kenya has recently been constructed. This improved version consists of earth bunds which surround the plot and diverge as collection arms upslope to increase the catchment area (MoALD 1984).

In 1984, a self-help project sponsored by Oxfam and known as Turkana Water Harvesting Project, was started in the Turkana district of Kenya. It was aimed at developing systems of water harvesting for crop production, while also introducing animal ploughing. This project has evolved into a long-term development programme involving women and is concerned mainly with pastoral production which is the main occupation of the villagers (Critchley *et al.* 1992a). In 1990, it became known as Lokitaung Pastoral Development Project and a local management board whose members are drawn from the local traditional institutions have since been managing the project.

5.4. NORTH AND SOUTH AMERICA

In the United States of America, research emphasis is on runoff inducement from catchments and the reduction of seepage losses. Combined and supplementary systems have been tested (Fig. 20).

The traditional check-dam known as "Bolsa" is still used in the cultivation of crops in Mexico. "Bolsas" are earthen-walled basins which catch water diverted from seasonal creeks ("arroyos") (Barrow 1987). After the arroyos have wetted the bolsas, plants are cultivated on the bolsas and mulch of dry sand is spread on it to avoid evaporation.

Figure 20. Inter-row water harvesting with treated catchment in North-Central Mexico.
Photo: Frasier

In NE-Brazil, a modified form of the "zay" systems was introduced in 1986.

5.5. AUSTRALIA

In Western Australia, topography modification in the form of catchment treatment has been practiced for a long time. These are known as "roaded" catchments. They consist of parallel ridges ("roads") of steep, bare and compacted earth, surveyed at a gradient that allows runoff to occur without causing erosion of the intervening channels (Frasier 1993, quoting Laing 1981). In 1980, it was estimated that there were more than 3,500 roaded catchment systems in Western Australia, and many of them have a top dressing or a layer of compacted clay to increase the runoff efficiency (Frasier 1993).

6. The Future Role of Water Harvesting

6.1. GENERAL CONSIDERATIONS

When analyzing agricultural production and natural resources utilization in (semi-) arid areas, some conclusions, especially regarding water harvesting, can be drawn:

(1) Government policy (within the agricultural sector) is mostly directed towards cash crop production. Cash crops, in order to be profitable, need a reliable water supply which can best be guaranteed by conventional irrigation (not water harvesting). Therefore support concerning extension services, loans, marketing support etc. are

given primarily to (exportable) cash crops.

(2) Substantial amounts of rainfall in (semi-) arid areas are lost (e.g. by evaporation from soil surfaces), which could be utilized for agricultural production.

(3) In a number of countries where water harvesting played a major role in the past (e.g. North Yemen), its importance has declined (see chaper 3.5)

(4) Despite considerable efforts undertaken in recent years (especially by international/Western donors) to promote and disseminate water harvesting techniques, the overall success is much less than expected (Siegert 1993).

Figure 21 shows the relationship between some production issues and water management levels in agriculture.

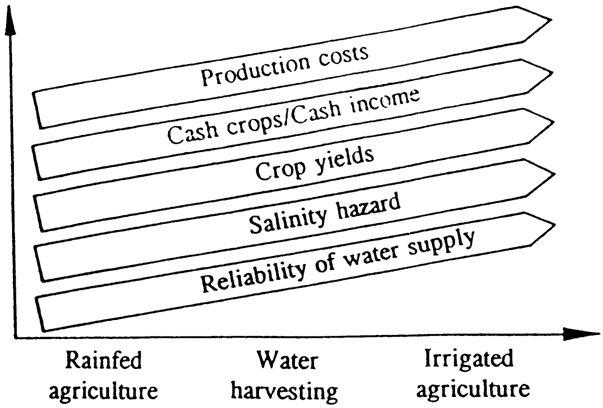


Figure 21. Water harvesting and some production issues

6.2. CHOICE OF WATER HARVESTING TECHNIQUES

Numerous water harvesting projects have failed because the technology used proved to be unsuitable for the specific conditions of the site (Siegert 1993). Each of the water harvesting methods has its advantages and limitations which can be summarized as follows:

(1) *Water harvesting for animal consumption.* In developing countries, the building or reactivation of cisterns and other rainwater tanks for animal consumption can save water which otherwise has to be lifted or pumped from groundwater or carried over long distances. In "developed" countries (the USA, Australia) the search for cheap, durable soil treatment substances (e.g. sodium methyl silanolate) or ground covers continues (Arar 1993). It is expected that the costs for such treatments will be low enough in the future to treat larger areas and to obtain toxic-free runoff water.

(2) *Inter-row water harvesting*. In regions with not less than 200 mm (winter-rains) to 300 mm (summer-rains) annual precipitation, inter-row water harvesting will have a high potential in low-income as well as in high-income countries. Contour ridges or bunds can be formed using hand tools, animal-drawn equipment or tractors. Therefore this technique is widely applicable for use in orchard establishment, general tree planting or for the cultivation of annual crops.
Under high-input conditions (e.g. in the USA), the space between the rows is often compacted and chemically treated to increase runoff.

(3) *Microcatchment systems*. Most of the research on microcatchment development has been done in Israel. A cost/benefit analysis carried out on negarin-type microcatchments in Israel in an area with less than 150 mm annual rainfall showed however, that the specific water supply was not sufficient for economic production (Oron *et al*. 1983). In this case, larger forms of Negarin microcatchment in higher rainfall areas seem to be more appropriate. The various other microcatchment types have their specific advantages. The quickest way to produce microcatchments is with the 'Dolphin' plough, being able to 'dig' 5000 microbasins per day, equivalent to a treated surface of 10 ha, with a water holding capacity of 600l/basin (Antinori and Vallerani 1993).

(4) *Medium-sized catchment water harvesting*. Medium-sized and microcatchment systems are regarded to have a high potential in the future. The desertification processes in many (semi-) arid regions have created large denuded surfaces, which are extremely difficult to revegetate. These surfaces often yield high quantities of runoff water, which could be utilized with MSC-WH systems, especially with 'hillside conduit systems'. Many problems were experienced with trapezoidal bunds; "liman" terraces worked well in the past, if hydrologically calculated correctly, and will be a positive asset for future development (re-vegetation) in pre-desert regions.

(5) *Large catchment water harvesting systems*. If the development of those area systems can be combined with flood protection works for ephemeral streams, then a limited increase in can be forecasted.

6.3. NEW DEVELOPMENTS

During recent years some technological developments took place in regard to water harvesting which might have some impact on the future role of WH in general:

(1) *Supplemental water system*. Runoff water is collected and stored offside for later application to the cropped area using some irrigation method. The water stored allows a prolongation of the cropping season or a second crop.

(2) *Dual purpose systems*. In a dual purpose system the runoff water flows first through the crop area, then the excess water is stored in some facility for later irrigation use. In Arizona, USA, runoff irrigation was combined e. g. with trickle irrigation, using sealed soil surfaces to increase runoff rates.

(3) *Combined systems*. If the irrigation water from aquifers or from rivers/reservoirs is not sufficient for year-round irrigation, a combination with runoff-irrigation (during the rainy season) is feasible. The combination of runoff- and furrow irrigation is reported from North Central Mexico (Frasier 1993).

(4) *Modelling*. If more information on hydrological, soil and crop parameters is available, models can be developed and applied to water harvesting for certain environments.

6.4. CONCLUSIONS

Water harvesting has proved to be a valuable tool especially in dry marginal areas:

(1) to increase crop yields and reduce cropping risk
(2) to improve pasture growth
(3) to boost reafforestation
(4) to allow a higher degree of food production
(5) to fight soil erosion
(6) to make best use of available water resources
(7) to suppress soil salinity and, in a few cases,
(8) to recharge groundwater.

However, there also some problems associated with water harvesting:

(1) a higher labour input than in rainfed farming
(2) higher difficulties due to unfamiliarity with the technology and/or an unreliable water supply
(3) a negative impact on soil and vegetation resources in the catchment area due to clearing or treatment
(4) a loss of individual control in large WH schemes and
(5) the possibility of increasing number of livestock which could cause more desertification.

In comparison to former times, farmers today have to produce in a very different social and economic environment. Nevertheless, the positive elements of WH remain valid and they can be used in future for the well-being of people in the dry areas of the world. Precondition is an adequate coverage of all technical, social, economic and environmental aspects of WH in planning and implementation (Prinz 1994) - as it was apparently the case in ancient times, when sustainability was reached for many centuries.

7. Conclusions and Recommendations

- The present social and economic frame conditions for farmers differ strongly from those in ancient times, when water harvesting was more common, whereas the natural conditions remained similar.

- The advantages of water harvesting remain valid and farmers in dry areas have to utilize them if they want to be able to master the future.
- Farmers need scientific and institutional support to start new projects.
- The failure of water harvesting projects in the past was sometimes due to technical failures but more often the attention given to social and economic aspects was insufficient.
- There should be a global cooperation between scientists and practitioners involved in water harvesting. By learning from failures and successes, a high degree of sustainability might be reached, similar to the one which apparently existed in the past and remained for a thousand or more years.

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PART III

ON-FARM WATER MANAGEMENT

MEASUREMENT AND ESTIMATION OF EVAPOTRANSPIRATION

B. ITIER
Département de Bioclimatologie - INRA
F 78850 Thiverval-Grignon
France

1. Introduction

Evapotranspiration is a major term of the soil water balance. Knowing the amount of water directly evaporated from the soil or through transpiration of plants is a point of interest not only for agronomists but for meteorologists, hydrologists and irrigation project managers. A large number of papers have been published in the last thirty years concerning both mechanisms, measurements and estimation techniques (for review see e.g. Brutsaert 1982, Seguin *et al.* 1982, Hatfield and Fuchs 1990, Jensen *et al.* 1990, Allen 1994). The aim of this paper is not only to review what is available today, for different time and space scales but also to see how it could be used by farmers or more generally by project managers. Recommendations are made to improve both knowledge and transferability to users.

2. Definitions

Before starting this review, it is necessary to make a point on some definitions in order to make clear both title and text. What is needed for a soil water balance is actual evapotranspiration (ET_a). It can be measured (directly or indirectly through the flux of latent heat) or estimated by means of appropriate crop coefficients (k_c) applied to a reference evapotranspiration (ET_o). Following ICID recommendations (Perrier 1977), the use of potential evapotranspiration will be avoided. The maximum value of ET_a is called maximum evapotranspiration (ET_m) and corresponds to the actual evapotranspiration of a crop not submitted to water stress.

Designing irrigation systems requires monthly or seasonal ET_o estimates on a large scale by means of simplified formulae using air temperature when other meteorological data are not available. Scheduling irrigation requires information at the field level of daily (or at least weekly) actual evapotranspiration ET_a. Then, the scope of this review includes, both direct measurements of ET_a in the field and estimates of ET_o which can lead to ET_a estimates through the use of crop coefficients. To begin with, it will mainly be based on the field experience of the author. Then, it will

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 171–191.

largely use recent works on ET_0 as the reports by the USCID. WG (Hargreaves *et al.* 1993), EEC (Choisnel *et al.* 1992) and FAO expert consultation (Smith *et al.* 1991, Allen *et al.* 1994a,b) to improve the use of FAO-24 methodologies (Doorenbos and Pruitt 1977).

The aim of a sustainable agriculture makes it necessary to improve ET_a measurements and estimates because over irrigation not only wastes water but contributes to environmental problems through nutrient leaching, salinization and water logging.

3. Measurements of Actual Evapotranspiration

3.1. DIRECT MEASUREMENTS

Direct measurements of actual evapotranspiration can be performed in several ways, adopting different time and space scales. Measurements (Pruitt and Angus 1960) of soil humidity profiles by means of neutron probes allow a weekly estimate of mean water consumption, provided that the zero flux level is below the measured profile (Rouse and Wilson 1971). This implies a necessary association of soil water content and suction measurements (Daudet and Vachaud 1977).

Weighed lysimeters allow daily measurements and, in some specific cases, could be used in an hourly basis (Ritchie and Burnett 1968; Perrier *et al.* 1974). Both methods raise problems of representativity : spatial variability imposes to make humidity profiles observations at several places in the field (Sharma and Luxmoore 1979). Frequent walking or the absence of drainage in the majority of weighed lysimeter enhance differences in crop growth between the lysimeter and the field. This has been overcome in some particular cases of weighed lysimeters coupled with a drainage system (Phene *et al.* 1989). Largely used by agronomists in the sixties and the seventies to obtain crop coefficients values, weighing lysimetry was progressively replaced by energy balance methods (see further).

At the field scale, two aerial direct methods can be used : the eddy correlation technique using the cross-correlations of vertical wind and specific humidity and the aerodynamic method with profiles of wind, temperature and specific humidity (Grant 1975). Both are too difficult to operate for farmers and even micrometeorologists prefer to undertake measurements by aerodynamic combined method or eddy flux of sensible heat flux coupled with net radiation measurements rather than using these two directs methods (see further).

Measurements of air humidity under movable chambers (Reicosky 1985) have been suggested to estimate crop water consumption but are restricted to physiological studies. The resort to sap flow measurements either by sap flux density technique (Huber and Schmidt 1937, Cohen *et al.* 1981 ; Granier 1987), or by the mass flow technique (Sakuratani 1981, Valancogne and Nasr 1989) is restricted to estimation of orchards transpiration by sampling of representative trees. The first technique is mainly applied to large trunk trees. Its main problem consists in knowing the cross sectional area of the water conducting tissue. The second one is more adapted to young trees or small trunk trees and gives good results because there are no hypothesis concerning the size of the active part of the trunk. By using this technique over vineyard, Riou *et al.* (1994) show that the ratio of transpiration to ET_o corresponds to radiative interception by the vines versus total net radiation. However recent experiments show that necrosis can result from measurements performed all over the dry season (Cohen *et al.* 1993). At present no easy way to perform direct measurements of ET_a on a long time basis is available.

3.2. INDIRECT MEASUREMENTS OF ET_a

Evapotranspiration of water either directly lost at the soil level or transpired through plants stomatas is associated with energy consumption through latent heat of vaporisation. This energy consumption corresponds to the latent heat flux and over a surface covered with an active growing crop, it represents the major part of the use of available energy due to the radiation balance. The energy balance is generally written as :

$$R_n - G = H + LE \qquad [1]$$

where R_n is net radiation, G the soil heat flux, H sensible heat flux and $LE = L.\ ET_a$ the latent heat flux. The energy balance equation leads to ET_a indirect measurements by means of

$$ET_a = \frac{R_n - G - H}{L} \qquad [2]$$

Then, if R_n measurements are available, measuring sensible heat flux gives an associated estimation of ET_a (G is generally small compared to R_n and can be neglected, at least on a daily time basis).

Two techniques are used by micrometeorologists : the Bowen (1926) ratio and the aerodynamic combined method. Their main advantages, compared with lysimetry or soil water measurements are :

- they are well adapted to the field scale, because turbulent exchanges inside the developing boundary layer provide a natural sampling ;
- they are neither destructive nor perturbing crop and surface exchanges ;
- they provide surface fluxes at a time scale less than one hour. This presents both pros (for physiologists) and cons (for farmers).

These methods are used in research and for experimental studies, not for scheduling irrigation on farmers fields.

3.2.1. *The Bowen Ratio Technique*

The Bowen ratio technique consists in estimating the ratio of sensible heat versus latent heat by means of the ratio of air temperature difference (ΔT) versus water vapour pressure difference (Δe) between two levels above the canopy (see e.g. Brutsaert 1982) :

$$L\,ET_a = \frac{R_n - G}{(1 + \beta)} \qquad [3]$$

where $\beta = \gamma\ \Delta T/\Delta e$ and γ is the psychrometric constant.

The usual way is to use differential psychrometry. This technique presents some advantages such as not requiring any exchange coefficient determination. It led to automatic devices such as EPER[1] (Mc Illroy 1971), BEARN[2] (Perrier *et al.* 1976) and AZET[3] (Gay 1988). Its accuracy was analysed by Fuchs and Tanner (1970), Sinclair *et al.* (1975), Revfeim and Jordan (1976). The main difficulty comes from the measurement of wet bulb temperature difference : for continuous recording, one has to keep the bulbs wet and clean to obtain good measurements ! Recently improvements have been obtained (Cellier and Olioso, 1993) by pumping air from two levels and measuring alternatively humidity by means of the same capacitive hygrometer. An instrument using a single cooled mirror dew point hygrometer (C.S.I., Logan, Utah) is presently under test at different USDA Centres.

3.2.2. *The Aerodynamic Combined Method*

It consists in determining sensible heat flux by means of scaling factors u_* and θ_* deduced from wind (u) and temperature (θ) profiles (see e.g. Grant 1975). In the sixties it has been criticised (Tanner 1963 ; Perrier *et al.* 1974) by users who didn't take stability corrections into account. When Businger-Dyer stability corrections are used (Paulson 1970), it provides good agreement with other methods (Grant 1975). Its main advantage consists in avoiding humidity measurements whose accuracy is not as good as that of temperature. Nevertheless it is necessary to use at least six levels of measurements of wind and temperature to undertake self consistent regressions on u (z) and T (z) leading to u_* and θ_*. Itier (1981) proposed a simplified technique for direct determination of sensible heat flux by means of only two levels of measurements. This led to the SAMER[4] device (Itier et al. 1985) which provided a more reliable way for continuous recording than the BEARN, which has been designed by workers of the same team (Perrier *et al.* 1976). Used as a tool for ET_a measurements in several agronomic or meteorological campaigns in the eighties (André *et al.* 1988), it has the advantage of avoiding systematic inversions of

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(1) EPER: Energy Partition Evaporation Recorder
(2) BEARN: Bilan d'Energie Automatique Numérique
(3) AZET: Arizona Evapotranspiration system
(4) SAMER: Système Automatique de Mesure de l'Evapotranspiration Réelle

measurements levels necessary for improving accuracy with Bowen ratio technique. It has however two drawbacks when compared with Bowen ratio :

a. levels of measurements above the canopy have to be fixed carefully because exchange coefficients depend on them. This implies to take care of this when measuring fluxes above actively growing crops (Itier *et al.* 1985).

b. above tall canopies as corn, in order to keep levels of measurement at reasonable height, it is necessary to take into account that exchange coefficients do not obey Monin-Obukhov theory (Obukhov 1946) inside the roughness layer (Mukammal *et al.* 1966, Garatt, 1978 ; Thom *et al.* 1975). Simple functions to make for this have been recently proposed by Cellier and Brunet (1992).

Included in the aerodynamic combined method, are also bulk formulae enabling to obtain sensible heat flux from air-surface temperature differences (see e.g. Brutsaert 1982). The main problem of these formulae is that exchange coefficients depend upon the roughness of the surface and wind velocity. To overcome this problem, Jackson *et al.* (1977) suggest to draw a linear relationship between air surface temperature difference and sensible heat flux, in order to promote thermography as a way to determine regional evapotranspiration by remote sensing. However, Seguin and Itier (1983) and Riou *et al.* (1988) demonstrated that the coefficient of this linear relation is site dependant.

To conclude with aerodynamic combined method, let us mention the use of eddy correlation technique to obtain sensible heat flux by means of sonic anemoters coupled with fine thermocouples. This is a direct measurement which is highly improving with time. Compared with instruments expensive and difficult to manage which were available by the end of the sixties (Garrat 1975), it is now possible to use instruments enabling to perform measurements down to 1 m above the canopy (Tanner *et al.* 1985; Brunet *et al.* 1994). However, the instruments are still fragile, restricting their use to micrometeorological campaigns.

To conclude the review on measurements of ET_a, it can be said that, at present, several types of instruments are available for micrometeorologists or agronomists to undertake experiments in the field for continuous periods of one to two months. These instruments can provide accurate measurements for establishing values of crop coefficients that are needed by users to estimate crop water consumption. However, right now, these instruments are not resistant enough and easy to be used, thus it is not appropriate to promote their use at farm level.

4. Estimation of Actual Evapotranspiration

The principle of ET_a estimation consists in the association of climatological data, which provide a way of determining the atmospheric demand of water (ET_o), with both agronomic knowledge and estimates of soil water availability which, combined, indicate how the soil-crop system can meet this demand. Then the questions to be answered are :

a) Which reference evapotranspiration formula will be recommended to estimate ET_o depending upon meteorological data availability which is not uniform worldwide ?

b) How can maximum evapotranspiration be assessed from ET_o ?

c) How long does ET_a correspond to ET_m during the interval between rains or irrigations and, if not, how does ET_a departs from ET_m? An additional item could be to review the available ways of controlling this correspondence or of estimating ET_a ratio versus ET_m.

4.1. THE REFERENCE EVAPOTRANSPIRATION ET_o

The concept of reference evapotranspiration is now widely accepted by both engineers and agronomists (Doorenboos and Pruitt 1977). The aim is to determine the water consumption of a reference crop making procedures and results comparable worldwide. This implies avoiding both aerodynamic differences and biological regulations. For many years two crops have been used :

- alfalfa (*Medicago sativa* L.) with 30 to 50 cm of crop height (Jensen *et al.* 1990)

- well adapted varieties of clipped grass, 8 to 15 cm high, actively growing (Doorenboos and Pruitt 1977).

The use of the second tends to spread worldwide, alfalfa being restricted to western U.S.A.

Three ways are currently used to obtain ET_o values : measurements with lysimeters, estimation with Pan evaporimeters and calculation formulae using climatic factors.

4.2. MEASUREMENT OF ET_o WITH LYSIMETERS

Lysimeters are containers placed in a field, filled with soil and cultivated as the field around. Both weighable and non weighable lysimeters can be used to determine ET_o depending on the time scale of measurements. Drainage lysimeters (Gilbert and Van Bavel 1954) give weekly estimate of ET_o while weighable lysimeters enable daily estimates with an accuracy of more than 10 % (Perrier *et al.* 1974). Furthermore, they need a special care to ensure that vegetation inside is the same as outside and to minimize local traffic. Error in determination of evaporative area (Allen *et al.* 1994a) and failures in representativity of surroundings due to oasis effects (Itier et Perrier 1976, Brutsaert 1982) and to rim influence can lead to over 30 % in error on ET_o (For detailed discussion see e.g. Allen *et al.* 1994a).

Measurements by means of lysimeters are too few to provide worldwide means of obtaining ET_o. Nevertheless, they have been and are still largely used to calibrate both evaporimeters and formulae (See e.g. Seguin 1975) . Furthermore they are an excellent research tool for studying crops responses (Wright 1991) (see hereafter 4.5), especially when they can be refilled with water automatically (Phene *et al.* 1989).

4.3. ESTIMATION OF ET_0 WITH PAN EVAPORIMETERS MEASUREMENTS

Despite major differences in the energy balance and aerodynamics of pans and crops, evaporimeters such as class A Pan and sunken Colorado pan (see e.g. Brutsaert 1982) still are in widespread use all over the world. This is due to their simplicity of use. Doorenbos and Pruitt (1977) provide coefficients to estimate ET_0 from Epan, depending on the type of pan, wind velocity, air humidity and the nature of surroundings. When caution is taken to avoid problems as trivial as cattle or birds drinking (!), pans can provide acceptable estimate of ET_0 for periods of time not shorter than 10 days. The direct use of atmometers for ET_0 estimate are not included in this category. This use will be restricted to simplified estimate of analytical formulae as Penman or Penman-Monteith formulae (Stanhill 1962) (see further).

4.4. CALCULATION OF ET_0 USING METEOROLOGICAL DATA

Since reference Evapotranspiration was defined as atmospheric demand, there has been a large number of attempts to establish formulae giving its dependence on meteorological observations. These formulae can be classified in two groups : empirical formulae and physically based formulae.

4.4.1. *Empirical Formulae*

It is out of the scope of this paper to review all empirical formulae which were established to fit lysimeters measurements with meteorological data. The reader could find in Brutsaert (1982) an history of evaporation theory from the Greek antiquity to the beginning of this century. The word "evapotranspiration" appeared, for the first time in Thorntwaite (1948) (see Monteith 1985) who developed a function of air temperature and day length to estimate it. One can find in this formula the two main categories of empirical formulae : the radiation methods and the temperature methods.

Radiation Methods. The most well-known of these methods results from an extensive review of data from many places in the western USA (Jensen and Haise 1963) . It is recommended for time intervals of 10 days (Jensen 1974):

$$E = C_1 \, (T - C_2) \, Rs \qquad [4]$$

where Rs is solar radiation, T the mean temperature and C_1, C_2 appropriate coefficients.

In another radiation method based on data collected in mediterranean countries, Turc (1961) incorporated a correction factor to account for influence of air humidity in arid zone when RH% < 50 %. Seguin (1975) and Choisnel *et al.* (1992) presented comparative studies of several empirical methods showing that, after Hargreaves' formula (see below), this method fits best lysimeter measurements performed in many European countries.

Temperature Methods. The main advantage of temperature based methods is to utilise the most readily available climatological datum, i.e. temperature. Among these methods, the Thornthwaite (1948) and Blaney and Criddle (1950) methods have been extensively used. They are both based on mean monthly temperatures :

$$ET_0 = \frac{C_1 (T)^a}{F_1} \quad \text{(Thornthwaite 1948),} \qquad [5]$$

$$ET_0 = \left(C_2 + C_3 T\right) F_2 \quad \text{(Blaney and Criddle 1950)} \qquad [6]$$

where $C_{1,2,3}$ and a are constants and $F_{1,\,2}$ are functions accounting for day length.

More recently, Hargreaves (1974) proposed an improved temperature method including radiation effects by means of the difference between T_{max} and T_{min}, the maximum and minimum air temperature:

$$ET_0 = C_4 \left(T + C_5\right) \left(T_{max} - T_{min}\right)^b R_a \qquad [7]$$

where $C_{4,5}$ and b are constants, and R_a is the extraterrestrial solar radiation. Among 33 europeans stations used for the comparisons of six temperature methods (Hargreaves 1974 ; Jensen and Haise 1963 ; Haude 1955 ; Blaney and Criddle 1950 ; Linacre 1977 and Papadakis 1966) the improved Hargreaves' formula provide the best estimates in 16 cases. Hargreaves' formula appears as an interesting way to have radiation information in places where radiation measurements are lacking. To improve it, local calibration will probably be necessary to take mean humidity into account. Recently Allen (1993) evaluated the possibility to incorporate wind function and radiation function into this formula, showing that it could lead to better agreement with the ASCE data set on ET_0 . So one question arises : when wind and radiation are available, is it necessary to use empirical method such as Hargreaves ? Wouldn't it be preferable to use physically based method as Penman or Penman-Monteith methods ?

4.4.2. *Physically Based Formulae: The Combination Equations*

There are basically two combination equations : the Penman formula originally established for water or wetted surfaces (Pennman 1948) and the formula known as Penman-Monteith equation which was derived from the first one by taking into account additional resistance to transfert due to structure of the crop and stomatal regulation (Monteith 1965 ; Rijtema 1965).

The Penman Equation. This equation combines two terms usually called "the available energy" term and "the aerodynamic" term.

$$L\,ET_0 = \frac{\Delta(R_n - G) + \rho\,CP\,\frac{VPD}{r_a}}{\Delta + \gamma} \qquad [8]$$

where R_n is net radiation , G soil heat flux, γ psychrometric constant, Δ water pressure derivative, ρ air density, Cp heat capacity of air, VPD vapour pressure deficit and r_a aerodynamic resistance.

This equation simply derives from the energy balance equation by assuming that there is saturation at the evaporative surface. It allows to combine the former theories : the energetic approach from Angström (1924) to Richardson (1920) and the aerodynamic approach from Dalton (1802) to Thornthwaite-Holzman (1939).

Originally "this was pure physics, but for application, empiricism could not be avoided" (Monteith 1985). Briefly speaking, in a first step, this empiricism leads to neglect G on a daily basis, replace r_a by a calibrated wind function (f (U) = a + b U) and to calibrate a correction factor (C) accounting for non linear effects. This leads, among other formulae, to the worldwide known "FAO 24 corrected Penman method" (Doorenbos and Pruitt 1977) :

$$ET_0 = C\,\frac{\Delta R_n + (a + bU)\,VPD}{\Delta + \gamma} \qquad [9]$$

A large number of wind functions and calibrations of the Penman equation have been developed (see e.g. Cuenca and Nicholson 1982, Weiss 1983, Jensen *et al.* 1990) providing for a variety of forms of the Penman equation.

In a second step of empiricism, several attempts were made to obtain both "energetic" and "aerodynamic" terms by simple measurements. For instance, Brochet and Gerbier (1972) developed a simplified formula in which the first term depends on the percentage of sunny hours and the second term depends on screened Piche atmometer evaporation (Stanhill 1962).

Comparisons of different Penman formulae with ET_0 measured on lysimeter were performed in many places of USA and Europe (Seguin 1975 ; Jensen *et al.* 1990 ; Allen *et al.* 1994a; Choisnel *et al.* 1992). Penman formulae give generally better correspondence to measurements than purely empirical formulae (Seguin 1975) and when FAO Penman is criticized to systematically overestimate ET_0 (Allen *et al.* 1994a), the question could be solved by an empirical adjustment of the correction factor if the alternative was not to use Penman-Monteith (P.M.) equation. The question cannot be answered before having described P.M. equation and analysed its possible use for ET_a estimates.

The Penman-Monteith Equation. As Penman formula was combining "Energy" and "aerodynamics", the so called P.M. equation (Monteith 1965, Rijtema 1965) combines "Physics" and "Physiology". The basic idea is that a reference crop like a short clipped grass growing under fully water availability cannot be considered as a wet surface. This results from an additional resistance to water vapour transfer (r_c), called bulk stomatal resistance. Then ET_o is expressed as

$$L\,ET_o = \frac{\Delta\left(R_n - G\right) + \rho\,Cp\,\dfrac{VPD}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_c}{r_a}\right)} \qquad [10]$$

In a recent work (Smith *et al.* 1991, Allen *et al.* 1994a,b), the FAO expert consultation group proposed to replace the use of FAO 24 by a standardized P.M. equation. To do so, besides conventional ways of dealing with radiation and VPD estimates, they proposed an estimate of r_a which is a wind function including grass height n as a constant (n = 0.12 m). Furthermore, they proposed to enter a constant r_c value of 70 sm^{-1} in order to formulate a normalized ET_o definition to be used worldwide. Hence, the FAO P.M. equation could be reduced to (Smith *et al.* 1991) :

$$ET_o = \frac{1}{L}\;\frac{\Delta R_n + \gamma\, b\, U\, VPD}{\Delta + \gamma\,(1 + a\,U)} \qquad [11]$$

Because the wind function results from aerodynamics, Allen *et al.* (1994a,b) claim that this equation should not require local calibration.Using the comparison of 20 equations performed on ET_o measured at 11 locations in the USA (Jensen *et al.* 1990), they concluded that P.M. equation fitting better the lysimeter observations than the other methods, it should be recommended for the future in place of Penman FAO 24. In support of this idea, they also mention the work from Choisnel *et al.* (1992) who, while adopting "an approach different from that in the ASCE study.... support using the Penman-Monteith equation for ET_o estimates". However, Choisnel *et al.* (1992) concluded to the superiority of P.M. equation on classical Penman formula provided P.M. equation was used with a site calibrated value of crop resistance. They found that crop resistance of the well irrigated grass varies from 10 to 20 sm^{-1} in the humid climate of North-Western Europe up to 100 to 140 sm^{-1} in the mediterranean climate of southern Italy. It comes from the admitted dependence of r_c on VPD whose feed back effect has recently been underlined on advection effects over irrigated crop (Itier *et al.* 1994, McAnneney *et al.* 1994).

Consequently it would probably be necessary to enter VPD effects on r_c on a standardized formula in order to actually make it "not site dependant". Furthermore, the feed back effect of VPD on r_c which reduces the influence of the second term of P.M. equation, could probably give theoretical support to the use of simplified formula as Priestley-Taylor (1972) and Makkink (1957) which simply neglect the second term of Penman classical formula (De Bruin 1987). This is also probably why empirical formula as Hargreaves (1974) in which VPD is neglected can lead to reasonable results (Choisnel *et al.* 1992; Hargreaves *et al.* 1993).

To go a step further in a possible choice between Penman and Penman Monteith formula for generalised worldwide use, it is necessary to comment upon the use of crop coefficients as they are suggested in FAO expert consultation (Smith *et al.*, 1991).

4.5. ET_m AND ET_a ESTIMATES

Actual evapotranspiration (ET_a) and maximum evapotranspiration (ET_m) can be distinguished by making the difference between global crop coefficient (k_c), a basal crop coefficient (k_{cb}), soil surface wetness coefficient (k_s) and a stress factor (k_a) (Wright 1982):

$$ET_a = k_c \, ET_o \qquad [12]$$

$$ET_a = k_a \, ET_m \qquad [13]$$

$$ET_m = \left(k_{cb} + k_s\right) ET_o \qquad [14]$$

$$k_c = \left(k_{cb} + k_s\right) k_a \qquad [15]$$

Figure 1 (from Burman *et al.* (1983) adapted from Wright (1982)) gives a generalized crop coefficient curve depending upon phenological stages of a crop.

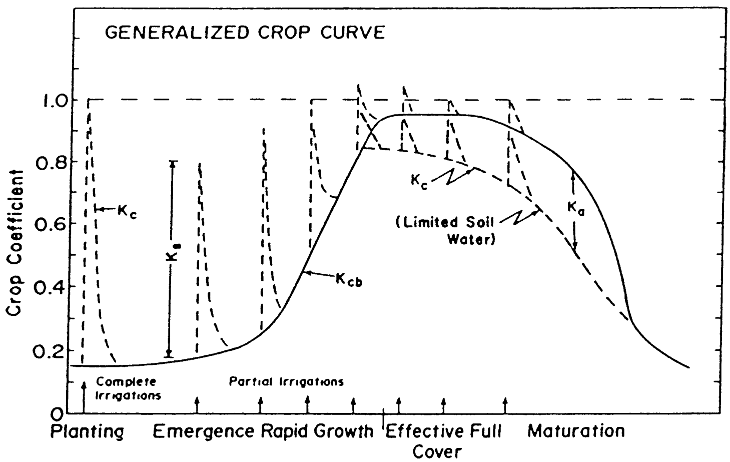

Figure 1. Generalized basal crop ET coefficient (K_{cb}) curve showing surface wetness coefficient (K_s) and coefficient (K_a) for limiting soil moisture, used to compute an overall crop ET coefficient (K_c) (from Wright, 1982)

During the initial stage (crop covering < 10 %), k_{cb} ranges around 0.2, increasing up to 1 for full cover, independently of the crop height and decreasing down below 0.5 at maturation. It is worthwhile to point out that there is now an agreement on maximum value (1 $\pm$ 0.1), contrary to what was admitted during the sixties that some tall crops could reach k_{cb} values as high as 1.4.! Obviously, basal crop coefficients used with a reference evapotranspiration need to be calibrated with the formula used to calculate ET_o . Thus, appropriate calibration is required with P.M. equation if it is adopted in a standardized form devoted to a worldwide use (Allen *et al.* 1994b).

A question that has to be answered is : what improvement could be obtained by applying adapted crop coefficients to P.M. equation ? Would it be possible to find another way consisting in drawing crop resistance variations of a particular crop under no water stress as a function of phenological stage ? When crop evapotranspiration would be computed directly from the P.M. equation (10), since the aerodynamic resistance includes the crop height effect, using a ratio between the crop resistance and the grass reference resistance could be a solution.

Concerning wet soil surface contribution to total ET_m, it is a common way to express it as a function of time after rain (Ritchie 1972, Wright 1982) :

$$ks = \left(1 - k_{cb}\right)\left(1 - \sqrt{\frac{t}{t_d}}\right) fw \qquad [16]$$

where t_d is a time characteristic (5 days for a loamy soil) and fw the fraction of originally wetted soil.

Concerning the dryness stress factor, two main models have been proposed (see Figure 2). Curve B corresponds to Jensen *et al.* formula (1970) which is widely used in the USA:

$$k_a = \frac{\text{Log (ASW + 1)}}{\text{Log (101)}} \qquad [17]$$

where ASW is the percentage of available soil water, i.e. between field capacity and wilting point in the rooted soil. This formula is very simple to be used but doesn't make differences between crops, soils and climates.

Curve A corresponds to a representation by Doorenbos *et al.* (1978) based on observations from many authors (e.g. Denmead and Shaw 1962, Gardner and Ehlig 1963, Van Bavel 1967, Ritchie *et al.* 1972) which enables ET_a to meet ET_m with decreasing ASW down till a water depletion factor (p) which varies with crops and ET_m.

Table 1 from Doorenbos *et al.* (1978) gives p values for several groups of crops and different values of ET_m. These p values are of high interest for irrigation scheduling because they help to calculate the time interval between irrigations for a crop under a given climate to ensure no water restriction. Unfortunately, their generalisation to soil types ranging from coarse sands to clays was highly criticized when measurements of ET_m and ET_a were performed simultaneously (Itier *et al.* 1990).

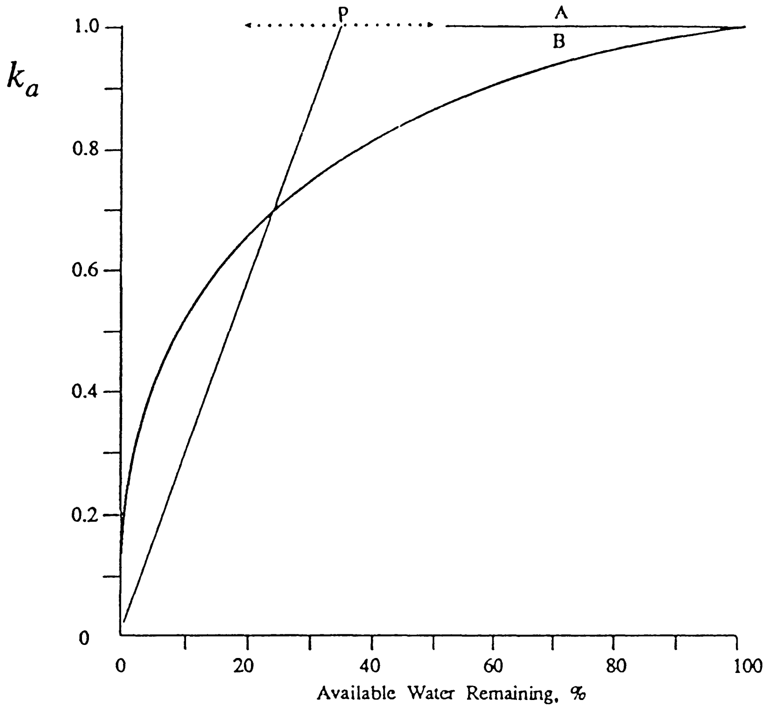

Figure 2. Frequently used relationship for relative evapotranspiration versus available soil water. Point moves from 20 to 80 % with increasing evapotranspiration. (from Doorenbos *et al.* 1978 and Jensen *et al.* 1970)

TABLE 1.a. Crop groups according to soil water depletion.

Group	Crops
1	Onion, peper, potato
2	Banana, cabbage, grape, pea, tomato
3	Alfalfa, bean, citrus, groundnut, pineapple, sunflower, watermelon, wheat
4	Cotton, maize, olive, safflower, sorghum, soybean, sugarbeet, sugarcane, tobacco.

TABLE 1.b. Soil water depletion fraction (p) for crop groups at various maximum evapotranspiration rates.

Crop group	ET_m mm/day							
	2	3	4	5	6	7	8	9
1	0.50	0.425	0.35	0.30	0.25	0.225	0.20	0.20
2	0.675	0.575	0.475	0.40	0.35	0.325	0.275	0.25
3	0.80	0.70	0.60	0.50	0.45	0.425	0.375	0.35
4	0.875	0.80	0.70	0.60	0.55	0.50	0.45	0.425

To improve such an approach, it is necessary to have a more detailed description of soil in connection with root extraction. Without entering in elaborated models using conservation equations as Darcy-Richard law (Feddes *et al.* 1976, Hillel *et al.* 1976, Molz 1981), simple ways have been tested in the last decade : the two reservoirs system where occasional rains refill first the upper one (e.g. Brisson and Perrier 1991) and the four level system (B.S.I. 1988) where the four quarters of the root depth account respectively for 40, 30, 20 and 10 %. The main interest of these systems is to be time self corrector. These models have been used to develop real time irrigation scheduling (see e.g. RELREG, from Teixeira *et al.* (1993).

Another way for improvement should be the simultaneous use of water balance calculation and water stress indicators. In the last few years several attempts have been made to link either physically based indicators as CWSI (Idso *et al.* 1981; Jackson 1981) and physiologically based indicators as predawn leaf water potential, PLWP, (Itier *et al.* 1992) to relative evapotranspiration, i.e. to k_a as defined in equation 13. Theoretical correspondence of CWSI to k_a (Jackson 1981) is CWSI : 1 - k_a while the experimental relationship between PLWP and several C3 plants (Itier *et al.* 1992) is given in Figure 3.

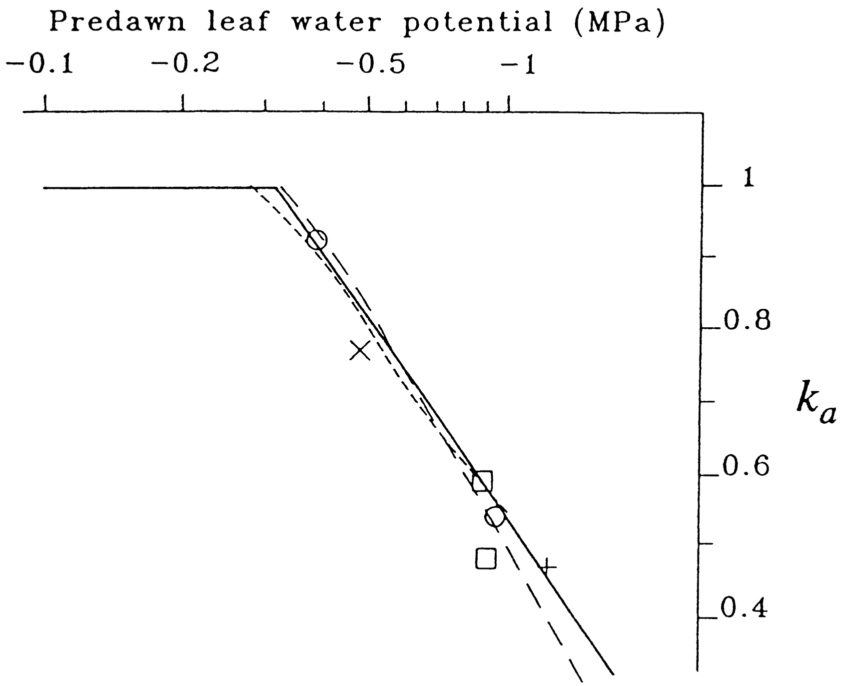

Figure 3. Comparison of global relations between k_a and PLWP for several C_3 plants :
—— Itier *et al.* (1992) - soybean; ----- Itier *et al.* (1990) - tomato; – – – Meyer and Green (1980) - wheat; + Jordan and Ritchie (1971) - cotton; O Riou *et al.* (1986) - alfalfa; x Sharrat *et al.* (1983) - alfalfa; ❑ Sojka (1974) - wheat

Finally another possible way should be to link directly r_c of a drying crop to available soil water (ASW) (Hatfield 1985). Then instead of using crop coefficients including basal coefficient (k_{cb}) and stress factor (k_a), it would be possible to go to the very end of Penman-Monteith approach :

$$r_c = f(\mathrm{Rg, LAI, VPD}, \text{ soil water potential or ASW}) \qquad [18]$$

where Rg is global radiation, LAI the leaf area index and VPD the water vapour pressure deficit (see Jarvis 1976, Jones 1978, Katerji *et al.* 1983, Fuchs *et al.* 1987).

For standard P.M. ET_0 calculation, R_g is not taken into account because this formula gives daily mean values and LAI is kept constant at 2.9 (Allen *et al.* 1994b). Empirical dependence on VPD comes from Choisnel *et al.* (1992) type studies.

For ETm calculation, LAI changes will imply r_c changes as :

$$r_{cm} - r_{cs} = \left(\frac{a_m}{LAI_m}\right) - \left(\frac{a_s}{LAI_s}\right) \qquad [19]$$

where subscript s refers to standard grass and m to the crop (Hansen 1979).

For ET_a, changes in available soil water (ASW) will imply changes in r_c as :

$$r_c = r_{cm}(ASW + b) \qquad [20]$$

where subscript m refers to ET_m (Hatfield 1985).

The global modelling using P.M. equation with parameterized r_c was summarised by Rutter (1975) by means of the set of following equations :

$$ET_a = f\ (\text{climate, height of the crop, } r_c) \qquad [21]$$

$$r_c = f\ (\text{Rg, LAI, potential of leaves}) \qquad [22]$$

$$\text{Potential of leaves} = f\,(\text{soil potential, } ET_a) \qquad [23]$$

This global modelling is still under the scope of research studies, far from a possible application for farmers'use.

5. Research Needs

Several ways of improvement can be identified from the previous developments.

- **At the field scale** : it is still of interest to find a simplified way of measuring ET_a on a long term basis by means of easy to run techniques. Progress was made compared with the sixties and seventies, by providing simplified aerodynamic methods or more reliable Bowen ratio techniques (Itier *et al.* 1985; Cellier and Olioso 1993). Even if it is still too complicated for farmers, it can be used by advisers. May be the way for the future would consist in developing water stress indicators for farmers associated with ET_o estimates provided by meteorological offices or, in some cases, directly calculated by means of automatic weather stations which tend to spread, at least in developed countries ?

For agronomists or at least for physiologists, reliable enough methods are now available to undertake long time based studies over homogeneous vegetations but it is of interest to develop methods or models permitting the same over row crops, orchards or vineyards (see e.g. Cohen *et al.* 1993), forests (Stewart 1989 ; Berbigier and Loustau 1994) and intercropping systems (Wallace 1994).

- **At a regional scale**, which is the scale of interest for project managers, research is going on to estimate ET_a by using thermography (Soer 1980 ; Seguin and Itier 1983 ; Moran *et al.* 1990). Recent work from Clarke *et al.* (1994) shows that it is possible to couple visible and thermal infrared to determine large scale CWSI. Developments in his direction, could be a very elegant way, when associated to ET_o estimates, to model water consumption at watershed scale.

- Concerning **reference evapotranspiration,** FAO-24 Penman formula is right now the more commonly accepted analytical formula. To promote Penman- Monteith standard formula, it appears necessary to solve the problem of VPD influence on standard crop resistance (Choisnel *et al.* 1992). It will be interesting to see if crop coefficients are still the best way of computing ET_m or if they can be replaced by the use of a crop resistance depending upon phenological stages (which takes into account not only phenology fut also soil covering and height of the crop). If P.M. equation is kept as the best reference, then crop resistance use would probably have to be extended to the calculation of ET_a so that it is of interest to analyse all these implications before making the selection.

The future use of this new knowledge requires, as pointed out by Jensen (1985), progress on teaching at the school level : It is probably time to let aside old empirical methods to emphasise the basic principles controlling and driving processes. Then the remaining formulae, as Hargreaves (1974) for instance, could be not only presented but also explained !

As a conclusion on sustainability, actual evapotranspiration measurements or accurate estimates cannot be used as universal ways of avoiding leaching or pollution : there are cases of high water tables where water stress indicators are necessary to determine when ET_a departs from ET_m. The two questions, "when" and "how much" to irrigate, need deepening of knowledge on both water balance calculation and water stress indicators.

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WATER USE EFFICIENCY

P. STEDUTO
CIHEAM-IAM-BARI
via Ceglie, 9
70010 Valenzano (BA) - ITALY

1. Introduction

Water is not a renewable resource. Its total amount on the earth is fixed and its allocation in space and time is governed by the hydrological cycle, on which human intervention plays an important role. Then, if the ever declining quantity of available water to agriculture is faced, while the agricultural yield needs to be sustained, a proportional increase of efficiency in the use of water is required.

Defining the efficiency term as the ratio between "output" and "input", one might evaluate the efficiency of a distribution system between a reservoir and farms by expressing it as the ratio of the water delivered to the farms to the water leaving the reservoirs (conveyance efficiency), or the efficiency in the application of an irrigation gift by expressing it as the ratio of the water to the effective root zone of a crop to the water applied to the field through irrigation (application efficiency), and so on. Every time one clearly recognize water as the constituent of both "output" and "input" in the efficiency expression, then we are talking of "efficient water-use". Such terminology should be kept distinguished from the alternative use of terms leading to "water-use efficiency", as introduced by Viets (1962), where the "output" is the carbon gained through photosynthesis by the vegetation while the "input" is the water lost by transpiration. The first definition represents the *hydrological* approach to the efficiency in water use, while the second definition represents the *physiological* approach to the efficiency in water use (Stanhill 1986). The *hydrological* efficiency can be easily understood and, similarly to many other efficiency terms, varies within the theoretical range 0-1. The *physiological* efficiency is more difficult to be framed as there is no association to the direct use of water in crop growth, neither a maximum value attainable by theory exists for reference (Monteith 1984, Monteith 1993).

Notwithstanding the limitations of the *physiological* efficiency term, its use is widespread among crop- and eco-physiologists. Unfortunately, the literature has rarely used a straightforward definition and terminology so that the ambiguous use of the terms is frequently encountered. Thus, we may synthesize the two major classes of efficiency, and indicate the corresponding terms and symbols, as follow:

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 193–209.

$$\text{Efficient Water - Use} = e = \frac{\text{water}_{\text{output}}}{\text{water}_{\text{input}}}$$

$$\text{Water} - \text{Use Efficiency} = \text{WUE} = \frac{\text{carbon gained through photosynthesis}}{\text{water lost by transpiration}}$$

When the *efficient water-use* (e) is improved less water is wasted and consequently become available for the irrigation of more agricultural land. When the *water-use efficiency* (WUE) is improved, more carbon is gained per unit land area per unit of water used by plants. When all possible saving in water is achieved, that is when e is at its maximum, it is still possible to sustain agricultural productivity by improving WUE.

This short review follows some more extended ones (Taylor *et al.*, 1983; Stanhill, 1986) differing, however, one from the other because of the many aspects offered by the subject, which do not allow any single article to be really exhaustive.

WUE has space- and time-scale implications which need to be explicitly defined in order to avoid additional confusion in the use of the terms. For instance, one can talk about *photosynthetic WUE* when the time scales are on short term (min, hours) and the space scale is the leaf or the plant. One can talk about *biomass WUE* when time scales are on medium and long term (day, season) and the space scale is the plant or the crop. Furthermore, it has to be specified if the biomass is total or only the aboveground, as well as the water lost is transpirational only or consumptive (evaporation and transpiration). Moreover, one can talk about *yield WUE* where the harvest index (HI) is introduced and when the time scale is the season, and the space scale is the canopy.

A summary of the most used terminology and definitions of WUE is reported in Table 1.

The attention will be paid to the three major aspects of WUE (*photosynthetic-, biomass-*, and *yield-WUE*) trying to scale up from leaf to canopy, and to explore the opportunities for further improvement in the perspective of a sustainable agriculture. Subsequently, a brief look at the impact on WUE by various environmental factors will be given, while concluding with some suggestions for future research needs.

2. Photosynthetic WUE

The *photosynthetic WUE* is defined as the ratio of leaf net assimilation to leaf transpiration (A/T). In terms of photosynthesis, the various species can be grouped in three major types according to the CO_2 fixation pathways: the C_3, C_4 and CAM plants. While all three types ultimately rely their CO_2 fixation on the Calvin photosynthetic carbon reduction cycle (Osmond *et al.* 1982), there are additional features characterizing those groups making the *photosynthetic WUE* of CAM plants higher than C_4 plants, which in turn is higher than C_3 plants, at comparable environmental conditions.

TABLE 1. Major definitions of water use efficiency terms

term	definition	time scale	space scale
photosyntheticWUE	$\frac{A}{T}$	min, hour	leaf, plant
CWFR	$\frac{\int_{t_o}^{t_f} NCF}{\int_{t_o}^{t_f} ET}$	hour, day, season	canopy
biomassWUE	$\frac{\int_{t_o}^{t_f} \text{above- ground biomass}}{\int_{t_o}^{t_f} ET}$	week, season	plant, canopy
BWR	as in biomassWUE when ET replaced by T_c	week, season	plant, canopy
glucose-equivalentWUE	C ´ biomassWUE	week, season	plant, canopy
yieldWUE	HI ´ biomassWUE	season	plant, canopy

WUE	water use efficiency
A	leaf net assimilation rate
T	leaf transpiration rate
CWFR	carbon water flux ratio (Baldocchi *et al.*, 1985)
NCF	canopy net carbon flux
ET	plant or canopy evapotranspiration rate
BWR	biomass water ratio (Monteith, 1993)
T_c	canopy transpiration rate
C	factor accounting for the difference in mole per mass of carbon between biomass and assimilated CO_2 (Hsiao, 1993b)
HI	harvest index
t_o and t_f	initial and final time limits for the integration

In C_3 plants, so-called because of the three-carbon phosphoglyceric acid (PGA) present in the basic photosynthetic reaction, the Ribulose-bi-phosphate-carboxylase/oxygenase (*RuBP-case*) is the enzyme starting the fixation of CO_2 in the mesophyll cells surrounding the substomatal cavities (Fig. 1a). *RuBP-case* may alternatively fix also O_2 which behaves as competitive inhibitor of the CO_2 to the same active sites of the enzyme. The product of *RuBP-oxygenase* is consumed in the photorespiration cycle, while the product of *RuBP-carboxylase* is consumed in the Calvin cycle. Furthermore, the enzymatic reactions follows the Michaelis-Menten kinetics with a Michaelis constant (K_m) of about 420 mbar bar^{-1} (equivalent partial pressure). Recalling that the K_m is the substrate concentration (CO_2 in this case) at which the speed of reaction is half of the maximum speed achievable, and that in well watered, well nutrient-fed, and healthy plants, the substomatal or intercellular CO_2 concentration (C_i) corresponds to about 220 mbar bar^{-1}, it turns out that the CO_2 carboxylation reaction runs much below its potential.

Among cultivated crops belonging to C_3 are wheat, sugarbeet, legumes, tomatoes, sunflower, cotton, and many others.

In C_4, so-called because of the four-carbon malic or aspartic acid present in the basic photosynthetic reaction, there is an anatomical or space separation (Fig. 1b) where two kind of specialized cells are involved in the overall carboxylation. Phospho-enol-pyruvate-carboxylase (*PEP-case*) is the enzyme present in the mesophyll cells surrounding the substomatal cavities. This enzyme "pumps" the CO_2 from the mesophyll cells into the bundle-sheath cells where the normal Calvin cycle occurs. Considering that the K_m for *PEP-case* is of about 30 mbar bar^{-1} and that in well watered, well nutrient-fed, and healthy plants C_i is about 100 mbar bar^{-1}, it is evident that the CO_2 fixation by *PEP-case* is running close to its potential. Furthermore, *PEP-case* is not sensitive to O_2 so that no inhibition occurs at ambient atmospheric conditions. Looking inside the bundle-sheath cells, because of the pumping action by the *PEP-case*, the values of CO_2 concentration are of about 2000 mbar bar^{-1} indicating that also the *RuBP-case* for the CO_2 fixation is running at its potential. Among cultivated crops, typical C_4, species are maize, sorghum, sugar cane, and many grasses.

The peculiarities in the previous two CO_2-fixation pathways clearly indicate that there is, always in comparable environmental conditions, a superiority in *photosynthetic WUE* of C_4 plants due to higher carboxylation capacity (A) relative to C_3 for the same transpirational flux (T). The *photosynthetic WUE* of C_4 plants (at leaf scale) can be about twice the one of C_3 plants (Ludlow 1976). The case of increased atmospheric CO_2 concentration, however, may be of greater advantage for C_3 than for C_4 as in C_3 the *RuBP-case* is far from running at saturation conditions. Furthermore, it has to be kept in mind that in C_3 plants the *oxygenase* activity of *RuBP-case* increases, relative to *carboxylase*, with increasing temperature, which in turn increases photorespiration (net assimilation decreases). This means that there is a comparative advantage of C_3 *vs* C_4 going from warmer to cooler climatic environment, or going from lower to higher latitudes (Osmond *et al.*, 1982), at least under the actual ambient CO_2 concentration.

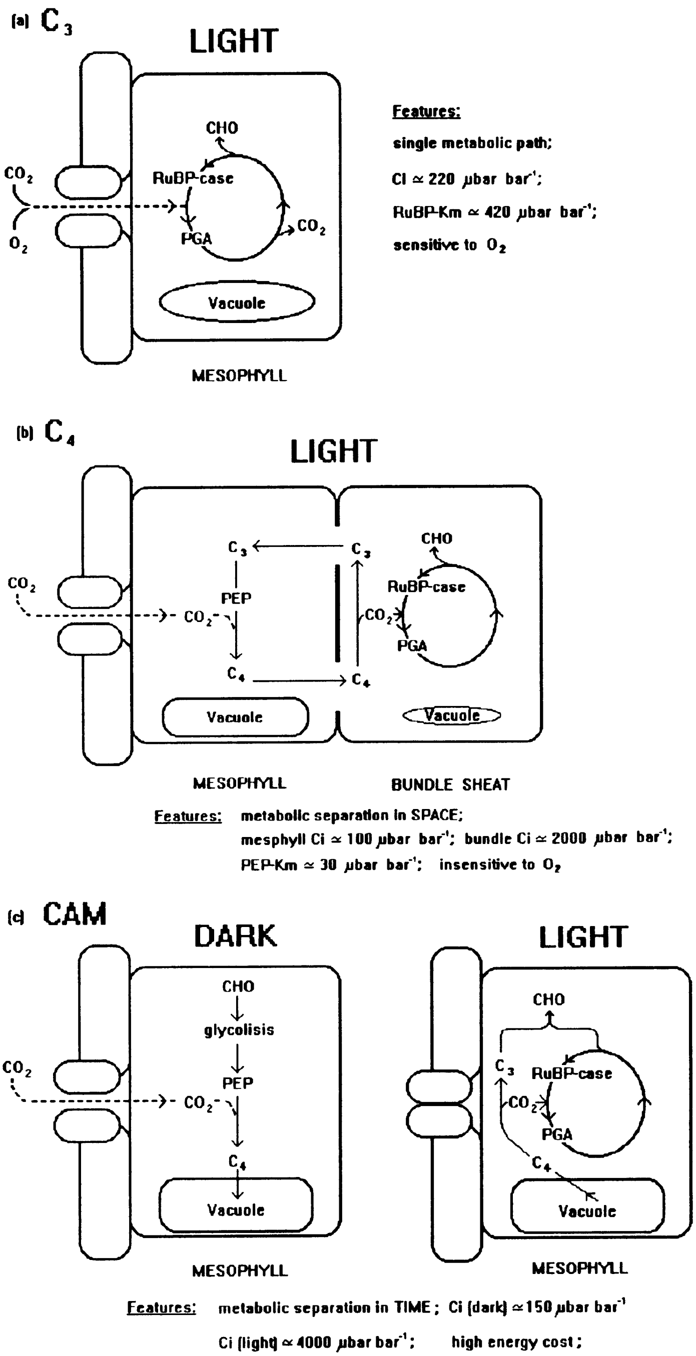

Figure 1. Schematic representation of the photosynthetic pathways and main features expressed by C3 **(a)**, C4 **(b)**, and CAM **(c)** plants (modified and redrawn after Osmond *et al.*, 1982)

In CAM plants, so-called for their *crassulacean acid metabolism*, there are the two same metabolic processes of CO_2 fixation as in C_4 but without anatomical separation. The two processes, in fact, occur within the same cells, though at different time (Fig. 1c), especially when water stress develops. In these plants, the CO_2 fixation by the *PEP-case* occurs generally during night time (in the dark) so that the leaves are under minimum net-radiation energy exposure, and consequently low transpirational losses, while having stomata wide open for uptaking CO_2 which is stored as malic acid into the cell vacuole. During day time, instead, stomata close and light activates the basic Calvin cycle of photosynthesis by assimilating the CO_2 from the vacuole while almost no transpirational losses are involved. Typical values of C_i in the substomatal cavities are about 150 mbar bar^{-1} during dark and about or greater than 4000 mbar bar^{-1} under light, making the CO_2 fixation by both *PEP-case* and *RuBP-case* running at their potential.

Among species of some agronomic interest, typical CAM plants are pine-apple, agave, and some opuntia cactus.

It is evident that having stomata open during night time and closed during day time, the expected *photosynthetic WUE* of these plants over the whole day is very high. In fact, the *photosynthetic WUE* of CAM plants (leaf scale) can be three to four times the one of C_3 plants and about 1.5-2 times the one of C_4 plants (Ludlow, 1976). Unfortunately, the enzyme turnover of CAM plants is such that a quite substantial energy cost is involved, making those species about those of very low growth rate and low productivity, though very valuable for some marginal or extreme conditions.

Although the previous considerations refer to leaf scale, they are quite fundamentally peculiar of the various species, and are also reflected at larger scale. At this basic biochemical level, opportunities for improving *photosynthetic WUE* may come only from genetics (molecular biology) acting probably on the enzymatic metabolism (e.g., different carboxylation enzymes or different K_m).

3. Biomass WUE

The *biomass WUE* is defined as the ratio of cumulative above-ground biomass of a crop canopy to cumulative evapotranspiration (ET) used by the crop. When soil evaporation (E) in ET is assumed negligible, *biomass WUE* equals BWR. The general time scale is not less than one-week/ten-days up to the whole crop cycle.

de Witt (1958) first analyzed the relationship between cumulative biomass and cumulative ET, observing a strictly linear relationship. Such relationship for many crop species varied in slope depending on the different weather conditions from year to year at the same climatic location, and from location to location. When the cumulative ET is normalized for a reference evaporative demand of the given climatic environment, then many crop species follow the same slope (Fig. 2) according to the expression:

$$\text{biomass} = m\left(\frac{ET_{crop}}{ET_{ref}}\right)$$

where the slope m showed to be governed by the species. Hundreds of such linear relationships can be found in the literature to indicate a somewhat conservative behavior of the *biomass WUE.*

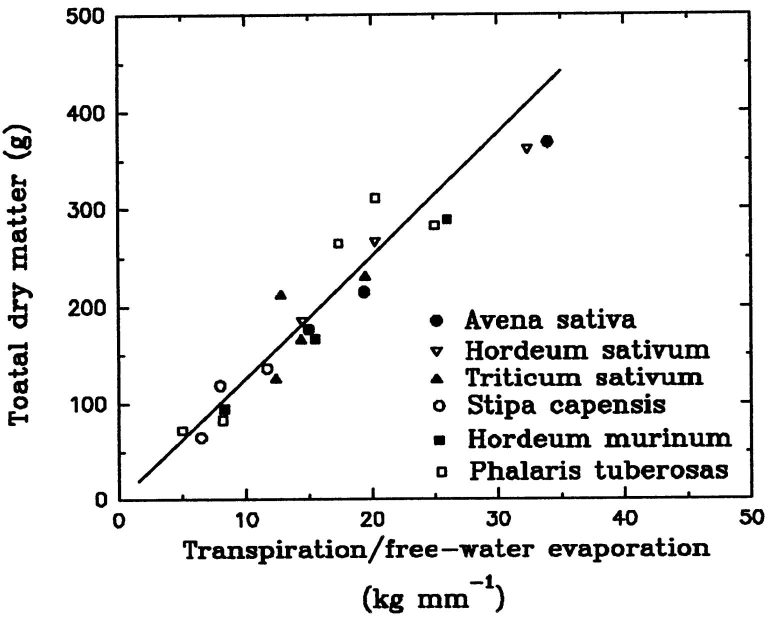

Figure 2. Relationship between cumulated dry matter and cumulated transpiration (normalized for climatic evaporative demand) of various field crops grown in containers (redrawn from de Witt 1958)

Two basic features can be invoked as the causes of such linear or conservative behavior (Hsiao 1993a): "the role of intercepted radiation in both assimilation and transpiration" and "the sharing of the transport pathway by CO_2 and water vapor between atmosphere and the intercellular air space of leaves". The role of intercepted radiation is actually dominant over the sharing of the pathway (Hsiao 1993a) as it will be discussed later. In Fig. 3, a conceptual framework (modified from Hsiao and Bradford 1983) of the similarities and differences between CO_2 assimilation and transpiration of a hypothetical crop canopy is reported.

The extend of radiation absorbed by the crop depends on the actual leaf area index (LAI), on the architectural distribution of leaves within the canopy (the leaf display), and the planting pattern. Assimilation and transpiration, then, share the same source of captured radiation, although only the photosynthetic active radiation (PAR » 400-700 nm) is used for CO_2 assimilation, while the whole (all l) captured radiation is used in transpiration. The PAR, however, is a fairly constant portion of the incident solar radiation (Meek *et al.* 1984, Varlet-Grancher *et al.* 1989), as constant is also the ratio of absorptance for PAR to non-PAR wave bands of leaves of many species (Stanhill 1981). A spectrally selective reduction in radiation out of the photosynthetic wave band might reduce the available energy for transpiration while keeping unvaried that for assimilation. Changes in radiative characteristics of plant leaves, though, seem scarcely attainable. Thus, in terms of the role played only by the intercepted radiation on A and T the constancy of the relationship between cumulative biomass and cumulative ET may hold quite robustly. The A and T per unit absorbed radiation, however, show more differences in terms of transport processes between atmosphere and inside the leaves (Fig. 3).

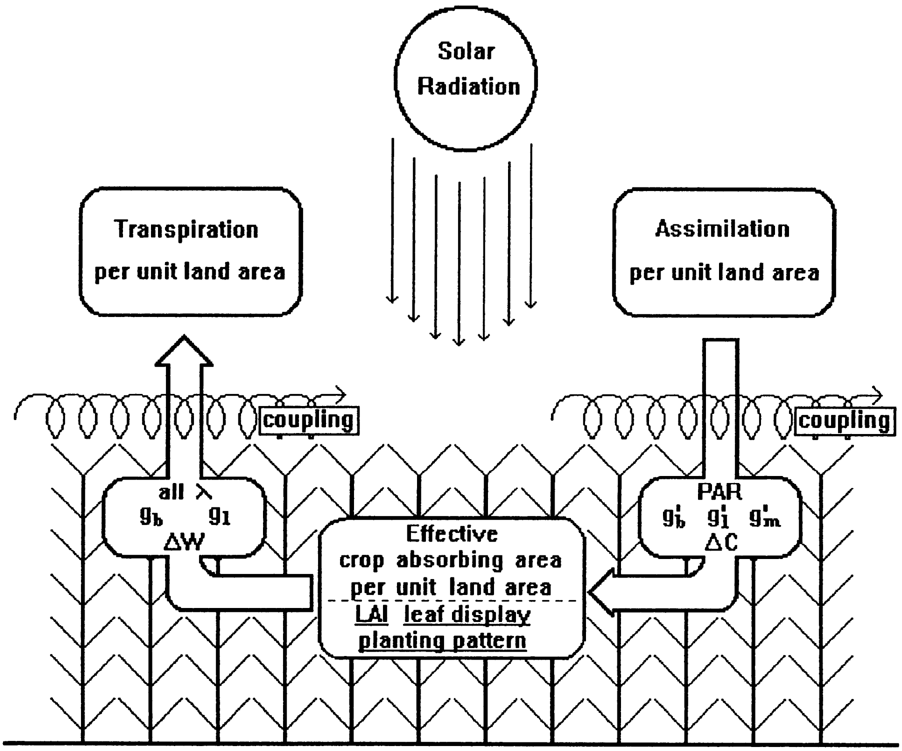

Figure 3. Schematic representation of commonalities and differences in the factors affecting transpiration and CO_2 assimilation per unit land area (modified and redrawn after Hsiao and Bradford, 1983)

Spanning the path from the cell wall inside the leaves to the bulk atmosphere, the water vapor flux (T) faces the boundary layer conductance (g_b) and the epidermal conductance of the leaf (g_l), more commonly indicated as stomatal conductance when cuticular conductance is neglected. A water vapor concentration differential (DW) between intercellular air space (W_i) and bulk atmosphere (W_a) takes then place. Spanning the path from the bulk atmosphere to the sites of carboxylation, the CO_2 assimilation flux (A) faces the same conductance segments as in T, up to the cell walls, though differing in their values (g'_b and g'_l) because of the difference in binary diffusivity in air between water vapor and CO_2. A CO_2 concentration differential (DC) between bulk atmosphere (C_a) and intercellular air space (C_i) is then established. On the additional path from the cell wall up to the sites of the carboxylation reaction, a metabolic conductance (g'_m) is further faced by A.

The variation in conductances occurring between bulk atmosphere and intercellular air space will have similar impact on T and A, as differences between g_l and g'_l, and between g_b and g'_b, are only due to binary diffusivity.

Symbols utilized are:

a) for transpiration, all l=all wave length of net radiation; g_b=leaf boundary layer conductance for water vapor; g_l=leaf epidermal conductance for water vapor; DW=water vapor concentration differential between leaf interior and bulk atmosphere;

b) for assimilation, PAR=photosynthetic active radiation (0.4-0.7 mm); g_b'=leaf boundary layer conductance for CO_2; g_l'=leaf epidermal conductance for CO_2; g_m'=metabolic, or mesophyll conductance for CO_2; DCO_2=CO_2 concentration differential between bulk atmosphere and leaf interior.

What makes the real difference between A and T, instead, are: (a) g'_m, corresponding to the biochemical carboxylation capacity of the plant, which is a specific feature of A only (Fig. 3); and (b) the concentration differentials (DW and DC). DW is mainly function of weather variables and the surface temperature of the leaves, while DC is function of the bulk atmospheric CO_2 concentration (about constant over a crop cycle length), and the intercellular airspace concentration (C_i), which in turn is dependent on CO_2 concentration at the carboxylating-reaction sites. Because in many species, although not for very extreme environmental conditions, C_i is also about constant, then by normalizing the weather variation by the reference evaporative demand of the environment (or DW as well), the constant slope of the relationship between A and T is returned again. This has been shown at canopy scale also by Monteith (1993).

In Fig. 3, a modification to the original framework of Hsiao and Bradford (1983) is represented by the coupling between crop and atmosphere. The coupling concept, expressing the efficacy of the energy and mass exchange between the two systems, was drawn to the attention of agriculturalists by Jarvis (1985a, 1985b), and further revised later (McNaughton and Jarvis 1991).

Coupling is linked to aerodynamic conductance which in turn is linked to turbulence at the crop/atmosphere interface. Also in this case, however, any change in coupling conditions will act in a relatively similar way on the concentration gradient of both CO_2 and water vapor (at least within the limits of the observable differences). These effects are implicitly accounted for in the boundary layer conductance of leaves (g_b).

Thus, the similar impact of the previous features (Fig. 3) on transpiration and assimilation explains why the *biomass WUE* is constant for a given species, and the only way to improve it in the consumptive water use (ET) is through the reduction of the soil evaporation (E), as it does not go through the plant for transpiration (T). Only if a species is genetically improved, so that the carboxylation capacity is increased, then the slope of the cumulative biomass vs cumulative ET can be made steeper, other factors being kept unchanged.

4. Yield WUE

The *yield WUE* is defined as the product of above-ground consumptive biomass WUE (*biomass WUE*) times the Harvest Index (HI). In this case, the time scale is the whole crop cycle. If for *biomass WUE* there is not much room for improvement, for *yield WUE* the opportunities are greater because of the unreached potential in HI.

Unfortunately, knowledge of the mechanisms controlling the processes related to assimilate partitioning, and especially the level of their inheritability, is still lacking. Linked to partitioning is also the possibility to confer functional balance to the root-to-shoot ratio, which in turn might have a relevant impact on the HI of crops in arid and semi-arid regions.

Similarly to wheat cultivars bred over time (Fig. 4), many other crops were bred for higher productivity through an indirect (and most of the time unconscious) selection for higher HI. For many crops, maximum values of HI have not been reached and plant breeders are still working on it.

5. Environmental Impacts on WUE

5.1. CO_2

There have been quite a few speculations on the possible impact on various type of vegetation of the continuous increase in atmospheric CO_2 concentration, which seems to increment at about 1.5 to more than 2 ppm per year (Lemon, 1983). The major effect of higher CO_2 observed experimentally on plant (Wong 1979, Morison 1985; Eamus 1991), is the corresponding, though not proportional, increase of WUE in C_3 plants with greater advantage over C_4. From what has been said in relation to *photosynthetic WUE*, the *RuBP-case* is the major cause of increase in WUE along with the fact that less nitrogen might be invested in this enzyme, increasing also the nitrogen use efficiency of the plants. For further treatments and framework analysis on the impact of high CO_2 on WUE the reader is referred to Hsiao (1993a), and Tyree and Alexander (1993).

5.2. WATER STRESS

As discussed earlier, the conservative behavior of *biomass WUE* is mainly due to the role of absorbed radiation and to the pathway shared in the transport process for A and T. What is not however well discussed in the literature is that the dominant cause making the *biomass WUE* conservative is the role of radiation interception rather than the sharing of the pathways. This has been demonstrated in many crops undergoing moderate water stress (Hsiao 1982), and it seems that it should hold also under moderate to severe water stress conditions. Hsiao (1993a), in fact, by analogy between the single leaf and the "big" leaf model (Monteith 1980) indicated that if WUE=A/T=aDC/DW, for the common path shared by water vapor and CO_2 (from the bulk atmosphere to the intercellular air space), and if C_i remains constant so that DC can also be considered constant, then WUE would be an inverse function of DW. Thus, the ratio of WUE under non-stressed conditions (WUE_O) to WUE under stressed conditions (WUE_S) would be consequence of the ratio of water vapor concentration differential under non-stressed conditions (DW_O) to the one under stressed conditions (DW_S). Under some water stresses which may induce stomatal closure, with consequent increase in leaf temperature and DW_S as well, then $WUE_S < WUE_O$.

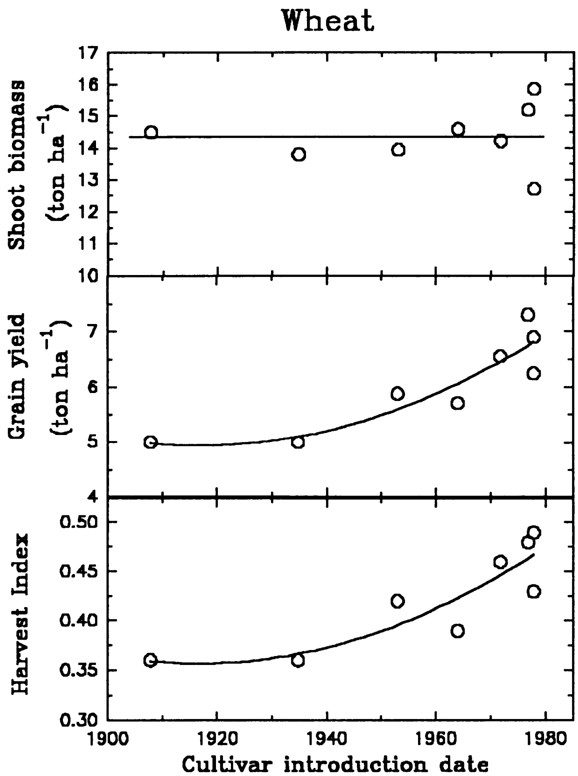

Figure 4. Above-ground biomass, grain yield, and Harvest Index comparison of eight English wheat cultivars as function of the time of their introduction in the market (from Gifford *et al.*, 1984)

Hsiao's hypohesis ($WUE_S < WUE_O$) in sweet sorghum at both leaf and canopy level (Fig. 5). The fact that the decline in WUE was observed in parallel fashion at canopy level also indicates the similar impact of the occurring coupling conditions on both assimilation and transpiration. Though, the straight line relationship between cumulative biomass and cumulative ET shows that these events are mostly circumstantial, and however limited in time length, under many field conditions. Thus, it is most likely that radiation interception is the major reason for the conservative behavior of *biomass WUE* also under moderate-to-severe water stress.

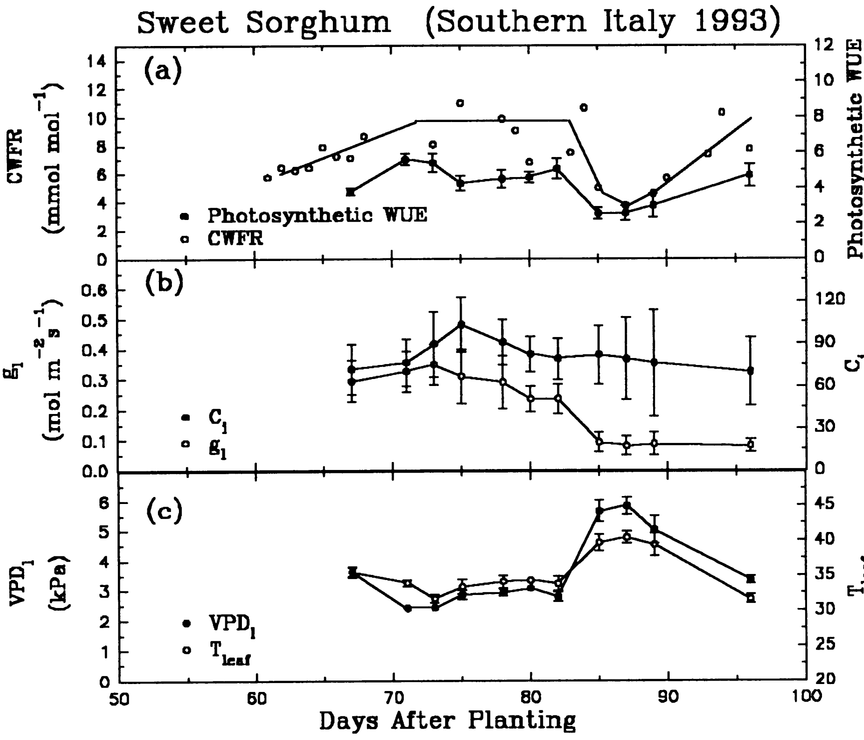

Figure 5. Daily Carbon Water Flux Ratio (CWFR) and noon time *photosynthetic WUE* **(a)**, noon time leaf conductance to water vapor (g_l) and C_i **(b)**, and noon time leaf-to-air vapor pressure deficit (VPD_l) and leaf temperature **(c)** of sweet sorghum, during vegetative growth and under progressing soil-water deficit (vertical bars indicate standard deviations)

At *yield WUE* level, one has to consider the effects of the water stress on the HI (not necessarily negative) through reduction of the sinks for assimilates (e.g., grains, fruits) and/or through impairment of pollination. These effects dependent on intensity and duration of the stress, along with the phenological stage of the plant at which stress is occurring, as well (Hsiao 1982).

5.3. NITROGEN

There is a clear-cut relationship between nitrogen leaf content and net photosynthesis (Field and Mooney 1986) as the consequence that about 50% of the soluble protein in the leaf is represented by *RuBP-case* (Fiedrich and Huffaker 1980), and that the leaf nitrogen invested in the whole photosynthetic apparatus may be well over three quarters of the total leaf nitrogen (Field and Mooney 1986). The general decline of photosynthesis with age was suggested (Field 1983) to derive from the translocation of nitrogen from sources (leaves) to sinks (grain and/or fruits) during leaf aging (e.g., Bolaños and Hsiao 1991, on tomato).

Nitrogen (N) is then essential to plants, but the quantitative use in growth, photosynthesis and partitioning is a question of optimal use and interaction with other resources as water and light (Mooney and Gulmon 1979). For instance, photosynthetic response of plants grown under abundant nitrogen availability, but at various light conditions showed that the nitrogen content in the leaves was in amount enough to match the maximum carboxylation capacity of each light level (Gulmon and Chu 1981). That is, a high level of enzymes in the leaves would have high energy costs of turnover, and this occurrence is not appropriate in terms of optimal nitrogen use if there is no corresponding gain.

A given nitrogen content in the soil may not be available to plants if water for transpiration is not enough to act as transport carrier of N. The interactive effect of N and water on carbon and water vapor exchange are not well explored and in many ways crop responses to low nitrogen content in the soil are similar to crop responses to soil water deficit (Jones *et al.*, 1986). Some trade off between WUE and nitrogen use efficiency (NUE) has been observed in natural environment (Field *et al.* 1983) though with some exceptions. Then, WUE and NUE indices may provide a way of approaching a more comprehensive resource-use efficiency within the context of sustainability.

5.4. SALINITY

Along with nitrogen, probably the direct impact of salinity on WUE is the less studied. It has been elicited quite clearly that nutrient uptake by plants is affected by salinity through competition between ions, ionic imbalance, and decreased osmotic potential of the solution or a combination of them (Grattan and Grieve 1992). The general observation is that both nitrogen uptake and transpiration by plants are reduced by salinity (Lea-Cox and Syvertsen 1993).

Short and long-term experiments may induce to observe either increase or decrease in WUE with increasing salinity. Some authors (Richards 1992) have even argued if increasing salinity tolerance of some plants may be worthwhile, since constant WUE were observed at increasing salinity level. It is suggested that manipulating WUE genetically or through management may lead to more successful results than improving salt tolerance and productivity in saline soil. It has to be clear, in fact, that mechanisms of salt tolerance (e.g., osmotic regulation, ion avoidance, ion exclusion and/or extrusion, ion compartmentation, etc.) are known to be energetically expensive (Flowers et al. 1977, Greenway and Munns 1980). Consequently, the high WUE whic could be obtained through breeding for salt tolerance may be paid through a loss in productivity.

6. Conclusion and Future Research Needs

WUE is extremely useful in rationalizing the basis on which crop management decision and breeding criteria are made. If this is true in a general sense, it is essential for regions where water availability is scarce relative to the demand and if agricultural productivity must be sustained. Improving WUE through management and through genetics can be considered short-term and long-term tasks, respectively. A further distinction can be made between *rainfed* and *irrigated* agriculture. In irrigated agriculture the overall efficiency in water use, combining both the *hydrological* and *physiological* aspects, is imbibed into the water product functions of the various crops. Thus, the management can be approached in terms of optimization through adequate selection, design, and operation of irrigation systems and proper irrigation scheduling.

As soil evaporation remains a loss of water without any gain in biomass production, and because it may be as large as 30% or more, its prevention is generally propitious, for both irrigated and rainfed agriculture. Appropriate nutritional supply is essential for maximizing WUE, although interactions water-nutrients under suboptimal conditions are scarcely known. The appropriate cultivar choice for a given environment where relative time-length of the phenological phases allows to gain advantages from the climatic conditions is also a way for improving WUE, especially under rainfed agriculture. Beyond genotype selection, additional opportunities in improving WUE is offered by shifting the time of sowing date and/or modifying the population density. Though, effects of temperature on crop growth needs to be thoroughly evaluated.

Relatively more can be done to improve *yield WUE*, still in terms of management, by alleviating or governing any possible impact of water stress on the harvest index (HI), either through direct or related effects influencing the reproductive stage and fruit setting.

Through breeding, the most promising way of improving *yield WUE* still remain the increase in harvest index. Transfer of carboxylation pathways between species, though possible in principle and technologically by molecular biology, shows a complexity in the coordination of enzymatic processes that some positive results are expected on time period much longer than those expected for more qualitative genome modification.

What seems auspicious in terms of near future needs is to orient research more on system analysis of the various agricultural systems where the environmental conditions are target, and the actual boundary conditions are truly considered. This is because conceptual frameworks, theoretical and technological tools, where homogeneity and uniformity of conditions are the rules, are available while there is a lack of knowledge from real agro-environmental systems where uniformity is the exception and variability of conditions is instead the rule. Interaction of water with other factors (e.g., nutrient, salinity) are necessary to quantitatively optimize production response functions. Also water quality, of course, should be considered in WUE research.

In crop-water relation studies, tree crops are generally the most penalized so that a major emphasis should be placed on those, as well as on mixed-cropping systems, which might be of greater interest for sustainable agriculture. This, as usual, implies that multi-disciplinarity must be supported if integrated analysis are willing to be achieved. In this context, modeling can be helpful for integration. Consequently, research funding agencies should privilege applied research projects where inter-disciplinarity and networking among scientist is dominant, and objectives to pursue are significant to the sustainability of real systems. On more long term, some break-through results are expected from plant breeding.

Furthermore, embodying efficient water-use (e) and WUE in an overall approach of water use and productivity, the resource use analysis can be scaled up from farm to region without solution of continuity.

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MODELING OF WATER FLOW AND SOLUTE TRANSPORT FOR IRRIGATION AND DRAINAGE

J.C. VAN DAM AND R.A. FEDDES
Agricultural University Wageningen
Department of Water Resources
Nieuwe Kanaal 11
6709 PA Wageningen
The Netherlands

1. Introduction

Earth's total land surface equals 13.2×10^9 ha, of which no more than 7×10^9 ha is arable and only 1.5×10^9 is cultivated (Massoud 1981). Of the cultivated lands, about 0.34×10^9 ha (23 %) is saline and another 0.56×10^9 ha (37 %) is sodic. Fig. 1 (Szabolcs 1989) shows that saline and sodic soils cover about 10 % of total arable land distributed over 100 countries. Although natural factors are the main causes of the occurrence of saline/sodic soils, also man induced salinity and sodicity problems occur in large areas as a consequence of improper irrigation drainage design and management.

Figure 1. Global distribution of salt-affected soils (after Szabolcs 1989)

For instance in Pakistan the introduction of perennial irrigation has increased seepage from the unlined canals causing problems in areas of limited natural drainage. It is

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presently estimated that after the monsoon period 4.7 million ha have a groundwater table within 1.5 m below soil surface. Prior to the monsoon this area is about 1.5 million ha. The area affected by salinity is estimated at 4.2 million ha, of which 1.9 million is slightly saline, 1.0 million moderately saline and 1.3 million highly saline (IWASRI/UNDP 1989).

The construction, operation and maintenance of irrigation systems involves large investments. Irrigation systems can only be profitable if they are sustainable on the long term. However the analysis of the soil water flow and transport processes is complex. For instance, percolation of soil water is affected by weather conditions, irrigation amounts and timing, type of crop, soil physical properties, drainage conditions, and the degree of salinity of the irrigation water and the groundwater.

It is time and money consuming to determine the optimal water management with field or lysimeter experiments only. In the past many of those experiments were analysed by determining the regression between independent variables and their effects. The resulting correlations were site specific and were of little use to generalize management options and long term salinity effects.

Instead, physically based simulation models of short running time might be used to characterize the flow and transport processes in the soil. Moreover simulations allow for predictions at other field sites and for dif&^{2}ferent boundary conditions to assess long term salinity effects. For instance, leaching of the soil profile is necessary to remove the salts that will enter the soil profile. In the past leaching fractions of 0.3 were applied. Research shows however that considerable amounts of water to dispose saline drainage water can be saved when using smaller leaching fractions, while the salinity stress to the crops is still restricted (e.g. Dirksen 1983, Hoffman 1990).

Also drainage design may profit from developments in simulation models. Traditionally tile drains were installed at depths that prevented capillary rise of saline water. Also steady state discharge criteria were used to calculate the spacing between the drains. Future irrigation and drainage designs might be based on a dynamic interaction between percolation and capillary rise while still keeping salinity levels within acceptable limits. Then less irrigation water may be needed as plants may profit from capillary rise. Moreover the costs of installation and maintenance of the drainage system and of the disposal of low quality drainage water may be reduced.

The increasing pressure of population and industrialisation on resources and the growing concern for environmental protection in many parts of the world urge to make optimal use of water in agriculture. The combined use of agro-hydrological-environmental models with economical models, as shown by Knapp (1992) may help to develop a sustainable approach.

In this contribution we will focus on the physically based model SWATRE which describes transient water and salt transport at field scale. In our opinion such a model has a large potential to meet the current challenges in water and salt management. We pay attention to some developments in the simulation of transport processes and show the results of some simulation experiments for the Punjab, Pakistan.

2. Recent Developments in the Description of Soil Water Flow and Solute Transport

A survey of currently used and well documented subsurface drainage models can be found in Lorre and Lesaffre (1994) and Madramootoo (1993). Concepts of processes affecting water transport in the unsaturated zone have, among others, been described in Feddes *et al.* (1988) and Feddes and Bastiaanssen (1992) and will not be repeated here. In this contribution we focus on some recent developments in the description of the processes, using our experience with the program SWATRE (Feddes *et al.* 1978, Belmans *et al.* 1983, Kabat *et al.* 1992, Working Group SWAP 1994).

2.1. WATER FLOW

Soil water flows due to differences in soil water potential. For one-dimensional vertical flow, the Darcy flow equation can be written as:

$$q = -K(h)\frac{\partial(h+z)}{\partial z} \qquad [1]$$

where q is the soil water flux (LT^{-1}), K is the unsaturated hydraulic conductivity (LT^{1}), h is the soil water pressure head (L) and z is the vertical coordinate (L) taken positively upward.

The continuity equation reads as:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q}{\partial z} - S(h) \qquad [2]$$

where q is the water content (L^3L^{-3}), t is the time (T) and S is the root water extraction ($L^3L^{-3}T^{-1}$).

Combination of eqs. (1) and (2) results in the well- known Richards' equation:

$$\frac{\partial\theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S(h) \qquad [3]$$

where C is the water capacity (dq/dh) (L^{-1}).

Although the concepts are simple, the numerical solution of eq. (3) is not easy due to the highly non-linear relationships between q, h and K. For instance many schemes try to average C during a time step, which causes large mass balance errors when simulating infiltration in dry soils. A simple but effective adaptation was suggested by Celia *et al.* (1990). Instead of applying during the *time* step the equation:

$$\theta_i^{j+1} - \theta_i^{j} = C_i^{j+1/2}\left(h_i^{j+1} - h_i^{j}\right) \qquad [4]$$

the change of q during an *iteration* step was computed as:

$$\theta_i^{j+1} - \theta_i^{j} = C_i^{j+1,p-1}\left(h_i^{j+1,p} - h_i^{j+1,p-1}\right) + \theta_i^{j+1,p-1} - \theta_i^{j} \qquad [5]$$

where (see Fig. 2) the subscript i is the node number, the superscript j the time level and the superscript p the iteration level. In this way the error due to averaging of C is circumvented, as $(h_i^{j+1,p} - h_i^{j+1,p-1})$ is almost zero when convergence is reached.

We have favourable experiences with the following finite difference scheme:

$$C_i^{j+1,p-1}\left(h_i^{j+1,p-1} - h_i^{j+1,p-1}\right) + \left(\theta_i^{j+1,p-1} - \theta_i^{j}\right) =$$

$$\frac{\Delta t^j}{\Delta z_i}\left[K_{i-1/2}^{j}\left(\frac{h_{i-1}^{j+1,p} - h_i^{j+1,p}}{\Delta z_u}\right) + K_{i-1/2}^{j}\right] \qquad [6]$$

$$-\frac{\Delta t^j}{\Delta z_i}\left[K_{i+1/2}^{j}\left(\frac{h_i^{j+1,p} - h_{i+1}^{j+1,p}}{\Delta z_l}\right) + K_{i+1/2}^{j}\right] - \Delta t^j S_i^j$$

where $Dt^j = t^{j+1} - t^j$, $Dz_u = z_{i-1} - z_i$, $Dz_l = z_i - z_{i+1}$, $Dz_i = (Dz_u + Dz_l)/2$. The values of K and S are evaluated at the old time level j. The mean K between the nodes is calculated as the geometric mean.

This numerical scheme applies both to the saturated and unsaturated zone and is mass conservative. Application of eq. (6) under the prevàiling boundary conditions to each node results in a tri-diagonal system of equations which can be efficiently solved. Starting in the saturated zone the groundwater level is simply found where $h = 0$. Calculations show that to simulate infiltration and evaporation accurately, the distance between the nodes should be small near the soil surface. For this reason the nodal distance has been made variable.

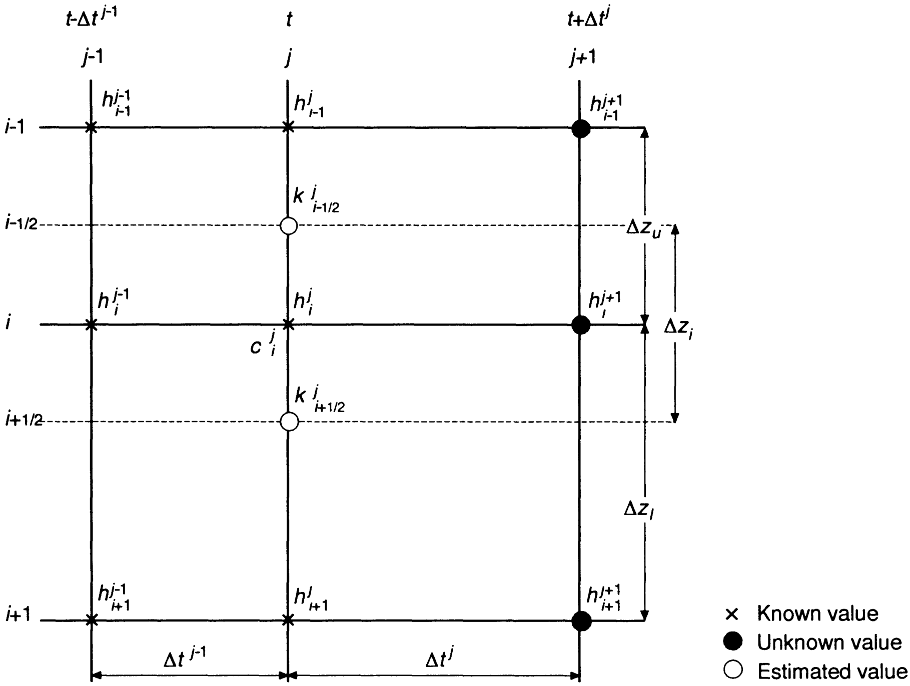

Figure 2. Discretization in space and time of the Richards' equation

2.2. SOIL HYDRAULIC FUNCTIONS

To solve eq. (3), the water retention function $q(h)$ and the unsaturated hydraulic conductivity function $k(q)$ should be known. Although the measurements of h and q in a soil are relatively simple, the large and strongly non-linear variation of h and k make the derivation of the soil hydraulic functions in the relevant range cumbersome and time consuming (Dirksen 1991). Indirect methods, which relate the soil hydraulic functions to easier measurable soil properties such as dry bulk density, organic matter content and texture, may alleviate the need for soil physical information (van Genuchten *et al.* 1992). Also the formation of accessible data banks will facilitate the use of indirect methods.

At present the possibilities of parameter estimation techniques (i.e. *inverse* modeling) are explored (Kool *et al.* 1987, van Genuchten *et al.* 1992). This involves flow experiments in the laboratory or in the field during which characteristic flow data (e.g. outflow, h, q) are collected. Next the experiment is repeatedly simulated with a numerical model. The parameters which describe the soil hydraulic functions are then found by minimizing the difference between simulated and measured data. The main advantages of inverse modeling are that less and easier obtainable data are needed and that the boundary conditions may change in time. This parameter estimation technique may save considerable experimental effort.

2.3. SPATIAL VARIABILITY

Natural soils show a large heterogeneity. In general it is not feasible to model the heterogeneity deterministically as this would require enormous amounts of data and computational effort. A practical approach is to differentiate between subareas with different sequences of soil horizons, and find an equivalent uniform porous medium for either each horizon or the total soil profile. Depending on the chosen scale of the subareas, a larger or smaller amount of the natural heterogeneity will be lost.

In a purely stochastic approach, Russo and Bresler (1980, 1981) used five parameters to describe the spatial variability of the soil hydraulic functions. To generate random values of these parameters, they needed the distribution functions and their moments for each parameter, as well as the correlation coefficient between the parameters.

A different way to deal with soil heterogeneity, is *scaling* as proposed by Miller and Miller (1956). By assuming geometrically similar media, they showed that the variability in both the q(*h*) and *k*(q) relation could be described by just one scale factor. The scale factor a_i at a certain location *i* is equal to:

$$\alpha_i = \frac{\lambda_i}{\lambda_r} \qquad [7]$$

where l_i is the characteristic length at location *i* and l_r is the characteristic length of the reference soil (Fig. 3).

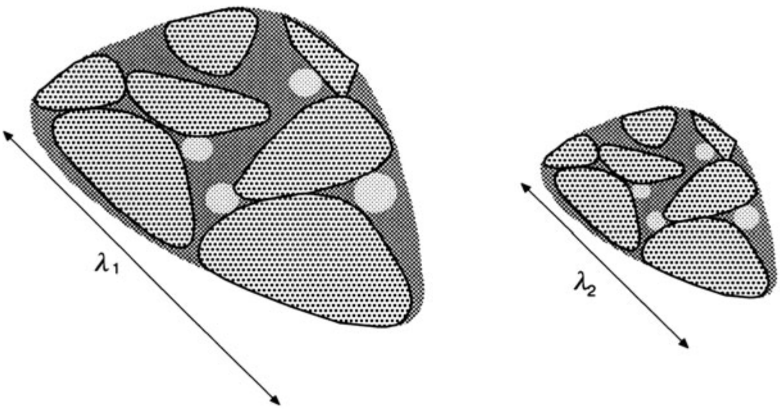

Figure 3. Characteristic lengths in geometrically similar media

$$h_i = \frac{h_r}{\alpha_i} \qquad [8]$$

It can be derived from capillary theory that, at a certain water content, the pressure head h_i at location i is related to the pressure head h_r at the reference location r by

For viscous flow also a relation between k_i and k_r exists :

$$k_i = \alpha_i^2 \, k_r \qquad [9]$$

Natural soils will (to a smaller or larger degree) deviate from geometrically similar media. Youngs and Price (1981) measured microscopic characteristic lengths for porous materials ranging from glass beads and washed sands to sieved arable soils. They concluded that even for dissimilar soils the scaling concept is a good approximation. Jury *et al.* (1987) point out that due to dissimilarity, scaling of different soil properties results in different statistical properties of each scaling factor distribution. This implies that the correlation coefficient should be used to generate scale factors for each of the two hydraulic functions. Clausnitzer *et al.* (1992) developed a scaling program in which the retention function and unsaturated conductivity function can be scaled either independently or simultaneously. Field studies in which scaling was applied were, performed e.g. by Peck *et al.*, (1977), Warrick and Amoozegar-Fard (1979), Ahuja *et al.* (1984), Hopmans and Stricker (1989), Wösten (1989) (Fig. 4) and Unlü *et al.* (1990).

2.4. ROOT WATER EXTRACTION UNDER SALINE CONDITIONS

Root water extraction in case of non-saline water has been described by Feddes *et al.*, (1978). Under conditions of optimal soil moisture the potential transpiration is uniformly or triangularly distributed over the root zone. Then for either too wet or too dry conditions root water uptake is reduced for those pressure heads that are non-optimal for water uptake (Fig. 5A). Van Genuchten (1987) transformed the linear functions of Fig. 5A and suggested reduction of water extraction according to (Fig 5B):

$$\alpha(h) = \frac{1}{1 + \left(\frac{h}{h50}\right)^p} \qquad [10]$$

where h/h_{50} is the reduced pressure head (at $h = h_{50}$ the value of a is reduced by half) and $p = 3$ for many crops. Cardon and Letey (1992) show that this approach yields realistic results.

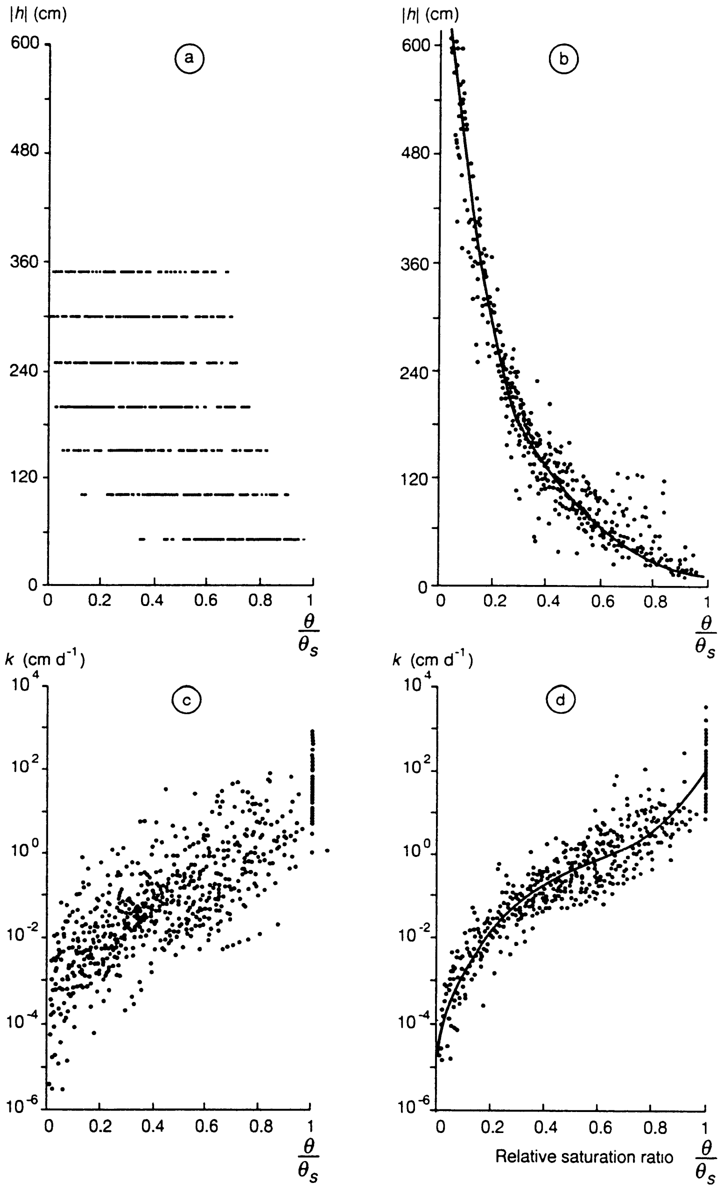

Figure 4. Unscaled (a) and scaled (b) water retention (*h*) data and unscaled (c) and scaled (d)hydraulic conductivity (*k*) data as a function of the relative saturation ratio for a coarse textured soil group (after Wösten, 1989)

According to Maas (1990) the osmotic head p of a saline soil can be related to the electrical conductivity of the soil solution *EC* as:

$$\pi\ (\mathrm{cm}) = 4521 - 360\ \mathrm{EC}\ (\mathrm{dSm}^{-1}) \qquad [11]$$

Combination of *water and salinity stress* to determine the reduction of root water uptake can be achieved in several ways.

One approach is to add h and p and use the total head h_{total} to derive a according to Figure 5A. As the effect of p on root water uptake varies between crops, a crop specific coefficient k_{osm} could be used:

$$h_{total} = h + k_{osm}\pi \qquad [12]$$

The latter approach taking k_{osm} = 1.335 has been applied in the numerical simulation experiments described in section 3 of this paper.

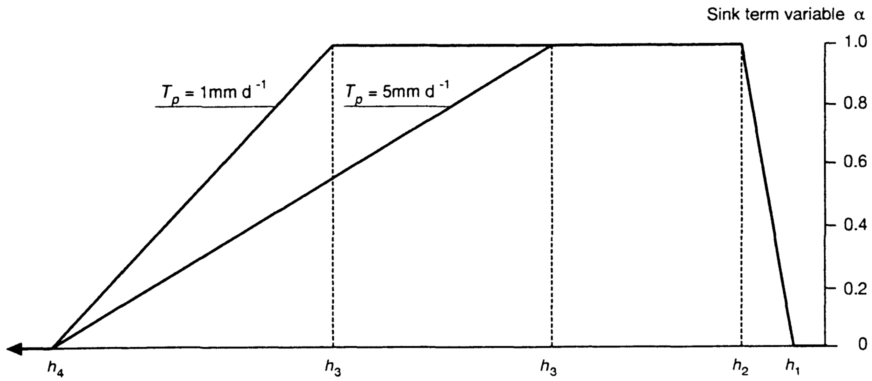

Figure 5A. Water stress response function (after Feddes *et al.* 1978)

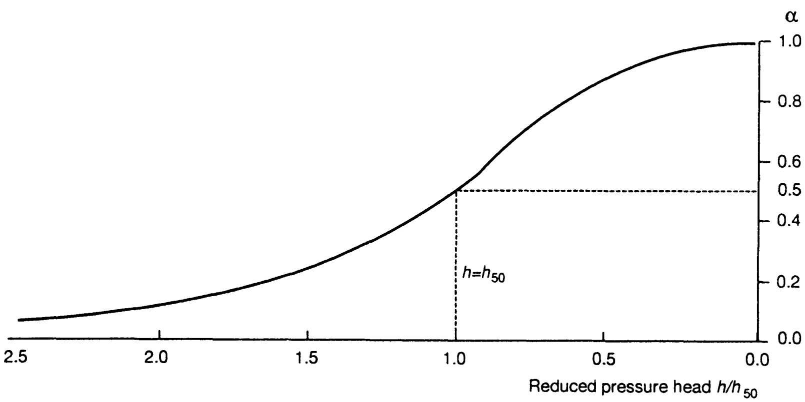

Figure 5B. Water stress response function (after Van Genuchten, 1987)

2.5. BOUNDARY CONDITIONS

Different methods exist to derive as top boundary condition (besides maximum possible infiltration rate) the daily potential evapotranspiration ET_p from basic meteorological measurements (solar radiation, air temperature, relative humidity, and wind speed). In 1991 the FAO organised an expert consultation to review FAO methodologies for estimating crop water requirements. The experts recommended to use the Penman-Monteith equation (Monteith 1981, Smith, 1991), which has been incorporated in the program CROPWAT (Smith 1992). The latter program has a users friendly interface and is distributed by FAO.

As lower boundary of the schematic soil profile either the groundwater level or the flux can be prescribed. Also the description of the flux as function of the calculated groundwater level can be used. The relation between flux and groundwater level might be based on steady drainage flow equations (Toksöz and Kirkham 1971), regional groundwater levels (Van Bakel 1988) or fitted analytical relations (Hopmans 1987).

2.6. TRANSPORT OF SOLUTES IN THE UNSATURATED ZONE

In general the flux of salts w (M L^{-2} T^{-1}) through unsaturated soils is described with the convection-dispersion equation:

$$w = qc - \theta D \frac{\partial c}{\partial z} \qquad [13]$$

where c is the salt concentration (M L^{-3}) in the liquid phase, D the dispersion coefficient (L^2 T^{-1}) and z the vertical coordinate, taken positively upwards.

If we include adsorption to account for observed retardation phenomena, the continuity equation reads:

$$\frac{\partial (\theta)}{\partial t} = - \frac{\partial w}{\partial z} \qquad [14]$$

where r_b is the soil dry bulk density (M L^{-3}) and X the amount of salts adsorbed (M M^{-1}).

Combination of eqs. (13) and (14) results in the final transport equation :

$$\frac{\partial (\theta)}{\partial t} = - \frac{\partial qc}{\partial z} + \frac{\partial (\theta)}{\partial z} \qquad [15]$$

The numerical discretization scheme of eq. (15) is in most cases implicit (e.g. Van Genuchten 1987, Wagenet and Hutson 1989, Vanclooster *et al.* 1992). After comparing various schemes we choosed for an *explicit* central difference scheme as applied by Boesten and Van der Linden (1991):

$$\frac{\theta_i^{j+1} c_i^{j+1} + \rho_b X_i^{j+1} - \theta_i^j c_i^j - \rho_b X_i^j}{\Delta t^j} = \frac{-q_{i+1/2}^j\, c_{i+1/2}^j + q_{i-1/2}^j\, c_{i-1/2}^j}{\Delta_{Zi}} + \frac{1}{\Delta_{Zi}}\left[\frac{\theta_{i-1/2}^j\, D_{i-1/2}^j \left(c_{i-1}^j - c_i^j\right)}{\Delta_{Zu}} - \frac{\theta_{i+1/2}^j\, D_{i+1/2}^j \left(c_i^j - c_{i+1}^j\right)}{\Delta_{Zl}}\right] \quad [16]$$

where the subscripts i-1/2 and i+1/2 for c and q refer to the values at the upper and lower compartment boundary respectively, being derived by linear interpolation.

Due to the central differences, numerical dispersion is suppressed (Van Genuchten and Wieringa 1974) and is generally smaller than field-scale physical dispersion. Advantages of the explicit scheme are the clear program structure and the easy incorporation of non-linear adsorption, mobile/immobile concepts, and other non-linear processes.

2.7. SOLUTE TRANSPORT IN THE SATURATED ZONES

Whereas in the unsaturated zone water and solutes move predominantly vertically, in the saturated zone water flows according to the local hydraulic head gradient, causing a three dimensional transport of solutes.

Kamra *et al.* (1991) used the analytical solutions of Kirkham (1958) for steady flow conditions in homogeneous as well as two-layer soils to construct a two-dimensional model for water and solute movement in tile-drained soils. An interesting aspect of their study is that they discretize the space domain but use exact-in-time analytical solutions of the water and salt transport advancement in time.

Another approach is based on residence time distributions as applied in chemical reactor engineering. The input signal is transformed into an output signal with a few key parameters which mimic the physical behaviour of the system (Jury 1982). This approach has been applied by Van Ommen (1986; 1990) to analyze field scale bromide transport. Sardin *et al.* (1991) show the large potential of this approach in case of linearly interacting solutes for both homogeneous and heterogeneous soils.

3. Irrigation and Drainage in the Punjab, Pakistan

3.1. INTRODUCTION

In Punjab the rainfall (about 350 mm yr^{-1}) is far less than the pan evaporation (about 1650 mm yr^{-1}). To meet the crop water requirements, the province uses large quantities of fresh water from the Indus and its contributing rivers Jhelum, Chenab, Ravi and Sutlej. In the second half of the 19th century perennial irrigation was introduced to supply water both during the Kharif (monsoon, June-September) and Rabi (dry) season. Already in the beginning of this century, waterlogging and salinity posed such large problems that remedial measures became necessary. Measures taken to lower the groundwater table were canal closures, lowering of canal levels, lining of canals, planting of eucalyptus trees, drainage by open channels, drainage by tile drains and water extraction by tube wells.

3.2. HORIZONTAL DRAINAGE BY TILE DRAINS

3.2.1. *Scenarios*

The common situation in the Faisalabad region of the Punjab is denoted here as the reference situation, which is characterized by the following properties. The hydraulic properties of the *sandy loam soil* have been taken from Beekma *et al.* (1992). The cropping pattern consists of *wheat during the Rabi* season and *maize during the Kharif season*. The *irrigation water (600 mm yr^{-1})* is evenly distributed over the year in *12 irrigation gifts of 50 mm*. The *canal water and shallow groundwater* have an *EC of 0.2 and 3.0 dS m^{-1}* respectively. *Pipe drains are installed at a depth of 2 m* and at a spacing of 300 m. *Seepage* from the underlying aquifer due to canal water losses *amounts to 126 mm yr^{-1}*. For more details see Van Dam (1992).

The following scenarios were simulated:

1. Reference situation: 600 mm irrigation water is applied in a year
2. Less irrigation water is applied: 480 mm irrigation water in a year
3. Drain depth is increased from 2 m down to 3 m
4. Different times of application of the 600 mm irrigation water
5. Fallow during the Kharif period (June - October)

The simulations started at November 1 at the beginning of the Rabi season and last until October 31, corresponding to the end of the Kharif season.

3.2.2. *Simulation results and discussion*

Figure 6 shows the yearly water fluxes for the five scenarios while Fig. 7 depicts the corresponding salinity profiles. Table 1 shows the salt balance of the upper 4 m soil layer.

TABLE 1. Salt balance components (g salt m^{-2} yr^{-1}) for five scenarios

Scenario	Salt Irrig	+	Salt Seep	-	Salt Drain	=	D Salt Stor
1. Reference	76.8		241.9		448.9		-130.2
2. Less irrigation	61.4		241.9		217.6		+85.8
3. Drain depth at 3 m	76.8		241.9		443.1		-124.3
4. Timing irrigation	76.8		241.9		425.1		-106.3
5. Fallow period	38.4		241.9		475.4		-194.9

Reference situation, i.e. irrigation 600 mm.yr^{-1}

The initial soil water profile was generated by simulating firstly the year preceding the experimental year under consideration.

The initial salinity concentrations were derived from measurements. The percolation is an important criterion for sustainable irrigation and is calculated as the soil water flux below the root zone at 120 cm depth. The irrigation and rainfall amounts are sufficiently large to achieve net percolation (Fig. 6). This results in leaching of salts (Table 1 and Fig. 7). The salinity concentrations near drain depth do not depend on the leaching fraction and the *EC* levels of irrigation water and groundwater only, but also on the build-up of salts during dry/wet years and on the horizontal distance to the drains. Hence the depicted *EC* values at 2 m depth are just indicative. No water or salinity stress for the plants occurs and actual transpiration T_a equals potential transpiration T_p. Figure 8 shows the water balance components for each month.

Percolation occurs mainly during the monsoon period. Actual soil evaporation E_a is high during the hot months of June and July when the soil is partly covered by the crop and constitutes a relatively large portion of the water balance. During the monsoon period the groundwater table (not depicted here) reaches a maximum height of 1.75 m below soil surface. Hence, waterlogging is no problem.

In the following the results of the scenarios 2-5 will be compared with those of the reference situation.

Less irrigation water applied, i.e. 480 mm.yr^{-1}

Shallow drains may considerably contribute to capillary rise in dry periods. This will be enhanced when irrigation amounts are limited. In some areas the water duty is less than 600 mm yr^{-1}. Also due to spatial variability some parts of the field will receive less water than other parts. In scenario 2 the total amount of irrigation was reduced from 600 to 480 mm yr^{-1}. Potential transpiration however, still occurs, but the flux at 120 cm depth changes from 106 mm downward to 13 mm upward (Fig 6). Instead of a decrease of the salt content of the profile with 130 g m^{-2} yr^{-1}, the salt content increases with 86 g m^{-2} yr^{-1} (Table 1). Hence, in order to decrease the rate of salinization, either the irrigation amounts should be increased or the drainage depth should be lowered.

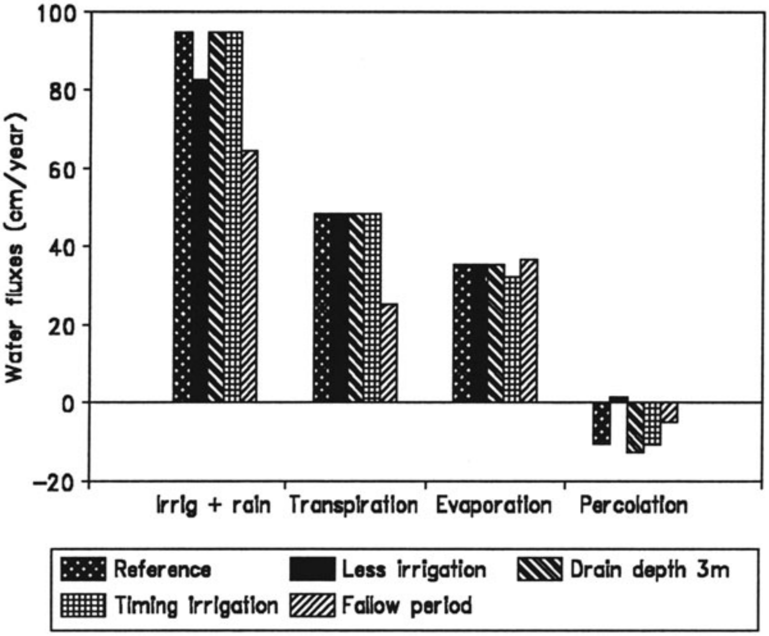

Figure 6. Yearly water fluxes for five scenarios

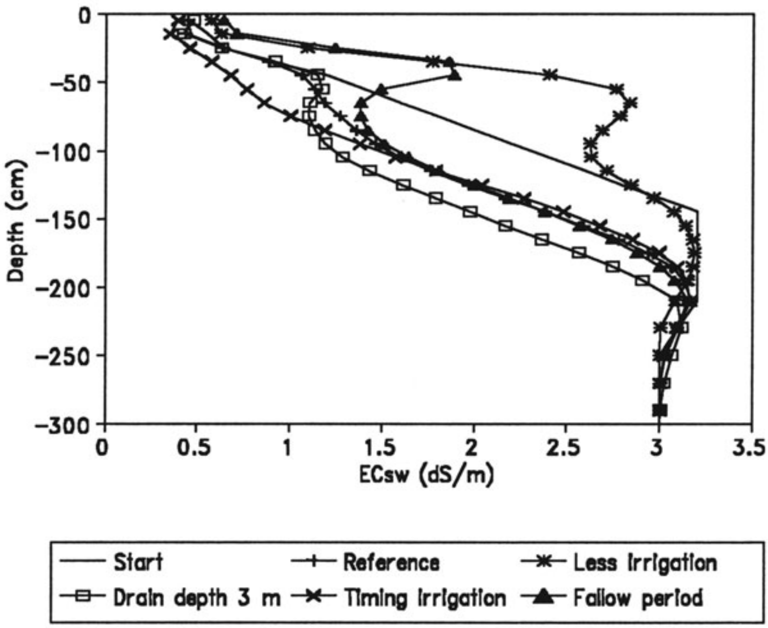

Figure 7. Salinity profiles on November 1, initially and after one year of simulation for five scenarios

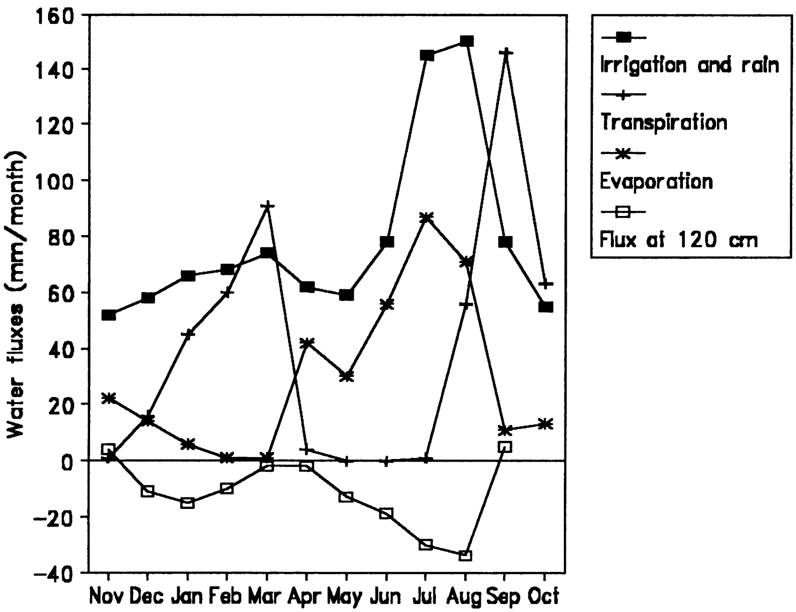

Figure 8. Monthly water fluxes in the reference case

Drain Depth at 3.0 m. Besides drain depth also the initial water content was changed in order to achieve zero change in water storage over the year. It appears that plants still transpire potentially. Also E_a is hardly affected; probably the soil transmitting properties are no extra restriction for E_a. As all the fluxes are almost identical to the reference case, also the salt balance is the same (Table 1). However, as Fig. 7 shows, the salinity concentrations decrease more rapidly than in the reference case. This is caused by the lower water content of the soil profile, making leaching more effective.

Different Timing of Irrigation. When the 12 irrigation gifts of 50 mm are evenly spread over the year, considerable water losses occur through soil evaporation, E_a. In scenario 4 therefore no irrigation water was applied during November, June and July and the gained amounts of irrigation were added to the irrigation applications of March, August and September. In this way E_a is reduced by about 10%. About 28 mm of water is stored in the profile. This will increase percolation during the following years. Because of the higher irrigation amounts in August and September, the salinity level EC_{sw} in the root zone at the beginning of November is lower as compared to the reference case.

Fallow Period. Water shortage urges the farmer to include fallow periods for part of the land. The amounts of water saved might be used to leach other fields or to apply one or more pre-irrigations before sowing the crop. However fallow periods might induce salinization when the groundwater table is at shallow level. In scenario 5 a pre-irrigation gift of 50 mm in October is used and regular gifts of 50 mm are applied in the period November - March (Rabi). In this way only 300 mm irrigation water is used. Fig. 6 shows that net percolation at 120 cm depth still occurs. Less salts enter the soil profile by irrigation, while slightly more salts are leached to the drains (Table 1), which is favourable for the salt balance. Fig. 7 shows that during the Kharif period the salinity level EC_{sw} increases at shallow depth due to the high soil evaporation. Near the soil surface the fresh monsoon rains temper the salinity levels.

Other Scenarios. Also a scenario was calculated with the seepage of unlined irrigation canals being increased three times. The results showed that, although the groundwater table is $\pm$ 40 cm higher than in the reference situation, the salinization of the profile is hardly affected. Due to the high transmissivity of the underlying aquifer the extra seepage water flows directly to the pipe drains. This is a favourable situation: spatial and temporal variations of the seepage flux do not affect the simulations to a large extent.

Another scenario was simulated taking twice as much rainfall (during the monsoon rainfall is highly variable). Under these conditions the water storage increases with 120 mm, while the rate of leaching increases also. In spite of the intensive rainfall during the monsoon, the drainage system keeps the groundwater table deeper than 80 cm below the soil surface, which means that there is no waterlogging problem.

3.3. VERTICAL DRAINAGE BY TUBE WELLS

3.3.1. *Introduction*

In stead of subsurface horizontal drain pipes, vertical tube wells might be used to lower the groundwater table. Other advantages of tubewells are the availability extra irrigation water, leaching of saline/sodic soils and more flexibility in timing and amount of irrigation. The Indus plain is underlain by deep deposits of unconsolidated sediments consisting of fine to medium sand. The high transmissivity of this aquifer favours the use of tubewells. Kuper and van Waiijen (1993) mention a survey among 200 farmers in 40 water courses in the Fordwah and Azim distributaries of the Punjab, which showed a decrease of salinity levels during the past 6-7 years. Kuper and van Waiijen attribute this decrease to the recent use of private tube wells. However, despite the advantages, also some serious concern exists of the long term effects of irrigation with tube well water: salts in the subsoil might be brought back in the root zone and hence sodification might increase.

3.3.2. *Reference Situation*

Field data were collected by IIMI in the period November 1991 until June 1992, including data of electrical conductivity EC_e, soil textures at different depth, cultivation pattern, amount of irrigation water and groundwater levels. The monsoon of 1991 was relatively dry. The groundwater level was more than 4 m deep. This implies that no capillary rise will occur and that as bottom boundary condition one may consider free drainage. IIMI data show that in this area for cotton in the Kharif season 1992 on the average 8 irrigations were applied, and for wheat in the Rabi season of 91/92 5-6 irrigations, i.e. totally about 1020 mm. Computer simulations were made for the period June 1991 - June 1992 for a silty loam soil.

Figure 9 shows the computed salinity profiles at various time, being expressed as the electrical conductivity of the extract, EC_e. The latter might be related to EC_{sw} by:

$$EC_{sw} = \frac{\theta_s}{\theta_a} EC_e \qquad [17]$$

where q_a and q_s are the actual and saturated water content respectively.

In the root zone the EC_e values increase during the development of cotton and wheat due to water extraction by roots. However, the relatively large amount of percolation water leaches the salt. In Fig. 9 this is resembled by downward moving salinity waves during the two seasons. The increasing and decreasing pattern of the EC_e values in the upper soil layers might explain why the EC_e field data in the upper 90 cm of the soil profile are scattered without a clear trend. Percolation occurs mainly during the initial stages of crop development.

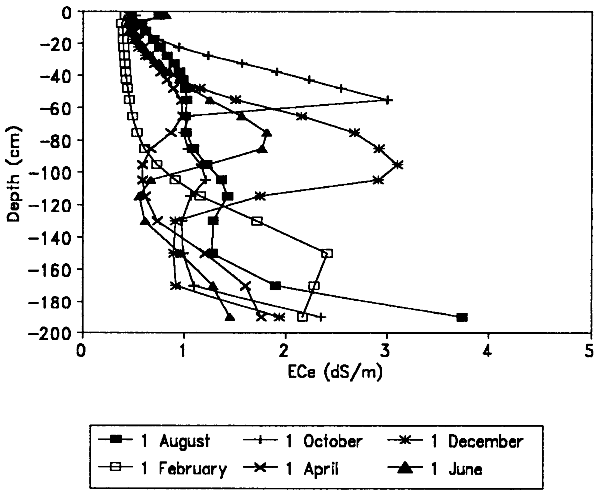

Figure 9. Salinity profiles during the year for the reference situation in the Hasilpur area

3.3.3. *Effects of Spatial Variability*

Spatial variability was analyzed for a sandy loam soil. We used the distribution of scaling factors as derived by Hopmans for a catchment in the Netherlands (Hopmans and Stricker, 1989). Table 2 shows the results for a more coarse sandy loam, with only 5 % of the soil horizon being more coarse.

TABLE 2. Cumulative water flows over the period June 1991 - June 1992 for a sandy loam soil in the Hasilpur area, showing the effect of spatial variability of the soil texture.

	Irrigation + rain (mm)	Actual transpiration (mm)	Actual evaporation (mm)	Flux at 120 cm depth (mm)
Reference	1081	877	113	- 90
Spatial Variability	1081	846	107	-128

As compared with the reference case the percolation increases considerably, while plant transpiration is reduced. In this specific case we used the mean infiltration amount of the entire field. In reality the infiltration amounts at the coarser parts of the field will be higher. This will increase the percolation at the coarser parts even more.

4. Conclusions

The movement of salts through the root zone is a highly dynamic process, which favours the use of physically based dynamic simulation models. For the case of irrigated soils in Pakistan, we applied a physically based model to assess the consequences of various scenarios. In our opinion the combination of dynamic simulation models with carefully selected field experiments is the only way to improve irrigation management and design of drainage systems.

Proper calibration and validation of simulation models is important. The increasing communication facilities might help us in this respect as they allow us to intensify the international exchange of data, computer programs and research experiences. Exchange of ideas on the proper design of field and laboratory experiments at the appropriate locations is also of utmost importance.

Inverse modeling techniques might alleviate the experimental effort to determine soil physical properties. The water balance is rather sensitive to these functions. Various studies appeared on inverse modeling with respect to unsaturated water flow (Carrera and Neuman 1986, Kool *et al.* 1987, Russo and Bresler 1991, Feddes *et al.* 1993, Hopmans *et al.* 1994). More effort is needed to prescribe which flow conditions and measurements are needed for well-posed inverse problems and to provide reliable confidence regions of the derived parameters.

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IRRIGATION SCHEDULING

DALE F. HEERMANN
Agricultural Engineer
Agricultural Research Service-USDA
AERC-Colorado State University
Fort Collins, CO 80523

1. Introduction

The sustainability of irrigated agriculture and the efficient use of water resources in agriculture will require improved management of the whole crop production system. Irrigation scheduling is an important management aspect of efficient crop production. The history and development of irrigation scheduling technology are summarized. Future research needs include the development of whole system management decision support systems to recommend irrigation schedules. Tools which are cost effective and minimize labor are needed to implement the irrigation scheduling decisions.

2. Development of Irrigation Scheduling Technology

Scheduling is defined as a timed plan for a procedure or project. Therefore, irrigation scheduling is a timed plan for one or more irrigation events. A key element of an irrigation event is the amount of water applied. Irrigation scheduling as a subject has been introduced in the last twenty five years. More emphasis had previously been devoted to the design of the physical system for improving the efficiency of water use to maintain sustainable systems.

2.1. HISTORICAL SCHEDULING OF IRRIGATION

In 1932, Israelsen authored one of the first irrigation texts used by many of the US universities for teaching irrigation science. The fourth edition of "Irrigation Principles an Practices" authored by Hansen, Israelsen and Stringham, (1979) has a chapter entitled "When to Irrigate--How Much Water to Apply". The title is a definition of irrigation scheduling. They list three major considerations that influence the timing of irrigation and how much water should be applied. They are: 1) water needs of the crop, 2) availability of water with which to irrigate, and 3) capacity of the root-zone to store water. The major factor in arriving at the desirable frequency and time of irrigation is the water needs of the crop. The major headings in this

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chapter are: 1) Limiting soil moisture conditions, 2) Appearance of crop, 3) Seasonal use of water by different crops, 4) available water supply, 5) Fall irrigation, 6) Winter irrigation, 7) Early spring irrigation, 8) Soil moisture removal by plant roots, 9) Effect of moisture content on rate of removal of soil moisture, 10) Influence of a restricting soil layer, 11) Stage of growth affects irrigation practice, 12) Depth of root zone, 13) Frequency of irrigation, and 14) Irrigation efficiencies. There is no discussion of forecasting irrigations or establishing an irrigation schedule.

Hansen *et al.* (1979) first discuss the estimation of seasonal crop water needs. Visual colors and temporary wilting can be used to detect the need for water. The selection of crops that match the available water supply is important in determining the appropriate schedule. Flexibility of the available water is an important consideration. Off season irrigation can store available water during times of high flow in anticipation of limited seasonal water. The rate of soil-water extraction by plant roots and soil profile conditions are important in determining the frequency of irrigation. The stage of growth and root development affect both the rate of water use and the water storage capacity to meet the demand. The frequency will change during the season as the root zone expands and crop water needs change.

The volume needed for an irrigation depends on soil water depletion, water availability and irrigation system efficiency. The amount of water used from the root zone without reducing crop production due to water stress determines the maximum irrigation depth. Applying the maximum depth minimizes the number of irrigations which is important when considering the irrigation labor requirements for many surface irrigation systems. For many surface irrigation systems larger depths can be applied more efficiently than smaller depths and thus reduce the gross seasonal irrigation volume required. Hansen *et al.* (1979) presented a general discussion of sprinkler irrigation systems with more focus on design and very little discussion on scheduling. Trickle irrigation was only briefly discussed with no mention of scheduling considerations.

2.2. IRRIGATION SCHEDULING PRACTICES

The irrigators scheduling flexibility is significantly controlled by the water source. Many early irrigation developments diverted water directly from a surface stream to the adjacent fields. The schedule was then dictated by the availability of water in the stream. The lower summer flows following high spring runoff limited the amount of water available for diversion. Storage provides a seasonal distribution of available water when direct stream diversions are not available. The crop water requirements for the early irrigation systems were empirically determined from irrigator experience. Irrigation companies and districts constructed diversion, delivery and storage reservoirs to improve water supply reliability and availability. Irrigation water was often delivered on a rotation basis among the members of the irrigation companies. The rotation could be on a fixed schedule or frequency. The delivery schedule was usually prepared in advance of the irrigation season.

Many irrigators prefer to receive water on demand. Demand systems can only operate if there is sufficient delivery capacity and water is available. Reservoirs were constructed to provide storage and deliver water on request. Sources of water that are under complete control by the irrigator such as with groundwater and some surface waters provide more flexibility in scheduling. The water can be delivered on demand as required by crop needs.

An irrigation is generally applied to refill the soil profile. The frequency is determined by the water holding capacity in the root zone and the peak water use. The efficiency of the irrigation system determines the volume of water that must be delivered for an irrigation. The number of irrigations and labor input are minimized when using the largest depths that are practical for surface systems. Hand move sprinkler irrigation systems are managed similarly to surface irrigation systems with respect to application depths. The labor to move the system from one set to another is minimized by using the largest irrigation depth to satisfy demand without water stress. The closed systems such as sprinkler and trickle irrigation systems that do not require labor for sets are often used to apply smaller depths at higher frequencies and still maintain high efficiencies.

The challenge for improving irrigation management is to upgrade the scheduling technology used by irrigators. Many irrigators, with automated moving irrigation systems, turn the system on and irrigate continuously during the growing season. The next sections will review the developments of tools and systems for improving the water management through irrigation scheduling.

2.3. TOOLS FOR IRRIGATION SCHEDULING

The shovel was and still is in many countries a tool used in diverting water from earthen ditches and spreading of water with surface irrigation systems. This same tool was often used to determine the soil water status. The irrigator visually evaluated color changes and the onset of wilting for scheduling an irrigation. Post-hole augers were used by irrigators to sample deeper depths to assess the soil water availability. With experience an irrigator can feel the soil samples and estimate the time to the next irrigation.

Soil probes and augers were developed and promoted by the Extension Service and other irrigation technologists for field sampling and measurement of the soil water status. Again irrigator experience was required to judge the amount of water needed to refill the profile. Power sampling tools were developed and used extensively by researchers to take samples and gravimetrically determine the water content.

2.3.1. *Soil Water Sensors*

Tensiometers (Richards 1949) were one of the first tools developed to measure the soil water potential for determining the timing of irrigation. Other tools were discussed at the American Society of Agricultural Engineers sponsored conference on Irrigation Scheduling for Water and Energy Conservation in the 80's in 1981. Cary (1981) presented an analysis of the accuracy of using gypsum blocks for scheduling irrigations. He concluded that they were of sufficient accuracy to provide the needed soil water information for scheduling irrigations. He recommended that three to four blocks connected in series should be used to instrument a site. These methods have been promoted by many Irrigation Extension specialists but have not been adopted by many irrigators.

Phene *et al.* (1981) discussed the use of a new soil moisture sensor for scheduling and monitoring irrigations. Similar efforts to promote this and develop new sensors has been conducted by many researchers and companies. Neutron probes have been used by both researchers and consultants to determine the soil water status. Time domain reflectometry (TDR), thermocouple psychrometry, and thermal dissipation measurements have all been studied and suggested for use in irrigation scheduling. The adoption of these methods by irrigators is limited.

2.3.2. *Plant Water Sensors*

Scholander *et al.* (1965) designed a pressure chamber for measuring leaf water potential. The complexity of this procedure has limited its application to researchers and has not generally been promoted for real time irrigation decisions. Stomatal resistance measurements and stem diameter measurements have also been suggested for determining the water status of plants and their need of additional water for optimum growth. The thermocouple psychrometer technique for measuring plant stress has generally been limited to studies of physiological processes and has not been suggested for field application of irrigation management. Fiscus *et al.* (1984) demonstrated the use of a stomal sensor to automatically control a trickle irrigation system for Zea mays. However, this has never been developed for commercial application.

2.3.3. *Remote Sensing*

A number of remote sensing devices have been proposed and studied for both soil and plant water status. Infrared thermometry has been studied extensively and has been commercialized for irrigation scheduling. Jackson *et al.* (1981) and Idso *et al.* (1981) developed a theoretical and empirical approach, respectively, for scheduling irrigations which defines a crop water stress index (CWSI) that is a function of foliage temperature compared to air temperature. Stegman and Soderlund (1992) demonstrated the use of infrared thermometers for scheduling spring wheat using the CWSI. Wanjura *et al.* (1992) automated a drip irrigation system based on measured canopy temperature for cotton. The adoption of this technology by commercial farmers is small.

Spectral measurements in the visible and near infrared region of the spectrum have been used primarily to estimate the amount and type of vegetation. Jackson and Pinter (1981) found that the plant stress can be observed with reflectance data. However, this gives a history of plant growth and not an indication of plant stress which is desired for irrigation scheduling. Neale *et al.* (1988) demonstrated the use of spectral measurements for estimating crop coefficients for use with water budget techniques for irrigation scheduling.

2.3.4. *Evaporation Measurement*

Evaporation pans are often used to measure the evaporation from a free water surface. Coefficients have been developed to relate the pan evaporation to crop evapotranspiration (ET). Altenhofen (1992) developed a modified atmometers that provide a measure of the evaporation potential which correlates with the Penman-Monteith 0.95 or greater. ET is also estimated from climatic data. Temperature has been the basis of a number of empirical estimates of ET. Many automated weather stations measure temperature, solar radiation, precipitation, wind movement, and vapor pressure for use in various equations for estimating ET. Several states in the USA such as California, Colorado and Nebraska operate weather station networks which make data available by telephone, computer, radio and commercial satellite systems. The ET equations will be discussed in later sections.

3. Maintaining Water Budgets

Crop water requirements were used primarily for the design of system capacity. Jensen (1969) introduced the use of computers for maintaining a water budget and scheduling irrigations. The first program used time sharing on a main frame computer for scheduling irrigations. He pioneered the use of computers in cooperation with an Irrigation District in Idaho and the Salt River Project in Arizona. In Idaho, post cards were sent to the farmer when an irrigation was recommended. Other researchers and consultants have since written many computer programs for scheduling irrigations with a water budget.

A number of water budget programs have roots to the first model written by Jensen. Models have been developed in many countries and several were presented at ICID workshops on 1990 and 1993. De Goes Calmon *et al.* (1992) Teixeira and Pereira (1992), and Mastrorilli *et al.* (1992) are water budget models presented at the first ICID workshop on crop water models. Teixeira *et al.* (1993) and Danuso (1993) illustrate the continuous interest developing water budget models for scheduling presented at the second ICID crop water use workshop. Kabat *et al.* (1992), Xevi and Feyen (1992), and Tyagi *et al.* (1993) include crop models to estimate production with the irrigation scheduling program. Verhaeghe and van der Krogt (1993) includes a hydraulic model to route the irrigation water through a canal system. Jacucci *et al.* (1993) developed a decision support model that uses GIS to model and characterize the non uniformity of soil and identify physical features of the fields. Giannnerini (1993) presented a demonstration and operational program scheduling irrigations in large areas of Italy. Personal communication with the author indicated similar experiences to that in the USA where many irrigators discontinue the program after three to five years when no loner subsidized. Scheduling services were demonstrated in many parts of the United States by the US Bureau of Reclamation, Soil Conservation Service and the Extension Service at many universities.

3.1. WATER BUDGET PARAMETERS

The water budget is maintained on a daily time scale for the current condition and in forecasting the next irrigation. The soil water balance equation is

$$D_i = D_{i-1} + ET_i - I_i - R_i - U_i \qquad [1]$$

where

D - soil water depletion,
ET - evapotranspiration,
R - precipitation,
I - irrigation depth,
U - upward flux (negative for deep percolation), and
i - index for day number.

The water balance equation can be updated with measured weather data to calculate $\mathbf{ET_r}$ (reference **ET**) and measured **R**. The reference is defined for either short grass or alfalfa with approximately 40 cm of top growth. The calculated reference $\mathbf{ET_r}$ is adjusted for actual **ET** with crop coefficients. The crop coefficient may need to be adjusted upward to account for increased evaporation from a wet soil surface. The effect of water stress can be included by a reducing the crop coefficient.Expected ET calculated from normal climatological data are used to forecast the next irrigation date. The soil water depletion is the amount of water that is needed to refill the root zone to field capacity. Water applied and infiltrated in excess to this will eventually result in deep percolation. Field experience has shown that some of the water in excess of field capacity may be used by the crop during the drainage process. Irrigation scheduling programs model the excess water in different ways. Adequate accounting of excess water is more important for frequent irrigations which is common with center pivot sprinkler and trickle irrigation systems, than for surface irrigation.

The $\mathbf{ET_r}$ can be calculated with a number of equations. Penman and Penman-Monteith equations are recommended where the temperature, solar radiation, wind run, and vapor pressure data are available. Jensen-Haise and Priestly Taylor are often used when vapor pressure or wind run is not available. Pan evaporation or atmometer data could also be used. Hatfield and Fuchs (1990) summarized evapotranspiration models that can be used to calculate $\mathbf{ET_r}$ for use in a water budget and to schedule irrigations. The accuracy of the **ET** term in the water budget should be of the same order of magnitude as the other variables in Equation 1. Experience has shown that the current technology allows prediction of **ET** as accurately as water is typically measured.

The precipitation, **R**, should be measured for each field. It must be adjusted for runoff if it occurs. The density of rain gages depends on the expected variability in rainfall and the field size. Water measurement is essential to determine the effective irrigation depth applied with an irrigation system. Experience has shown that many irrigators do not know the amount of water applied. In some surface irrigation scheduling applications it is assumed that the irrigation depth refills the soil profile with the excess leached below the root zone. The irrigation depth, **I**, must be evaluated for the irrigation system. The irrigation depth, **I** does not include runoff but is only that infiltrated. It is important to measure the flow and duration of water for each irrigation. The gross application volume is multiplied by the irrigation efficiency and divided by the area irrigated. The accuracy of this input is difficult to determine when considering the change in irrigation efficiency during the season.

3.2. SYSTEM UNIFORMITY EFFECTS

The uniformity of an irrigation must also be considered when determining the appropriate **I** for use in Equation 1. Surface irrigation systems are often assumed to irrigate a uniform and homogenous soil. The difference in uniformity of application is estimated based on intake opportunity time. The lower end of the field generally has a smaller application time and consequently depth. To avoid crop water stress, the irrigation time must be long enough to apply the required depth at the location infiltrating the minimum depth. The remainder of the field receives excess water and results in deep percolation. The depth, **I**, used in equation 1 equalled the depth applied at the lower end of the field and is chosen to attain maximum yield. However, this is not the best selection if the leaching of chemicals to the ground water is of concern. It may be best to apply a smaller depth which reduces the deep percolation and accept some water stress which may cause some crop yield reduction.

Sprinkler irrigation and trickle irrigation systems control the application to the soil and are generally designed to have no surface movement or translocation. An irrigation depth may be selected which does not refill the profile. The allowable depletion may be more than the depth applied for an irrigation. Figure 1 illustrates a typical relationship between the allowable depletion and a net irrigation depth. Smaller application depths require more frequent irrigations to maintain adequate soil moisture. The schedule can keep the soil profile full or leave a deficit that can store precipitation even right after an irrigation.

A decision must be made as to the appropriate **I** for sprinkler and trickle systems as a function of the distribution uniformity. If the mean depth is selected for **I** in the water budget, part of the field will be over-irrigated and another part will be under-irrigated. The low-quarter depth is often chosen with sprinkler irrigation to minimize the area under-irrigated. The low-quarter depth is defined as the mean depth on one-fourth the area receiving the least amount of water. This selected depth will lead to very little crop stress but will increase the leaching below the root zone. The amount of leaching increases with decreased uniformity.

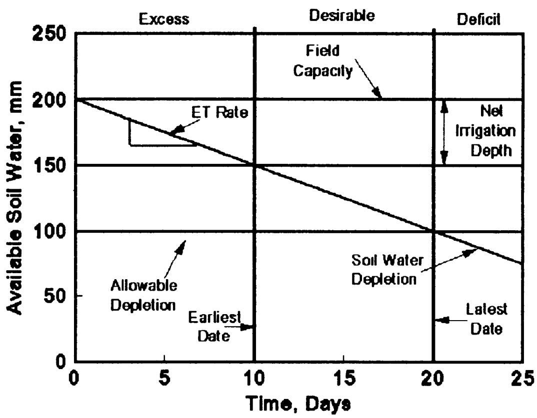

Figure 1. Illustration of the scheduling window for acceptable irrigation

Heermann and Duke (1992) analyzed the effect of the effective depth as a function of uniformity. Figure 2 illustrates the water stored, applied in excess and the deficit volume for a system with a coefficient of uniformity (**CU**) equal to 80%. The volume shown in Figure 2 is the dimensionless volume of water needed to meet the crop water requirements. To avoid crop water stress storage of a dimensionless volume of one is required.

The relative depth is the ratio of the volume of water applied to the volume of water needed. For example assume a 50 ha field has a seasonal requirement of 400 mm, the required volume in 200,000 m^3. If 500,000 m^3 were applied during the season, the dimensionless volume is 2.5. Thus, a relative depth of 0.4 (200,000/500,000) indicates that the volume applied is 2.5 times the volume required for crop water needs. One dimensionless volume would be stored in the soil profile and 1.5 dimensionless volumes would be excess. If the uniformity is perfect and every location in the field received the same amount of water a relative depth of one would satisfy the seasonal requirements. If the uniformity of a system is CU = 80%, at the midpoint (relative depth=1) 0.9 of the volume is stored for crop production and 0.1 of the volume is in excess to the water holding capacity. The distribution results with part of the area over-irrigated and part of the area under-irrigated. As the relative depth is increased above one, the excess increases but the volume of deficit decreases.

Historically, excess irrigation was applied if water was available to assure no water stress. However, with the concern of polluting the ground water, the leaching volume must be reduced to limit chemical movement into ground water. Systems must be designed to apply the water uniformly to minimize pollution and use limited water efficiently.

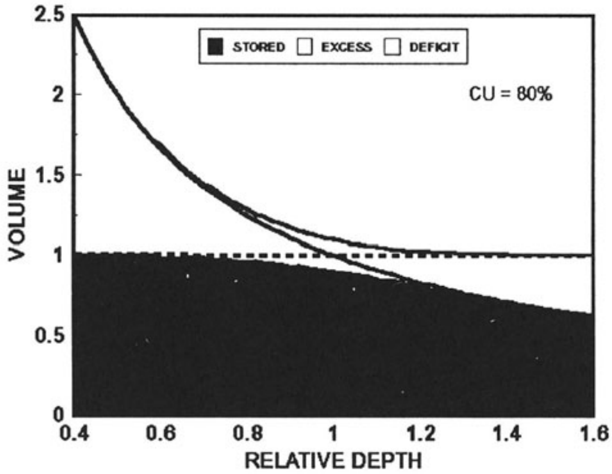

Figure 2. Distribution of volumes for management selected depth/mean (relative depth)

The amount contributed to deep percolation, **U**, is often assumed to be the amount in excess of field capacity which is equal to the magnitude of **D** when it becomes negative after a daily update of the water balance equation. The upward contribution from high water tables also can be an important input to the water balance. For this case the value of **U** is positive and decreases the depletion. This is one area that has not been included in most water budgets for irrigation scheduling. It can be very important for sustaining irrigation with limited water availability. Paulo *et al.* (1993) developed a model for including the upward flux from a water table.

4. Irrigation Scheduling with Water Budgets

4.1. SCHEDULING WITH WATER AVAILABLE ON DEMAND

The most successful applications of water budgets for irrigation scheduling are in areas where water is available on demand. Demand systems enable the irrigator to adjust for changes in water use more easily than with systems that deliver water on rotation or a fixed schedule. I had my first experience scheduling the irrigations for the Panhandle Experiment Station at Scottsbluff, Nebraska. The program was run on the main frame computer at Colorado State University and the recommended schedule mailed to the irrigation manager. Kincaid and Heermann (1974) adapted the irrigation scheduling program for a programmable calculator. The schedules could be run at the farm and provided real time output for the irrigator.

Heermann *et al.* (1976) developed the logic for scheduling center pivot irrigation systems. The program was tested on a number of farms in eastern Colorado. The results indicated that approximately 30% less irrigation water could be applied for corn production. Table 1 illustrates the output developed for center pivot systems in cooperation with the farmers. This format provided the recommendations with the desired detail for their use. The water budget was updated with climatic data collected on the farm. Table 1 (upper section) shows the water budget update for the previous week. Note that a water budget was maintained for the **start** and **stop** position of the center pivot. The **start** position is the first location to be irrigated when the system is started. It follows that the **stop** position then would be irrigated when the system had made a complete revolution which was 60 hours for this example.

Table 1 (middle section) is the forecast of the water budget. The forecast is based on the average reference ET for the area based on historical climatic data. The depletion at the start position is estimated with ET projections for the next 10 days. These projections were used to recommend the irrigations for the next week. Table 1 (lower section) forecasts the irrigations needed during the next week. Separate forecasted dates are given for several scenarios of precipitation. The recommended irrigation dates are given as a "no sooner date" and a "no later than date". The "no sooner date" is the date at which time the forecasted depletion at the **start** position is equal to or larger than the application depth to be applied with the center pivot system. The "no later than date" is the date at which the system must be started to irrigate the **stop** position before the depletion reaches a maximum management selected depletion. The earliest date and latest date are illustrated in Figure 1. The management allowed depletion (difference between field capacity and allowable depletion in Figure 1) is often selected as 50% of the available water which is assumed to prevent any significant crop water stress. The 50% allowable depletion is generally adequate for crops such as corn, sorghum and small grains. However, with potatoes and vegetable crops both yield and quality can be enhanced with lower levels of depletion. The allowable depletion can also change during stage of growth for many crops. Cotton and soybeans for example can have stress during the vegetative growth period and actually increase the marketable yield.

5. Adoption of Irrigation Scheduling

Government agencies and private consultants have promoted the adoption of irrigation scheduling in many of the irrigated areas in the USA. The life of the government demonstration projects have been approximately three to five years. Even private consultants that have built up sizeable businesses have had limited success in keeping the clients for more than five years. Irrigators learn from the consultants and after five years the recommendations are anticipated before they are delivered. It is unclear as to the level of improved management that will continue by irrigators when they no longer retain the services of consultants. Surveys of irrigators indicate that they are interested in obtaining the current **ET** data for their own scheduling of their irrigation systems, indicating they are maintaining water budgets without the complexity of running a computer program.

TABLE 1. Example irrigation scheduling output

OWNER - SMITH REGION - CROOK
DATE - JUL 29 1981
FIELD - C - 3 CROP - CORN

DEPLETION UPDATE

Day	START WATER mm	IRRIGATION AND RAINS mm	APPLICATION	DEPLETIONS START mm	DEPLETIONS STOP mm
THU JUL 23	6.0			6.0	10.2
FRI JUL 24	5.9	17.8	IRRIG	0.0	0.0
FRI JUL 24			EXCESS	5.9	5.7
SAT JUL 25	5.6	15.2	RAIN	0.0	0.0
SAT JUL 25			EXCESS	9.6	9.6
SUN JUL 26	1.2			1.2	0.0
SUN JUL 26			EXCESS		16.6
MON JUL 27	5.6			6.8	5.6
TUE JUL 28	5.0			11.8	10.6
WED JUL 29	7.6			19.5	18.3

TOTAL EXCESS APPLICATION THIS PERIOD = 15.6 mm

----------------FORECAST DEPLETION TABLE--------------------------

MAXIMUM USEFUL IRRIGATION AMOUNTS ARE SHOWN BELOW.
TIME TO IRRIGATE FIELD = 60 HOURS (2 1/2 DAYS)

DAY	START POSITION mm	STOP POSITION mm
THU JUL 30	26.0 -	24.8 -
FRI JUL 31	32.5 -	31.2 -
SAT AUG 1	38.9 -	37.7 -
SUN AUG 2	45.3 -	44.1 -
MON AUG 3	51.7 -	50.5 -
TUE AUG 4	58.1 -	56.9 -
WED AUG 5	64.4 -	63.2 -
THU AUG 6	70.7 -	69.5 -
FRI AUG 7	76.9 *	75.7 *
SAT AUG 8	83.0 *	81.8 *

AUG 8 ALLOWABLE DEPLETION = 73.2 mm
NOTE: '-' INDICATES DEPLETION > AVE APPLICATION DEPTH
NOTE: '*' INDICATES THE ALLOWABLE DEPLETION EXCEEDED

IF 20.3 mm ARE APPLIED IN 60 HOURS, STARTING TIMES ARE:

AMOUNT OF RAIN mm	NO SOONER THAN	NO LATER THAN
0.0	THU JUL 30	WED AUG 5
5.0	THU JUL 30	THU AUG 6
10.0	FRI JUL 31	FRI AUG 7
15.0	SAT AUG 1	SAT AUG 8
20.0	SUN AUG 2	SAT AUG 8

ASSUMING THE SYSTEM WAS STARTED ON THU JUL 30 THE NEXT STARTING TIMES ARE:

AMOUNT OF RAIN mm	NO SOONER THAN	NO LATER THAN
0.0	SUN AUG 2	SAT AUG 8
5.0	MON AUG 3	SUN AUG 9
10.0	MON AUG 3	MON AUG 10
15.0	TUE AUG 4	TUE AUG 11
20.0	WED AUG 5	WED AUG 12

The Extension Service in many states in the USA has promoted simple checkbook procedures for maintaining the water budget to schedule irrigations. Experience working with a number of farmers has indicated that they do not have the time or incentive to operate irrigation scheduling programs on personal computers. Heermann *et al.*(1984) demonstrated the use of an automated monitor and control system which automatically scheduled irrigations. The system had a weather station that upon request would telemeter the data to a PC via radio. The integrated system also monitored and controlled 15 center pivot irrigation systems. The monitoring provided the rainfall and irrigation time and amount for the water budget of each field. The irrigator could go to the computer each morning for an updated irrigation schedule for his systems. The integrated system was readily accepted and used by the irrigator. However, without the complete automation of data input, the irrigator did not have the time nor incentive to manually enter the data necessary to run the program. I know of a limited number of farmers that are using the USDA scheduling program.

The Soil Conservation Service is releasing version 3.0 of the SCS Scheduler program. They report that a number of farmers are using the program. Assistance is provided by government agencies to collect the weather data and provide technical assistance.

5.1. IRRIGATION UNDER LIMITED WATER SUPPLY

The water budget techniques are most appropriate for conditions where an adequate supply of water is available. Where water is limiting, the irrigator may need to select crops that can tolerate water stress. Selection of crops with water demands more nearly meeting the timing of available water is also a way of minimizing stress. Ground water that is pumped from declining aquifers should be conserved by selecting crops requiring less water and using practices that maximize the use of precipitation. It is often impossible to schedule irrigations to meet all crop needs under limited available water supplies.

6. Frontiers of Technology

6.1. RESEARCH TECHNOLOGY

Research technology is beyond what is classified as state-of-the-art technology. It is found in the scientific literature but is beyond that which has been transferred to the end user. Optimization theory is such a technology that provides the ability to improve on irrigation scheduling technology. However it is premature to transfer this technology prior to the full acceptance of the irrigation scheduling technology described previously.

6.2. IRRIGATION SCHEDULING OPTIMIZATION

Trava *et al.* (1977) demonstrated the use of linear programming to minimize the cost of labor for allocating water for plots on an experiment station. Pleban *et al.* (1984) expanded the capability of the optimization model by using dynamic programming to overcome the problem size limitations of the linear model. These optimization models have not been tested beyond the research environment. Buchleiter and Heermann (1990) developed an optimization model for minimizing pumping energy cost for a complex of center pivots systems with water pumped from a river into a network pipeline. The system included several pumping stations each with multiple pumps. The desired combination of center pivots to be operated was input and the individual pumps that were needed to satisfy the hydraulic demand of the irrigation system was output. The program has been demonstrated and is used by several farms for management of their systems.

7. Technology Transfer Problems

7.1. LIMITED ACCEPTANCE OF SCHEDULING TECHNOLOGY

We often ask why irrigators are not anxious to use the new technologies as they are developed. Probably the biggest deterrent is the low cost of water. The extra effort and cost of management inputs are not justified economically. Management may take efforts to reduce runoff since it is quite visible. The water that is lost to deep percolation is not obvious and currently there is little incentive to change. Environmental concerns and regulations may provide the incentive or need to adopt improved management. As water availability becomes more limited, greater efficiency and improved management will be needed to sustain irrigated crop production.

7.2. ELEMENTS FOR SUCCESSFUL ADOPTION

The successes of adopting improving irrigation scheduling are with irrigators that feel comfortable with water sensors, plant sensors and computer technology. Consultants that provide an integrated management service continue to be retained by the irrigator. The integrated management service includes water; salinity, fertility, herbicide, and insecticide recommendations. Energy management is another key element that should be included in an integrated management system. The whole system must be considered and not attempt to manage a single operation in isolation.

8. Future Research Opportunities

8.1. IRRIGATION MANAGEMENT INFORMATION SYSTEMS

The implementation of scheduling technology must identify the appropriate irrigation management information systems for the unique physical and social conditions. Demonstration projects, installation of weather stations and providing **ET** data were needed to educate the irrigators of water budget technology. Consulting services or government supplied technical services have been successful in introducing the new technology. Irrigators were then able to adapt the water budget technology in their own way. Some use complex computer programs with and without technical assistance while others use the data in simple check book procedures. Irrigation scheduling training and continued demonstration programs are needed for wide spread use of the technology. Continued irrigation scheduling and management information services for system operators and farmers must be defined and established. Irrigation scheduling technology may need to be subsidized by all who benefit from more efficient use of water. If the technology is not cost effective, the chance of success is limited. USA experience has shown that irrigators are busy and are not willing to commit significant time for complex scheduling technology.

8.2. IMPROVING WATER BUDGETS

Irrigation scheduling can be enhanced with improved water budgeting, use of improved field tools and sensors or integration of management systems. The key to the development of new irrigation scheduling technology is simplicity with low labor costs. Sustainable systems must adapt to limited water and protect the environment from degradation. Providing water on demand is desirable for efficient irrigation scheduling. A decision support system that assesses risk and provides recommendations that can be implemented within the constraints of the whole system is needed. Cultural practices and energy costs are important considerations in a sustainable system.

There are many social issues that are important to understand when developing the new scheduling technology for sustainable crop production. A better understanding of the irrigator's objectives and constraints is helpful. Complex equipment and computer programs are sometimes difficult to operate and maintain, so computer programs intended for irrigators must be extremely user friendly. The programs can be complex internally but should be easy to use with sufficient on-screen help. As an example, expert systems potentially could provide the user the ability to implement complex management systems with minimum training. The users do not need to become technical experts in all aspects to adopt the latest in improved technology. Recommendations should be customized to the particular irrigation systems and to the language and understanding of the operator.

Research opportunities for improved water budgeting include more accurate information of water input and **ET**. Success can best be achieved with simple and economical irrigation scheduling strategies. The modern trickle and sprinkler irrigation systems make it possible to very accurately control the irrigation depth, **I**. Improved **ET** estimates are important for increased accuracy in the water budget. High frequency irrigations require shorter time period estimates of **ET**. Simulation models offer solutions for estimating the translocation of water and chemicals including the contribution from high water tables. Where high water tables exist, a challenge is to develop the technology that can be used at the field level to estimate contributions from high water tables.

8.3. AUTOMATIC CONTROL OF IRRIGATION SYSTEMS

Another approach is to use sensors for direct control of irrigation systems. Many of the potential sensors were discussed in section 2.3. Remote sensing of field conditions can provide real time feedback into the integrated management system. New sensors for the remote sensing of water, fertility, weeds and other pests are needed for collection of management data. Quasi permanent sensors must be interfaced with remote acquisition of data in real time for feedback. Easy to use and accurate instruments for water measurement are an important input to improve scheduling. All sensors must be reliable and require minimum maintenance. Automatic sensors may actually replace the need for using a water budget in scheduling irrigations.

8.4. DECISION SUPPORT SYSTEMS

The development of decision support systems that integrates the management technology of the whole production system is a high priority. New computer technology will be an integral element in the system. GIS (geographical information systems) provide the opportunity to store data bases and combine different layers of data which can support prescription farming systems. Where water and chemicals are not needed uniformly over the entire field, irrigation systems need to deliver variable rate application. GPS (global positioning systems) technology will provide the technology to collect field data on the go and relate it to its spatial location for inclusion in the GIS data base. Yield maps can be generated with monitoring scales and GPS systems on harvesting equipment.

9. Summary

The future irrigation scheduling technology could use any combination of water budgets, tools, sensors and integrated management systems. The adoption of new technology will be a function of the economic incentives and social acceptance. The products and knowledge gained from research will provide various alternatives from which irrigators can choose to meet their own conditions.

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IRRIGATION SCHEDULING IN THE AGRONOMIC PRACTICE

A. YAZAR R. KANBER B. ÖZEKÝCÝ
Agricultural Engineering Department
Çukurova University
01330 Adana
Turkey

1. Introduction

Accurate irrigation scheduling, based on sound scientific principles, is becoming more important each day as water supplies become scarce, as the competition for agricultural water by urban areas and industry increases, and as the price of water continues to rise. The public's concern for quality of the groundwater supply is also growing rapidly. Indiscriminate use of pesticides and fertilizers with poor irrigation management has caused pollution problems in the groundwater as well as in soils. In order to minimize the effect of this contamination, agriculture must make more efficient use of its irrigation water by applying the proper amount of water on crops at the proper time in order to optimize crop productivity and protect the environment.

Irrigation scheduling is a critical management input to crop production in all, particularly in arid and semi-arid regions that practice irrigation. Thus, the purpose of optimum irrigation scheduling is to ensure an adequate supply of soil moisture to minimize plant water stress during critical growth stages (Wanjura *et al.* 1990).

Irrigation scheduling is commonly defined as determining when to irrigate and how much water to apply for optimal crop production. Irrigation scheduling allows an irrigator to supply water in a timely manner and in sufficient amounts to alleviate soil water shortages. Therefore, successful irrigation depends upon understanding and utilizing scheduling principles to develop a management plan, and then on efficiently implementing the plan (Cassel 1984; Martin *et al.* 1990; Heermann *et al.* 1990).

Irrigation planning and management involves decisions concerning the design of irrigation schemes and the consequent management of water at all levels of the scheme, covering the determination of water delivery schedules at the scheme level as well as for the individual farm, i.e. the decision on when, where and how much to irrigate. Irrigation scheduling decisions have to be based on the observation of some aspects of the soil-plant-atmosphere system that is the subject of the irrigation practice. Irrigation strategies may be based on long-term data, representing average conditions, or may be developed as the season progresses using real time information

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and short term predictions. In both cases, information about crop, soil, climate, irrigation system and water deliveries, and management objectives must be considered to tailor irrigation scheduling procedures to specific situation. Conflicts and trade-off must be anticipated in time to make adjustments (Abdulmumin *et al.* 1990, Hillel 1990, Heermann *et al.* 1990).

The farmer's management objective must be considered first when developing an irrigation scheduling strategy. Maximizing net return is a common objective, the others may be to: minimize irrigation cost, maximum yield, optimally distribute a limited water supply, minimize ground water pollution, or optimize production from a limited irrigation system capacity. The available water supply and irrigation costs are usually the most critical factors for determining the appropriate management objective. The supply of irrigation water and irrigation costs are often such that it is optimal to produce near maximum yields on the entire area that can be irrigated; a situation called the land limiting case. In this case the entire area should be irrigated and the optimal depth of irrigation is usually about the same as required to produce the maximum yield. Therefore, the appropriate irrigation strategy is to prevent crop water stress throughout the growing season. This has been the most common application of traditional irrigation scheduling (Hillel 1990, Martin *et al.* 1990).

For other situations where the supply of water is insufficient to achieve maximum yield on the entire field, the area irrigated or the seasonal application depth, or both, must be reduced. The manager must also determine how to distribute the limited water supply throughout the season. Scheduling deficit irrigations within a season is an uncertain process due to varying climate and price conditions. Traditional irrigation scheduling practices, which only consider the next couple of irrigations, are of little use for deficit irrigation. The management strategy of deficit irrigation is to optimize production per unit of applied water, rather than to maximize yield per unit of land. A major advantage of limited irrigation is to increase total farm yield and water use efficiency by reducing the area allocated to dryland cropping (Hillel 1982; Martin *et al.* 1990; English *et al.* 1990).

The major objective of this paper is to provide an overview of the irrigation scheduling methods used in agronomic practice and to provide a discussion on their advantages and shortcomings along with the research needs for an effective irrigation scheduling for sustainable agriculture.

2. Irrigation Scheduling Techniques

Irrigation can be scheduled using several methods varying from simple soil water monitoring to computer programs that predict crop growth and/or optimize an objective function. Using any of the methods has advantages and disadvantages. Scheduling involves both updating field information and forecasting the future irrigation date and amount. Irrigation is not complete without both processes. In principle, it is possible to schedule an irrigation program on the basis of monitoring the soil, the plant, and/or the microclimate (Hillel 1990; Heermann *et al.* 1990; Hsiao 1990; Martin *et al.* 1990). An overview of these methods are presented in the following paragraphs.

2.1. MONITORING METHODS

There are many factors that determine whether irrigation scheduling is optimum for yield or production efficiency. Assuming that plant water status is accurately indicated from soil and crop monitoring or climatologic techniques, additional information is needed that quantifies factors such as the critical level of plant water status for applying irrigation, the quantity of water to apply, the effect of plant growth stage on sensitivity to water stress, and the effect of irrigation application frequency on plant response (Wanjura *et al.*, 1990).

For the monitoring methods, the soil water content or matric potential is generally measured at several places in the field to decide when to irrigate. Methods based on plant measurements generally involve monitoring leaf water potential or canopy temperature. Soil water balance calculations require estimates of soil water storage capacity, rooting depth, allowable depletion and crop evapotranspiration to develop an irrigation schedule. Numerous water balance techniques, ranging from simple to very sophisticated, have been developed (Stegman *et al.* 1980, Campbell and Campbell 1982, Martin *et al.* 1990).

Some scheduling practices are based solely on monitoring either the crop or the soil. Irrigations are called for when the crop or soil reaches a critical level. Accurate monitoring will provide the manager information at the time of measurement. However, the data may not be available when the irrigation decision must be made. Also the measurements should be timed to ensure that the field can be irrigated before stress occurs. Thus, monitored data must be extrapolated into the future to predict an irrigation date. When past data are extrapolated forward, it is implicitly assumed that the future will resemble the past introduces random errors due to climate changes and systematic errors due to crop development. Weather forecasts should provide a guide of when to irrigate if the future evapotranspiration is higher, the same or lower than the current rate. Frequent measurements will still be necessary for dependable scheduling (Jensen *et al.* 1990, Martin *et al.* 1990).

Monitoring is essential for efficient irrigation management, but can be tedious and expensive, and inaccurate if personnel are inadequately trained and supervised. The monitoring schedule should be synchronized with irrigations. Monitoring too soon after an irrigation may not accurately reflect the soil or crop status. The monitoring frequency should also be altered relative to the irrigation frequency to determine if the intended schedule is actually being followed. The field should be periodically monitored just before an irrigation to provide better management information.

Several problems can occur with monitoring methods. One problem is that the critical value of the monitored quantity may change depending on the measurement of location, time of year, climate, etc. Monitoring crop conditions can be used to estimate irrigation timing, but does not provide any information on the depth of irrigation to apply. Another problem with crop monitoring is that the cycle time needed to irrigate the field is not included in the timing decision. Thus, stress may occur unless the crop response can also be forecasted (Heermann *et al.* 1990, Martin *et al.* 1990).

2.1.1. *Soil Moisture Monitoring*

Irrigation scheduling by soil moisture measurement is probably the oldest method in existence. The fact that irrigators still trust the "feel" and color of a shovelful of soil in preference to many other irrigation scheduling procedures indicates that scheduling by soil moisture is still the most popular of any of the methods. Newer methods for scheduling irrigation by monitoring crop or atmospheric factors have provided additional understanding of the system and guidance for irrigators lacking experience, but have not fully satisfied the need for an unambiguous criterion for scheduling irrigation (Campbell and Campbell 1982, Cassel 1984, Hillel 1990).

Soil moisture content can be determined using gravimetric sampling, tensiometers, resistance blocks, or a neutron moisture meter. A new method of monitoring soil moisture, called time domain reflectometry (TDR), may eventually replace the neutron meter, but at this stage only a few commercial models are available (Topp and Davies 1985). Irrigations are scheduled by allowing the crop to deplete the "available" soil water in the root zone to an established level for a particular crop and soil conditions. In the case of monitoring soil moisture, the amount of water application can be a prescribed quantity that can be uniformly applied by the irrigation system or calculated based on the amount required to fill the crop root zone or a lesser value (Bucks *et al.* 1990, Hillel 1990, Heermann *et al.* 1990).

In order to schedule irrigations using soil moisture measurements, one must select a site for monitoring soil moisture, choose a device for determining the soil water content or potential, set full and refill points for the particular soil being monitored, and establish some kind of record-keeping scheme which will show when irrigation is necessary and whether overirrigation has occurred. Once the monitoring site has been selected, one is ready to start monitoring soil water and scheduling irrigation.

Measurement of soil water should be made as frequently as possible. For high value crops which are irrigated frequently, daily measurements are advisable. For other crops and with lower frequency irrigation, measurements could be made less frequently. Measurements should be made at the depth of maximum root activity (Haise and Hagan 1967). A measurement below the root zone is also necessary to determine whether too much water is being applied and leaching is occurring. Irrigation should be scheduled so that the soil water content stays between the refill and full values (Martin *et al.* 1990).

For many scheduling programs, soil moisture monitoring is used for feedback to methods on computing the soil water balance. With such techniques, the accuracy of scheduling could be improved by combining several data sources rather than just re-initializing the soil water balance after monitoring. A simple approach is to combine results from the last several times that the field was monitored using a process called data filtering. English *et al.* (1981) showed how data filtering could be used to reduce the uncertainty of point estimates. When expanded to all data sources available at the time a scheduling decision is made, the dependability of the irrigation schedule could perhaps be improved. This technique might allow less frequent monitoring.

Soil sampling for direct determination of water content is simple but time consuming, and it can therefore be prohibitively expensive. Spatial variability of soil water content is a problem with this method since one cannot return to exactly the same location each time for measurement. An indication of the number of samples needed for a given precision can be calculated (Warrick and Nielsen 1980).

Tensiometers are frequently used to schedule irrigation. They have the advantage that they are relatively simple and inexpensive. Their primary disadvantage is that they are limited to potentials wetter than around 0.8 bar and require frequent servicing for proper function. Another disadvantage is that they measure potential only in the immediate vicinity of the unit, so that several tensiometers are needed to give a reliable spatial average (Campbell and Campbell 1982). Difficulties are experienced when the tensiometers are used in swelling clays, as the soil dries, the ceramic cup can break contact with the soil (Perrier and Salkini 1987).

Gypsum blocks are also simple and inexpensive. The main difficulty in using them is the uncertainty in calibration. One reads electrical resistance of the block and infers a water content or potential. The relationship between electrical resistance and water potential varies from block to block and may also vary from soil to soil and with time, due to the changes in the electrical conductivity of the soil solution. The electrical resistance-water content relationships varies from soil to soil because moisture characteristics differ among soils. It is therefore difficult to interpret readings quantitatively in terms of water stored or water lost. They can, however, be useful as a relative measure of crop water use. Several gypsum blocks are needed to adequately represent the water status of a measurement site since each gives only point measurement (Hillel 1982).

The neutron probe is widely used for soil moisture measurement, but its use for irrigation scheduling is relatively recent. It operates by producing fast neutrons from a radioactive source in a probe. The emitted neutrons are scattered and moderated by the water in the soil. The probe is inserted into the soil through an access tube, and the water content is directly related to the number of neutrons scattered back to a detector. The measurement is therefore an average for the soil volume surrounding the access tube, so a single measurement gives the same information that several measurements from tensiometers or gypsum blocks would give. The calibration for the probe is relatively constant from soil to soil, and once it is known, it should not change with time. Once a calibration curve for a particular field or a portion of a field has been developed, the equipment is easy to use and it allows direct measurement of soil water (Campbell and Campbell 1982, Hillel 1990).

The main advantage of the neutron meter is that, once the access tube is installed, the irrigator can determine, time and time again, the soil water content at exactly the same location in the field. A series of measurements at different depths in each access tube allows the operator to determine how much soil water remains in the root zone.

Whenever radioactive techniques are used, there is always potential danger that the operator might receive harmful radiation. However, instructions provided by the manufacturer coupled with the built-in safety features of the meter virtually eliminates any radiation hazard. Relatively high cost of the neutron meter is the primary disadvantage.

Gypsum blocks and tensiometers are simple to install in the field and easy to read. One problem with the gypsum blocks and tensiometers is that the readings given by the instruments measured soil water potential and not soil moisture content. However, these readings can be converted to percent available water or water depletion using various figures and equations. The neutron gauge is accurate in determining soil water content and is simple to use, but it is expensive and requires special training and handling because of radioactive source. The gypsum blocks, tensiometers, and neutron gauge require too many trips into the fields in order to determine irrigation needs (Blume *et al.* 1988).

One of the simplest irrigation scheduling techniques is the checkbook method. Checkbook or book-keeping schedules rely heavily on soil moisture monitoring since complex, but more accurate, evapotranspiration procedures are too tedious for hand calculations. Some checkbook methods oversimplify crop water use and accuracy may be sacrificed for scheduling convenience. Checkbook methods can require substantial amount of time to update information, monitor soil water and to extrapolate into the future (Cassel 1984).

All aspects of irrigation management, and especially irrigation scheduling, require an understanding of the soil water balance. The soil water balance can be used to predict the timing and amount of irrigation if all the terms of the water balance equation are known or can be estimated (Jensen *et al.* 1990, Martin *et al.* 1990). Using a soil water balance to manage irrigation involves estimating the amount of water in the crop root zone at any time. The integration of soil water availability and plant indicators with climatic effects into a water balance method allows effective irrigation scheduling which maximizes economic production (Perrier and Salkini 1987).

The disadvantage of irrigation scheduling based on soil moisture budgeting have been pointed out by Hodnett *et al.* (1990) that any difference between crop requirement and applications of water will cause progressive wetting or drying of the soil. This may have serious consequences for yield and water consumption. A more effective method of maintaining the soil moisture potential within the optimum limits of the potential, and adjust the irrigation accordingly.

2.1.2. *Monitoring the Plant*

Plant observation is probably the oldest method of irrigation scheduling. The crop will be irrigated, when individual plants start showing visible signs indicating that they are beginning to experience water stress. The signs range from color changes and leaf curling to wilting during the afternoon. The method is easy and requires no data gathering or computations, but it has the disadvantage, that by the time plants show symptoms of stress they have already suffered some growth and yield reduction. More modern methods involve monitoring certain plant physiological states, such as stomatal closure using porometers, leaf water potential using psychrometers, leaf water status using pressure bombs and canopy temperature using infrared radiation. Most of these plant parameters change noticeably only after the plants have already been stressed to a level high enough to reduce yield. For this reason these methods are not used on a routine basis for irrigation scheduling (Turner 1990).

To determine when to irrigate a crop, there is no substitute for interrogating the plant itself. Neither the soil water status nor the atmospheric demand accurately represents the plant water status, for the plant integrates its total environment-soil and atmosphere. Only by measuring appropriate plant parameters one can evaluate a plant's general health, and using that information, decide when to irrigate (Reginato and Howe, 1985).

A quantitative estimate of impending plant water stress is a critical prerequisite for the efficient scheduling of irrigations. Ideally, the warning of stress should come from the crops themselves, obviating the need for precise information regarding available soil water, root distribution and evaporative demand of the atmosphere. Unfortunately, many of the methods for quantifying physiological plant stress are both labor intensive and tedious. Furthermore, they are subject to considerable experimental and sampling error (Ritchie and Hinckley 1975).

Numerous methods have been proposed for monitoring the state of water in plants including techniques to estimate transpiration using excised leaves, determination of leaf tissue hydration with punched disks or individual leaves, observation of stomatal aperture, monitoring stem diameter, pressure-cell and psychrometric measurements of leaf water potential, and more (Hsiao 1990). There are several methods of measuring the water status of plants, however not all are suitable for irrigation scheduling (Turner 1990).

A method that has been widely tested is the monitoring of crop foliage temperature using an infrared thermometer either hand-held above the crop (ground-based measurements) or mounted on satellites, aircraft, or space platforms (remotely sensed methods). Particularly in arid/semiarid regions, the temperature difference between the leaves and the adjacent air increases as state of the plant water stress intensifies. This temperature difference is used to determine a crop water stress index that can be a practical tool for irrigation scheduling (Idso *et al.* 1981, Jackson *et al.* 1981, Jackson 1982). Plant methods typically indicate only when to irrigate, and soil moisture measurements or other estimation procedures must be used to determine how much water to apply (Bucks *et al.* 1990, Hillel 1990, Stockle and Dugas 1992).

The use of canopy temperature measurements for irrigation scheduling became practical with the development of inexpensive infrared thermometers (IRTs) able to measure emitted thermal radiation. Tanner (1963) and Monteith and Szeicz (1962) reported the use of IRTs for measuring canopy temperature (Tc) a few decades ago, but the commercial use of these sensors is relatively recent development (Hatfield 1990, Gardner and Shock 1989, Stockle and Dugas 1992).

Some shortcomings of the technique for irrigation scheduling include the difficulty in measuring Tc of row crops in early stage of development (Jackson *et al.* 1981, Howell *et al.* 1984, Field and James 1989, Stockle and Dugas 1992), and the fact that Tc-based irrigation scheduling allows determination of timing but not amounts (Nielsen 1990). In addition, canopy temperature measurements are highly sensitive to the view angle of the sensor and its relation to the solar zenith angle (Huband and Monteith 1986, Fuchs 1990). Therefore, standardization and consistency in the procedure are important. The suitability of empirical crop water stress index (CWSI) (Idso *et al.* 1981) for irrigation scheduling under variable weather conditions is open to questions, because of its inability to account for changes in temperature due to radiation and wind speed (Jackson *et al.* 1988). This appears to restrict the utility of the technique for irrigation scheduling, particularly under low vapor pressure deficit conditions. Reliable identification of irrigation needs using empirical crop water stress index under variable weather may only be possible when stress has developed and CWSI has started to increase rapidly. This may generate problems with crops susceptible to water stress and with low water holding capacity soils. The use of the theoretical approach (Jackson *et al.* 1981) for determining CWSI may improve the reliability of the technique (Stockle and Dugas 1992). However, additional weather information required (i.e., net radiation, wind speed), and the uncertainty in the estimation of canopy resistance (r_c) and r_c limits its practical application, as recognized by Jackson *et al.* (1988).

Crop growth models are useful tools for studying the effects of irrigation on plant growth and yield and for determining the optimal irrigation practices at a site. The value of the comprehensive crop growth models now seems to be tailoring irrigation strategies for specific sites, crops, and economic conditions. However, crop growth models for irrigation management must be validated for the areas where they are intended to be used (Jones and Ritchie 1990).

2.1.3. *Monitoring the Weather*

The idea here is to follow the meteorologically imposed evapotranspiration demand as it varies over the time and to set the quantity of irrigation accordingly (Hillel 1990). Evapotranspiration (Et) has been used by researchers and irrigators for years to estimate the water used by a crop based on weather data. Many computer programs have been developed from this work. Reference evapotranspiration (Etr) is determined by using weather information consisting of maximum and minimum daily temperatures, wet and dry bulb temperatures, daily solar radiation, and daily wind run.

Irrigation scheduling by weather monitoring relies on computing or measuring evapotranspiration to update the soil water balance and to forecast future water use to predict when the allowable depletion will be reached. Crop Et is generally computed using the reference crop Et (Etr or Eto) and a crop coefficient to relate actual crop water use to the reference crop. Various methods are available to estimate Etr for grass or alfalfa. In general, combination based equations are the most accurate, especially for computation of Et for short intervals common with scheduling. Combination equations require climatic data for air temperature, vapor pressure, wind velocity, and solar radiation. These data are not available for some locations; therefore, simplified methods to compute Etr have been used to predict crop water use (Heermann 1988; Martin *et al.* 1990, Jensen *et al.* 1990).

The accuracy and variability of computed Et must be considered when updating the soil water balance. All Et models require local calibration for accurate estimation (Doorenbos and Pruitt 1977); thus, frequent soil moisture monitoring is recommended to ensure that the predicted soil water balance is accurate.

Pan evaporation (Ep) is a common measurements made at many weather stations, and is one method used to measure evaporative demand. Water evaporation from a pan differs from that associated with crop use. Water transport, solar radiation, reflectance and specific site conditions surrounding the pan differ from those associated with a crop. Water use from a complete crop cover may be approximately 75 to 85 percent of the amount of water evaporated out of a pan. When crops do not completely cover the soil surface, actual crop water use will be less than 75 percent of pan evaporation (Clark 1993).

The ease of use, simplicity of data, and low cost have prompted the wide adaptation of the evaporation pan. Pan evaporation data is so commonly used today that is one of the more routine methods. Thom *et al.* (1981) made a comprehensive analysis between the Penman model and pan evaporation and concluded that pan evaporation was adequately described by a combination equation with an adjustment in the psychrometric constant and wind function for the pan. Their adjustments provides a meteorological quantification of the adjustments given in tables provided by Doorenbos and Pruitt (1977).

Despite the major differences in the energy balance and aerodynamics of pans and vegetation surfaces, evaporation pans continue to be used widely over the world. This is due to the fact that they model potential evaporation (Ep) from a free water surface in a visible way and that this Kp.Ep can be related to a reference evapotranspiration (grass or alfalfa) by means of an empirical coefficient. The class A pan is the official network instrument in the USA as well as in many other countries. Howell *et al.* (1983) found that screen covering over a Class A evaporation pan reduced evaporation by 10% in a semi-arid environment. When installed in "standard" grass weather station environments with adequate maintenance, evaporation pans can reliably estimate Et, especially if the pan evaporation is averaged for time periods over 7 days or if automated measurements are made hourly. The importance of advective effects on the empirical coefficients Kp is discussed by Doorenbos and Pruitt (1977), and

Bosman (1987). The correlation between Eto or Etr and Ep can be improved by taking hourly measurements or by increasing the periods of time used for correlating these measurements.

Technology has also been introduced into the evaporation pan with several techniques proposed to automate the readings in order to make it compatible with data acquisition systems. Phene and Campbell (1975), and Phene *et al.* (1991) described techniques for automating a Class A evaporation pan.

The disadvantage of cumulative pan evaporation method of irrigation scheduling is that additions to soil moisture storage from precipitation or shallow groundwater table are not considered. It is therefore most appropriate at locations, where these additions do not occur during the irrigation season (Thom *et al.* 1981, Phene *et al.* 1991).

An irrigation scheduling program using meteorological data to calculate water use and maintain a soil water budget was developed by Jensen (1969), Jensen *et al.* (1970) and Jensen *et al.* (1971) for the US. Department of Agriculture. Many variations of the water balance approach have been developed and are in use, including a simplified check-book method developed by Lundstrom *et al.* (1981). Computerized scheduling is helpful when fields are irrigated frequently or when a large number of fields require scheduling; however, computer based scheduling models are not being widely used in developed or developing countries. The successful use of a soil water budget for irrigation scheduling requires accurate and timely field data that includes the amount of rainfall and irrigation water applied, meteorological data to estimate Et, soil water status, and crop water conditions (Martin *et al.* 1990).

Based on this earlier work, the USDA Soil Conservation Service in cooperation with Michigan State University has also developed a computerized irrigation scheduling program utilizing real time (daily) local weather station data to calculate a daily soil water balance for the crop root zone (Shayya and Bralts 1988). The soil water content is checked periodically with a neutron meter to assure accuracy. The purpose of the program is to make easy-to-use scientific irrigation scheduling that uses the latest technology available to individual farmers. The program can be used to optimize crop yield objectives and to protect ground water quality.

Computerized scheduling has allowed the inclusion of complex calculations into the decision making process that would be impossible using checkbook or other hand calculation methods. For example, computerized irrigation scheduling allows the use of the most advance methods of predicting Et. It allows for consideration of several locations within the field to generate specific schedules for individual fields to satisfy various objectives.

Development of microcomputers has lead to an array of computerized methods to schedule irrigations. For instance, CROPWAT developed by FAO; IRSIS developed by Katholieke Universiteit Leuven (Belgium); WATERPERFECT developed by Williams and Pogue (1992); SCS-SCHEDULER developed by SCS of the USA. Most models access several databases for soil characteristics, crop information, meteorological data and other information about the water supply, the irrigation system and economic data. The rapid development of automated weather station network has contributed to the use of computerized scheduling methods. The ability to access and process meteorological data from a regional station has greatly streamlined data entry and analysis which has been one of the major limitations to computerized scheduling.

Computerized scheduling has improved water use estimates and refined irrigation predictions. In some cases, crop growth models have been used directly in scheduling irrigations. This has provided more information to the irrigator for weighing economic considerations when making management decisions. These types of scheduling models also require more crop and soil data. These values may be difficult for the producers to obtain and can restrict the use of crop simulation models for scheduling.

Real time irrigation (RTI) is broadly defined as application of irrigation water based on the actual measured value of soil moisture at the plant root level. If the soil moisture is less than the optimum value, water is applied, if greater then irrigation is ceased. The application and duration of irrigation is hereby based on the true value of moisture at the time. As climate and plant demand vary, so too will the frequency and duration of irrigation. Under real time scheduling the climate conditions of the moment are taken into account i.e. Eto and effective rainfall are measured during the growing season, on the condition that daily weather data are available. This requires the processing of climatological data day-by-day and will only be used under technological well advanced conditions and skilled farmer, which can monitor the soil moisture on a daily base and which can effect irrigation at irregular intervals (Abdulmumin *et al.* 1990).

For any scheduling program it is necessary to measure rainfall amounts locally at the field being scheduled. The spatial variability of rainfall is too high for single measurements to be used over large areas. If possible, several rain gauges should be located around the farm to better quantify rainfall variability.

Soil moisture, rainfall, irrigation depth, Et and other components of the soil water balance are not known with absolute certainty. Spatial variability of soil water properties also increases the uncertainty of the soil water content estimate. Selecting representative sites and periodic monitoring of the same site would reduce the uncertainty. The confidence interval of the irrigation depth depends on the uniformity of the irrigation system and the accuracy of the depth control. If the uniformity is poor the confidence interval will be large and the date for the next irrigation will be uncertain. Additional uncertainty can occur because of inaccuracies in the system used to control the depth of application. If the actual mean depth deviates from the planned mean depth, the soil water depletion confidence interval will be even wider. Variation in depth might result from operator error in setting the controls, from variation within the controller, in system flow rate, etc. If the soil water depletion confidence interval is narrow, scheduling can be used for longer periods. If the confidence interval is wide, soil water content should be measured to update the soil water balance (Jensen and Wright 1978, Martin *et al.* 1990).

No single method of irrigation scheduling can provide an accurate assessment of the needs and balances of the soil-plant-water system. Therefore, the most effective scheduling approach does not rely on one method, but on a combination of two or more. Field information of evaporative demand and soil and plant water status should be used in conjunction with a water budget approach to determine if scheduled applications are sufficient; eliminating unintentional leaching of plant nutrients (Cassel 1984, Perrier and Salkini 1987, Martin *et al.* 1990).

3. Research Needs

Accurate irrigation scheduling, based on scientific principles, is becoming more important as water supply becomes scarce, and as the competition for water increases. Therefore, research is needed to reduce water and energy use and to increase profitability through better scheduling Development of deficit irrigation scheduling methods are required.. Future irrigation scheduling techniques must consider crop responses to water stress, evapotranspiration rates under stressed conditions, management objectives, system constraints and public policies. Better methods of forecasting climatic conditions are critically needed

In order to minimize the effect of groundwater contamination, agriculture must make more efficient use of its irrigation water by applying proper amount of water at the proper time in order to optimize crop productivity and protect the environment (Bucks *et al.* 1990). The maintenance and enhancement of water quality is a challenge facing irrigators that will cause factors other than crop evapotranspiration to become increasingly important in scheduling.

Presently a minimum amount of information is used in scheduling. We cannot continue to ignore nonuniformity of the irrigation system and the field. In the future, information from a variety of sensors will be available for management decisions. Methods are needed to analyze different types of data. For instance, soil water monitoring, canopy temperature measurement, and soil water balance computations can all be performed simultaneously and nearly continuously.

Relationships between climatic variables, soil water and plant for arid and semi-arid areas that are being developed for irrigation should be developed. Effects of water deficit on the quality of economic yield component should be evaluated for various crops grown under different cultural management systems.

The challenge to scientists is to develop new knowledge such that they will be able to distinguish not only the general status of plants, but also to be able to separate the kinds of stress a plant is experiencing (due to water deficiency or excess, salinity, elemental toxicity, disease, insects, and nutrition) (Phene *et al.* 1990, Hsiao 1990).

The most important challenge is to develop scheduling methods that readily transfer to and are adopted by the irrigators. Without economic and social incentives for scientific scheduling, adoption of technical, real-time scheduling procedures has been very slow or inextensive (Shearer and Vocomil 1981). On the other hand, producers would like something simple and inexpensive but accurate to determine when and how much to irrigate. It is, therefore, not surprising that despite all technological developments in this area most irrigators do not use real-time scheduling procedures. Management systems need to be developed that producers will use.

Research priorities need to be developed for each country in response to the major water problems. These priorities should be agreed upon by researchers and action agencies. There will always be a gap between research and actual irrigation practices. However, sound education and technical assistance program can reduce this gap in irrigation water use and management (Bucks *et al.* 1990).

New and improved irrigation systems that integrate knowledge of management of water, fertigation, and chemigation need to be developed.

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PART IV

ON-FARM IRRIGATION AND DRAINAGE SYSTEMS

SURFACE IRRIGATION SYSTEMS

LUIS SANTOS PEREIRA
Professor, Agricultural Engineering
Instituto Superior de Agronomia, Universidade Técnica de Lisboa
Tapada da Ajuda
1399 Lisboa, Portugal

1. Introduction

Sustainability of irrigated agriculture concerns the adoption of technological and management techniques which achieve production objectives, conserve land and water resources, and are environmentally non-degrading, technically appropriate, economically viable and socially acceptable (adaptated from FAO 1990). This perspective dictated the analysis that follows.

The practice of surface irrigation is millenaire and covers near to 95% of the world irrigated area. The sustainability of irrigated agriculture depends therefore on improvements and innovations in surface irrigation methods, their appropriateness for the different systems and their adoption in the field practice.

A review of recent developments in surface irrigation is presented under the perspective of sustainability of irrigated agriculture. The review starts from the theoretical aspects and the corresponding modeling approaches, with particular attention to infiltration. In fact, a large part of the research reported in literature, may be the most important, concerns these aspects. Thus, the analysis covers the theoretical aspects and is oriented to evidence how the different approaches contribute to solve main problems in design and management.

After this theoretical analysis, recent developments and tools for design and evaluation of surface irrigation systems are reviewed. It is evidenced the need for expanding the use of modern tools as well as for field evaluation. Progress for modernizing surface irrigation systems with increased performances and labour and energy savings are analysed. This can definitely contribute to the competitiveness of surface irrigation systems in relation to the pressurized ones. Nevertheless, several bottlenecks delay or impede the transferability of innovations to the irrigation practice, including extension, education and training.

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2. Basic Equations and Modelling

2.1. FLOW EQUATIONS

The process of surface irrigation combines the hydraulics of surface flow in the furrows or over the irrigated land with the infiltration of water into the soil profile. Unsteady and spatially varied flow occur. The discharge at a given section in the irrigated field changes with time and depends upon the soil infiltration behaviour. Performances necessarily depend upon the combination of surface flow and soil intake characteristics.

The equations describing the hydraulics of surface irrigation are the continuity and the momentum equations (Walker and Skogerboe 1987). In general, the continuity equation, expressing the conservation of mass, can be written:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + I = 0 \qquad [1]$$

where:

t	time
Q	discharge
x	distance along the flow direction
A	wetted area
I	infiltration rate per unit length.

The momentum equation, expressing the dynamic equilibrium of the flow process, is:

$$\frac{v}{g}\frac{\partial v}{\partial x} + \frac{v}{gA}\frac{\partial Q}{\partial x} + \frac{v}{gA}\frac{\partial A}{\partial t} + \frac{1}{g}\frac{\partial v}{\partial t} = \left(S_o - S_f - \frac{\partial y}{\partial x}\right) \qquad [2]$$

where:

g	gravitational acceleration
S_o	land (or furrow) slope
S_f	friction loss per unit length or friction slope
v	flow velocity
y	flow depth.

These equations are first-order non linear partial differential equations without a known closed-form solution. Appropriate conversion or approximations of these equations are therefore required.

2.2. INFILTRATION EQUATIONS

Several infiltration equations are utilized in surface irrigation studies. Most common are the empirical Kostiakov equation:

$$I = a\,k\,\tau^{a-1} \qquad [3]$$

and the modified Kostiakov equation:

$$I = a\,k\,\tau^{a-1} + f_o \qquad [4]$$

where:

I	infiltration rate
a	empirical (exponent) parameter
k	empirical parameter
f_o	empirical stabilized infiltration rate
τ	time of opportunity for infiltration.

The second is the most commonly utilized in furrow infiltration and in graded borders. When preferential flow occurs, case of swelling/cracking soils, the integrated form of equation (4) requires a fourth parameter.
Another empirical equation utilised is the Horton equation:

$$I = f_o + (I_i - f_o)\,e^{-\beta\tau} \qquad [5]$$

where:

β	empirical parameter
I_i	initial infiltration rate
f_o	final infiltration rate.

The semi-empirical equation of Philip has the preference of some authors given the physical meaning of its parameters:

$$I = 0.5\,S\,\tau^{-0.5} + A_s \qquad [6]$$

where:

S	soil sorptivity
A_s	soil transmissibility.

One physically based equation utilised by several authors is the Green-Ampt equation

$$I = K\left[1 + \frac{(\theta_s - \theta_i)\,h'}{Z}\right] \qquad [7]$$

where:

K	saturated hydraulic conductivity
θs	saturated soil moisture content
θi	initial soil moisture content
h'	suction at the wetting front
Z	cumulative depth of infiltration.

However, the equation that better describes the flow in porous media is the Richards equation. For border or basin irrigation, the one-dimensional form is appropriate while for furrow irrigation the two-dimensional form would be required:

$$C(h)\,\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\,\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] \qquad [8]$$

with:

$$C\,(h) = \partial\,\theta\,/\,\partial\,h \qquad [9]$$

and where:

θ	soil moisture
$h\,(\theta)$	pressure head
$K\,(h)$	hydraulic conductivity
t	time
x	horizontal distance
z	vertical distance from soil surface (positive downwards).

From analysing the equations above, it becomes evident that the use of the deterministic equation (8) in the continuity equation (1) not only increases the complexity of the solution of the flow equations but also requires much more detailed and accurate information on the hydraulic soil properties. However, the information provided by the corresponding model shall be more detailed and, hopefully, shall better represent the dynamics of the irrigation process.

2.3. MODELING

A great deal of research has been performed (and still is being done) for numerical solutions for both continuity and momentum equations (1 and 2) and infiltration equations (3 to 8).

The current approaches are: (a) the method of characteristics, converting these equations into ordinary differential ones, (b) the Eulerian integration, based on the concept of a deforming control volume made of individual deforming cells, (c) the zero-inertia approach, assuming that the inertial and acceleration terms in the momentum equation are negligible in most cases of surface irrigation, (d) the kinematic-wave approach, which assumes that a unique relation exists describing the $Q = f\,(y)$ relation. A consolidated review and description of those solutions, adopting the Kostiakov equation (3 or 4) for the infiltration process, are given by Walker and Skogerboe (1987).

These solutions are incorporated in the computer program SIRMOD (ISED 1989). Because it adopts user friendly menus and simplified input requirements, this software package has a world-wide distribution. Another powerful software package is SRFR (Strelkoff 1993 a, b) which results from a long term research with the zero-inertia model and applications to graded and level borders (Strelkoff 1985). SRFR solves the non linear algebraic equations adopting time-space cells with variable time and space steps and also includes a full hydrodynamic model. The Kostiakov equation $Z = k\tau^a + b\tau + c$ is adopted. The model adapts particularly well to describe level furrows and basins as well as the impacts of geometry of furrows on irrigation performances (Sousa *et al.* 1995 b). With the same origin (Strelkoff 1985), a menu-driven program for design of level basins has been developed: BASIN (Clemmens *et al.*, 1993). These user friendly programs correspond to the present trends in software development, which make easily available to users complete design tools.

The computer models mentioned above can be used to most of cases in irrigation practice, for both design and evaluation. Nevertheless, there are many other developments in modeling recently reported in literature, mainly relative to improvements in zero-inertia and kinematic wave models.

The kinematic wave, because of conceptual limitations, only applies to sloping fields. Studies by Turbak and Morel-Seytoux (1988 a, b) showed its applicability and that model performance was primely influenced by the time variability of infiltration rate. An analytical solution was adopted.

Recent improvements in zero-inertia models concern the adoption of analytical solutions for solving the governing flow equations. This decreases the prediction error but increases the computation requirements. Model ZIMBA, by Schmitz and Seus (1990), illustrates this approach for graded and level borders.

However, numerical methods are accurate enough. Researchers try new numerical schemes, namely for solving the complete hydrodynamic models for borders (Sakkas and Bellos 1991), as well as simplified assumptions in the initial values for solving the computational grid (Wallender and Rayej 1990). For this last case, the shooting method, advantage could exist to estimate infiltration (inverse problem) when advance time and flow depth are observed at given space steps. Another approach consists in the simplification of computation procedures using the zero-inertia for advance and the kinematic wave for the later phases (Singh *et al.* 1992).

Some authors developed improved solutions for the volume balance equation:

$$Q_o\, t = V_y\,(t) + V_z\,(t) \qquad [10]$$

where:

- Q_o discharge at upstream end
- t time after irrigation started
- V_y volume of water on the soil surface
- V_z volume of water infiltrated.

This describes the mass conservation and related models are particularly useful to study the advance phase and consequently to derive the infiltration characteristics from observations of advance. In general, one-dimensional infiltration equations are utilized, mainly equations (3) and (4).

Results from volume balance models are sensitive to the shape coefficients describing the surface water stream and the infiltration pattern.

Recent developments include the adoption of the volume balance for the entire irrigation cycle including recession in borders (Yu and Singh 1989, Singh and Yu 1989 a, b) and furrows (Yu and Singh 1990). Other approaches include the routing models developed for hydrology and applied to furrows (Singh and He 1988, Wilson and Elliot 1988) or borders (Singh *et al.* 1988). The modified Kostiakov equation (4) is commonly utilized for computing the infiltrated volumes. In a model for furrows, Levien and Souza (1987) adopted the simple Kostiakov equation (3).

The volume balance model is appropriate for real time (automatic) control because under these circumstances the advance phase is the most critical (Latimer and Reddel 1990). Simplified models proposed by Mailhol (1992) and Eisenhauer *et al.* (1993) also use the volume balance approach to optimize irrigation parameters - flow rate and time for cutoff - when a target irrigation depth is known. These models could be used for real time furrow irrigation management in combination with irrigation scheduling programs.

3. Infiltration

3.1. INFILTRATION MODELS

Several infiltration models could be utilized to describe water penetration and redistribution under surface irrigation.

The infiltration at each section of a furrow is typically two-dimensional. A two-dimension (2-D) equation, like equation (8) should be applied according to theory. To overcome this problem, existing models approach a solution to the problem by considering a variation in the wetted perimeter as well as empirical shape factors for the infiltrated water. The study by Samani *et al.* (1985) clearly shows how the wetted perimeter influences the infiltration rate. In a different experiment, Izadi and Wallender (1985) showed also a significant relationship between cumulative infiltration and wetted perimeters of furrows.

The modeling approach by Turbak and Morel-Seytoux (1988 a, b) showed that infiltration rate should not be considered as constant. The performance of the model significantly improved when, using the Horton equation (6), the infiltration rate varies as a function of time, of the infiltration parameters and of the flow depth. These results for borders agree with previous ones for furrows.

2-D infiltration under furrow irrigation has been modeled by several authors. Samani *et al.* (1985) report on the accuracy of their 2-D model but also recognize the limitations deriving from the very high computer time required for the simulations. Tabuada *et al.* (1994 a) adopted the 2-D Richards equation (8) and validated the model BIDISUL with field data. However, the computation time requirements are also a problem. Vogel and Hopmans (1992) also adopted the 2-D Richards equation (8). The model shows to be highly sensitive to soil hydraulic characteristics h (θ) and k (h). As for BIDISUL (Tabuada *et al.*, 1994 a), the model describes well the effect of furrow water level variations which accounts for the changing wetted perimeter (Hopmans and Vogel 1991).

Combining the surface flow equations with the 2-D infiltration leads to a complete simulation model with large capabilities for evaluating the irrigation performances (Tabuada *et al.* 1994 b). Nevertheless, despite using variable time steps for surface and subsurface flows and for the different irrigation phases, the computation time required is very high. Yen and Riggins (1991) also discuss this aspect. This fact limits the usefulness of those models for research objectives because requirements for repeated simulation when a model is utilized for design or evaluation purposes are not compatible with high computation time. Also, the need for calibrated h(θ) and k (h) curves highly limits the use of 2-D infiltration models in the irrigation practice.

Rawls *et al.* (1990) adopted an alternative approach combining the 1-D Green-Ampt infiltration and the Philip's 2-D geometry factor for transforming 1-D flow rates into 2-D flow geometries for infiltration from furrows. This approach requires less computation time, but the gain in information is not evident when compared with common simulation models using 1-D infiltration.

Consequently, the infiltration models commonly utilized for simulation of furrow irrigation are the Kostiakov models (3 and 4) and, in some cases, the Philip and the Horton equations (5 and 6).

The problems discussed above for furrows do not apply for borders and basins because infiltration is one-dimensional. Therefore the selection of empirical or semi-empirical models has less impacts since the model would be capable of considering the variations in infiltration rate (Turbak and Morel-Seytoux 1988 b). An example for using the Green-Ampt equation (7) for borders is given by Rendón *et al.* (1991).

3.2. SPATIAL VARIABILITY AND PREFERENTIAL FLOW

The difficulties in accurately representing the infiltration process in surface irrigation models increase when one intends to take into consideration the spatial variability of soil intake characteristics or the preferential flow in swelling and craking soils.

Good identification and methodological approaches to spatial variability along a furrow transect are presented by Bautista and Wallender (1985). Trout and Mackey (1988) analysed the furrow-to-furrow variability, thus looking to the field instead of the furrow scale. Variability is not only influenced by soil characteristics but also by variability in inflow discharges. As discussed previously, infiltration depends upon wetted perimeters and water depth. An interesting discussion on factors influencing cumulative infiltration in furrows is given by Strelkoff and Souza (1984).

Several studies considered the variability of wetted perimeters and of the parameters in the infiltration equation. As discussed by Schwankl and Wallender (1988) and Tarboton and Wallender (1989), main impacts from different modeling approaches result in different estimates of uniformity of application. In a very recent paper (Childs *et al.* 1993), it was shown that variability of soil characteristics can play a more important role in the variability of infiltrated water than parameters influencing the intake opportunity time.

Main consequences for management are analysed by Trout (1990). Variability induces tailwater runoff and deep percolation in some areas of the field while other areas are underirrigated. The irrigator tends to apply water for a longer time to overcome yield decrease in the area receiving less water. Solutions require improved irrigation scheduling, increased uniformity of inflow rates, appropriate soil management to reduce infiltration differences, and tailwater reuse facilities.

Preferential flow in swelling and cracking soils highly increase infiltration variability. This effect can not be easily considered in models since water intake through cracks does not correspond to processes described by infiltration models. However, Evans *et al.* (1990) studied the influence of this quick intake process on the parameters of Kostiakov equation in furrow irrigation. Accurate observation of infiltration in cracking soils are also difficult (Mitchell and van Genuchten, 1993). Appropriate management of surface irrigation in this type of soils requires appropriate field measurements. An interesting example for borders is given by Waller and Wallender (1991) who estimated the best time of cutoff from the advance.

3.3. INFILTRATION FROM ADVANCE

Several field techniques can be utilized to estimate the parameters of infiltration equations. However, results vary from one method to the other (Holzapfel *et al.* 1988) and may be quite different from those obtained from observing an irrigation. Field measurements prior to an irrigation are time-consuming, labor intensive, expensive and less appropriate in case of real time observations (Walker and Busman 1990).

The application of the volume balance method (equation 10) to the advance phase led to the development of a well proved methodology for estimating infiltration parameters, the so-called two-point method, appropriate for graded furrows (Elliot *et al.* 1983 a, b) and graded borders. Several authors report on successful use of this method, and its usefulness to design and evaluation is well established (Walker and Skogerboe 1987). Lately, a one point method has been proposed (Sheppard *et al.* 1993).

As other field methodologies, the two-point method presents some weakness since it is based on an unique power relation between advance length and advance time, but other relation than the power law could be assumed for the advance. An interesting evaluation of methodologies is provided by Rendón *et al.* (1986), who analysed several advance laws and infiltration equations, pointing out the unappropriateness for the case of the Philip equation (5), and by Smerdon *et al.* (1988) and Blair and Smerdon (1988), who also analysed different advance laws and several forms of the Kostiakov equation (3, 4), with favorable conclusions.

Modifications in the volume-balance method for estimating the infiltration parameters are proposed by DeTar (1989).

The estimation of the infiltration parameters, together with the roughness coefficient for surface flow, can also be done through the inverse surface irrigation problem. This is discussed by Katopodes (1990). Recently, the Kostiakov parameters (3) and the roughness coefficient are considered spatially distributed parameters (Katopodes *et al.* 1990) which opens new perspectives to the consideration of spatial variability. However, more research is needed along this line.

Peculiar interest have the methodologies aiming at real-time control of irrigation. The examples offered by Mailhol (1992) and Eisenhauer *et al.* (1993) concern simplified approaches, easy to implement. The simplex method, coupling the kinematic wave with an optimization technique (Walker and Busman 1990) looks to provide accuracy in estimating the infiltration parameters but requires improved calculation capabilities.

4. Design and Evaluation

4.1. DESIGN

The large advances in simulation modeling and progress in user friendly software for personal computers provide appropriate tools for design of surface irrigation systems. However, the use of these tools is, worldwide, far behind potentialities. Reasons for that situation may be: a) insufficient knowledge of the complex process involved, impeding the appropriate utilization of available software; b) lack of required input data, namely the infiltration parameters; c) difficulties in conceptually combining design and operation parameters, namely concerning performance of on-farm systems; d) need for using information from evaluation as design criteria or as input parameters, like those of infiltration; e) influences of land leveling and soil management on actual field performances; f) performances largely depending upon the irrigator decisions rather than on the equipment selection.

The derivation of infiltration from advance, discussed above, plays an essential role for design, either using the simulation models earlier presented, either adopting optimization techniques.

The simulation models are utilized for design in an iteractive process of searching the best geometric and inflow parameters that provide maximal values for the performance parameters DU, distribution uniformity, and e_a, application efficiency, assuming that the irrigation depth (D) is applied with opportunity regarding the crop demand.

The distribution uniformity DU can be functionally described by:

$$DU = f_1 (q_{in}, L, n, S_o, I_c, F_a, t_{co}) \qquad [11]$$

where:

q_{in}	inflow rate to the furrow (or per unit width of the border or basin)
L	length of the furrow (or border, or basin)
n	roughness coefficient
S_o	longitudinal slope of the field
I_c	intake characteristics of the soil
F_a	furrow (or border, or basin) cross-sectional characteristics

t_{co} time of cutoff.

If a similar function would be adopted for the application efficiency e_a, the same factors should be considered together with the soil moisture deficit (SMD) when irrigation starts:

$$e_a = f_2\,(q_{in}, L, n, S_o, I_c, F_a, t_{co}, SMD) \qquad [12]$$

However, the same variables do not play exactly the same role in the functional relations above.

The input parameters concern the infiltration characteristics I_c, as discussed earlier, the longitudinal and cross sectional characteristics of the furrows, borders or basins, the irrigation depth D, the roughness coefficient n. The slope S_o can be fixed previously or adjusted together with the other output parameters q_{in} and t_{co} (the time duration of the irrigation phases is also an output). Input parameters can vary from one simulation to another until the best solution is obtained. The capabilities of simulation provide for alternative best solutions concerning different processes of water application and different irrigation management conditions.

The prediction capabilities of simulation models increase when input parameters are close to reality. However, in many cases farmers are not able to control the inflow rates. Under these circumstances, design requires the consideration of uncertainity of parameters, like proposed by Wattenburger and Clyma (1989).
The optimization models include an objective function of type:

$$\max P = f\,(C, Y, D, e_a, DU) \qquad [13]$$

indicating that maximal profit or benefit P depends upon production costs (C), crop yield (Y), irrigation depths (D), application efficiency (e_a) and distribution uniformity (DU). The models may have different complexity depending on the definition of costs and benefits, the functional relations of yield adopted, the calculation procedures for the irrigation depths, and the dependency of system performances upon characteristics of the on-farm systems [equations 11 and 12]. Models apply either linear (Holzapfel *et al.* 1986) or non linear (Reddy and Martinez 1992) programming techniques; can be oriented for a given type of irrigation, like furrows (Popova 1991) or borders (El Hakim *et al.* 1993), or be of more wide application (Holzapfel and Mariño 1987, Sritharan *et al.* 1988).

Despite the interest of these optimization models, because they may be explored as decision support tools, they have limited use. Difficulties may arise from the requirements on good quality data for characterizing the costs and benefits components, and from the complexity of factors intervening in the relationships between geometric, hydraulic and performance parameters. These relationships require simplified but conceptually acceptable assumptions which are not easy to build.

The simulation models may also be utilized as decision support tools. In particular, the combination of furrow, border or basin simulation models with optimization models could constitute appropriate decision support systems capable of selecting the irrigation method and of optimizing their design and operation parameters under specified performance and economic objectives. Developments along these lines are expected.

4.2. EVALUATION

Field evaluation of irrigation systems, well consolidated by Merriam and Keller (1978), play a fundamental role in improving surface irrigation. On the one hand, they provide the information required for design, for model validation and updating, for optimization programming; on the other hand, they offer the most appropriate conditions for advising irrigators and to develop real time irrigation management decisions. As an example, the case for level basins is analysed by Dedrick *et al.* (1990).

As earlier discussed, the field evaluation gives the information on advance capable for deriving the parameters of infiltration (Walker and Skogerboe 1987, Smerdon *et al.* 1988), or the data on advance and recession which enables the inverse solution of the irrigation problem (Walker and Busman 1990, Katopodes *et al.* 1990). The resulting output data can be utilized for design using simulation models or, when complementary data is available, for making use of optimization models (Holzapfel and Mariño 1987).

Good examples of utilization of local information relating inflow rates, time of advance and infiltration to support irrigators advice is given by Skogerboe and Shafique (1990). The case reported by Chambouleyron *et al.* (1993) exemplifies the usefulness of evaluation to help farmers decide the time of cutoff for basin irrigation according to the inflow rate.

Field evaluation is the only procedure to actually measure irrigation performances (equations 11 and 12). The combined evaluation of distribution uniformities, yield variability and water use efficiency (Bucks and Hunsacker 1987, Hunsacker and Bucks 1987) highlights the importance of that performance indicator. The importance of evaluating distribution uniformities for appropriate definition of irrigation depths was recently discussed by Heermann and Duke (1992). For the case of application efficiency, the study by Lynne *et al* (1987) gives a good interpretation of its relation to yield and to economic efficiency. Losada *et al* (1990) suggest a method to consider the application efficiency when defining the irrigation depth. An update overview is provided by Wolters (1992).

5. Modern Surface Irrigation Systems and Automation

Modernisation of surface irrigation can be seen under different perspectives. Herein this is restricted to the methods and equipments that allow a better control of inflow rates and time of cutoff.

Referring to equations (11) and (12), it can be seen that during operation of any surface irrigation system, the factors L and S_o are fixed from design considerations; roughness n changes during the irrigation season and is influenced by soil management; cross sectional characteristics F_a also modify along the season and, mainly for furrows, depend on soil management practices; infiltration characteristics I_c, despite influenced by soil management, primarily depend upon soil characteristics. Thus, for given field conditions, the irrigator decisions to improve DU and e_a can be expressed by simplified functional relations:

$$DU = f(q_{in}, t_{co}) \quad [14]$$

and:

$$e_a = f(q_{in}, t_{co}, SMD) \quad [15]$$

Since the irrigator would be able to select the best opportunity for irrigating, thus the best SMD, he may achieve the best performances when inflow rate and time of cutoff are controlled.

Considering surface irrigation, modernization includes the adoption of headland facilities that allow appropriate inflow control and, hopefully, automation. Simple devices include gated pipes and layflat tubing (Smith *et al.* 1986, Renault 1988, Humpherys 1990 b, Pereira *et al.* 1994); underground tubing (Tsai *et al.* 1990); automated valves and gates (Humpherys 1987 1990 a and b, Renault 1988, Duke *et al.* 1990, Rieul 1992, Pereira *et al.* 1994) and riser valves (Yoder *et al.* 1990, Merriam 1992). Trash screens may be of fundamental importance for success of automated systems (Bondurant and Kemper 1985, Smith *et al.* 1991).

Among automation approaches two have been particularly successful: cablegation and surge flow. Cablegation (Kemper *et al.* 1987) applies a gradually decreasing inflow rate. Considering that infiltration rate also decrease with time, this can be a great advantage to decrease both deep percolation and tailwater runoff losses. To implement the appropriate combinations q_{in} - t_{co} field observations are required. Specific evaluation techniques have been made available (Trout and Kincaid 1993).

Surge flow developed after it was verified that surging leads to decreased advance times when compared with continuous water application, particularly when soil conditions favour high infiltration rates. Since surging requires control of inflow rates and time of application, surge flow became also an automation method (SCS 1986, Stringham 1988, Humpherys 1989 a and b).

Numerous studies are reported on surge flow. The mechanisms by which furrow infiltration rates reduce are relatively well known (Kemper *et al.* 1988, Trout 1991). Appropriate field evaluation methods are available (Mc Cornick *et al.* 1988). Results of field evaluation always report improved advance time and infiltration rates (Humpherys 1989 a), at least for the first irrigation (Gonçalves *et al.* 1993). Consequently, results from field evaluation also point out decreased deep percolation and tailwater runoff (Izuno and Podmore 1986, Musick *et al.* 1987, Coupal and Wilson 1990). Surge flow also applies to graded borders (Ismail *et al.* 1985).

In the case of basins, the adoption of laser levelling led to a modernized irrigation process, the level basins (Dedrick *et al.* 1982, Dedrick 1990). Several automation devices have been developed including automated operation of canal gates (Dedrick 1989, Sousa and Pereira 1989, Humpherys 1990 a). Similar solutions are available for borders (Malano and Patto 1992). Automated water distribution for level basins through underground pipes adopting the cablegation systems is also available (Trout and Kincaid 1989, Pereira *et al.* 1994).

Fertigation with surface irrigation (Pereira *et al.* 1994) can be adopted since irrigation techniques provide for appropriate distribution uniformity. However, adequate equipment for fertilizer application is not yet available in the market. Research is required.

It can be concluded that existing progress and research trends definitely contribute to make surface irrigation systems competitive with the pressurized ones since application efficiencies, distribution uniformities, labour requirements, automation and fertigation capabilities become similar for irrigation of field crops. Nevertheless, management still is more complex.

6. Management

6.1. LAND LEVELLING AND SOIL MANAGEMENT

Performances of infiltration systems highly depend on accuracy of land levelling (equations 11 and 12) particularly for level basins and level furrows.

Recent progress concern both computation procedures (Scalopi and Willardson 1986, Kumar and Chauhan 1987, Clough 1993) and land grading equipments, namely the use of laser control. Practicability of accurate land levelling is quite high but difficulties in achieving the highest levelling performances are real (Pereira *et al.* 1994).

It has been observed (Sousa *et al.* 1993) that the relative distribution uniformity (DU/DUmax) in level furrow irrigation depends upon the standard deviation S_d of elevations of the graded land and on the inflow rate applied (i.e., on the advance time)

$$DU/DUmax = f(S_d, q_{in}) \qquad [16]$$

Since the amount of infiltrated water can be computed from DU and a yield function relating the relative yield (Y/Ymax) with the relative amount of irrigation water applied (W/Wmax) has been established

$$Y/Ymax = f(W/Wmax) \qquad [17]$$

Therefore, it could be derived a function

$$Y/Ymax = f(S_d) \qquad [18]$$

which represents the impact of levelling accuracy on yields. The simulated yield increase due to accurate land levelling is given in Table 1.

From the results in Table 1 it is evident the need for appropriate maintenance and precision of land levelling (scenario 1). Poor land grading implies lower yields and higher maintenance costs.

To help maintaining appropriate land levelling without requiring yearly finishing operations, it is possible that furrows be opened with laser control (Pereira *et al.* 1994). Compaction of furrows after opening leads to improved furrow hydraulic conditions (Fornstrom *et al.* 1985, Trout *et al.* 1990, Allen and Schneider 1992) and furrow performance depends on the furrow form (Sousa *et al.* 1995 b). Therefore, the design of furrow opener systems should consider both the capabilities for furrow forming and firming, namely using compaction wheels which, in case of laser control, are also appropriate to regulate the depth of the furrowing tool (Pereira *et al.* 1994).

To avoid destruction of levelling by conventional tillage practices, it is required to develop alternative reduced tillage systems, including no-till. However, modifying soil tillage practices has impacts on infiltration. Sealing may have negative or positive impacts according to soil type (Trout 1991, Eisenhauer *et al.* 1992). Reduced till may have contradictory effects. Yonts *et al.* (1991), report both a slight decrease and a large increase of advance time when rotary till or minimum till are compared with plow.

TABLE 1. Yield increase for grain corn for three scenarios of laser controlled levelling

Variable	Scenario 1		Scenario 2		Scenario 3	
	Before finishing	After finishing	Before finishing	After finishing	Before finishing	After finishing
S_d (cm)	2.5	1.2	3.0	1.7	4.0	1.7
DU/DUmax	0.63	0.85	0.56	0.75	0.43	0.75
Y/Ymax	0.82	0.94	0.77	0.90	0.68	0.90
Yield increase (kg/ha)		1320		1430		2420
Water saving (mm)		164		180		396
B: C ratio*		3.9		1.4		1.15

*Benefit/Cost ratio includes also nitrates savings assuming fertigation

Contradictory results have also been obtained when application efficiencies were compared.

Soil management under surface irrigation seems to be an area of concern for future research, not only in relation to infiltration and, consequently, with system performance, but also erosion control (Kemper *et al.* 1985, Trout *et al.* 1990).

6.2. IRRIGATION MANAGEMENT

The analysis in precedent subheadings makes evident the complexity of management and, in particular, that performance depend primarily from soil infiltration conditions.

The control of q_{in} and t_{co} when mechanized or automation equipments are utilized, and the adoption of appropriate land levelling and soil management may do not be sufficient because soil intake characteristics vary. To help irrigation management, two main issues can be considered: feed-back control in automated systems and surface irrigation scheduling.

Feed-back control, also referred as real time control or self-adaptative control, concerns the application of a simulation model in real time. Observations made during the irrigation constitute the input variables of the model and allow generation of the information required for the irrigator to achieve the irrigation with the best performance. An example of adjusting the inflow hydrograph from advance observations is provided by Katopodes and Tang (1990). The utilization of telemetry and the derivation of infiltration parameters from the advance is reported by Latimer and Redell (1990). Feedback control in level basins, also with telemetry, was reported by Clemmens (1990), while Humphries and Trout (1990) presented a system of sensors and controllers for cablegation.

Surface irrigation scheduling concerns also the simple derivation of surface irrigation system parameters from observations of advance. The models by Mailhol (1992) and Eisenhauer *et al.* (1993) are developed in this perspective. Models can then combine with irrigation scheduling programmes in such a way that opportunity of irrigation, irrigation depths and irrigation performances can be optimized. When automated systems are utilized with computerized controllers, it is expected these would include such simplified software models that enable the irrigator to adjust the irrigation parameters, essentially q_{in} and t_{co}.

7. Conclusions and Recommendations

Under the perspective of sustainability of irrigated agriculture, some main conclusions and recommendations can be taken from the analysis made before.

a) Modelling: present progress is very important and a great diversity of modelling approaches became available. New advances are necessary regarding the use of simulation models, including user friendly interfaces in model software, extended education of irrigation engineers and managers on the modelled processs and data gathering to provide better use of models, and the developments of decision support systems oriented to design and management of surface irrigation systems.

b) Infiltration: there is evidence that dynamics of soil infiltration plays a major role in the performance of surface irrigation. Studies also have shown that procedures for modelling infiltration and its variability are not limiting factors for taking into consideration the infiltration characteristics for design purposes. The most critical aspects seem to be related to the appropriate characterization of infiltration parameters to be utilized in both design and management models. More effort can be placed in deriving infiltration parameters from field observations of advance and, for non graded fields of the whole irrigation phases.

c) Design: progress in describing surface and sub-surface flow enable the use of simulation models for design purposes, particularly adopting user friendly software and decision support tools. Combining simulation and optimization models should lead to improved design. However, the extended education of irrigation design engineers is very important, as well as to make extensive use of information from field evaluation, and field management concerns.

d) Evaluation: despite field evaluation methodologies are consolidated, the practice is far behind the needs in most countries. However, improvements are required concerning traditional surface irrigation techniques. New aspects must also be included in evaluation, like aspects related to labour and energy consumption, economic parameters, social constraints for adoption of improved techniques and environmental impacts.

e) The need for regional programmes of field evaluation should be underlined aiming at providing the necessary information for design, assessing the needs and opportunities for changes, calibrating and validating operational models, and testing modern technologies and equipments.

f) Modernization and automation: progress in these areas are enormous but their implementation in the field practice is limited. Equipment for pressurized irrigation is readily available but equipment for surface irrigation is not yet on the market and require extended and demanding support for management. Appropriate relations between manufacturers, dealers, researchers and extension officers need to be developed and associated to extensive evaluation of equipment use. However, modern tools and management techniques are able to provide for irrigation performances similar to those of pressurized systems, with positive impacts on yields, water and energy savings, erosion control, limited agro-chemicals impacts, namely through fertigation.

g) Land levelling: the importance of accurate levelling to obtain high irrigation performances is demonstrated. However, precise land grading techniques are only easy available for large farms and appropriate solutions have to be found for improvements required by the small farmers. The maintenance of levelling still is a problem requiring solutions relative to tillage techniques which should not be detrimental to levelling, or that combine furrowing with levelling with laser control, as well as relative to the economic decision for re-touch levelling.

h) Soil management: research demonstrated impacts of soil compaction, sealing and mulching on infiltration and advance in furrows. Results from alternative tillage systems are contradictory and depend upon the soil type and the crops. Field research is required not only for the control of infiltration but also regarding impacts on yields, maintenance of levelling, control of erosion, transport of agro-chemicals, and economic consequences.

i) Irrigation management: future issues point out self-adjustment techniques for real-time optimization of performances of surface irrigation. For large farms feed-back control may be utilized. However, for most surface irrigated areas world-wide these fully automated techniques do not apply. Improvements may be expected, and are desirable, regarding flexibility in delivery schedules, development of surface irrigation scheduling programmes, adoption of simplified models using data collected during irrigation, and installation of more developed software in automation irrigation controllers.

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SPRINKLER IRRIGATION SYSTEMS

JAMES R. GILLEY, P.E.
Professor and Head
Agricultural Engineering Department
Texas A&M University
College Station, TX 77843-2117
United States of America

1. Introduction

Irrigated agriculture has played a critical role in helping humankind satisfy its basic needs and increase its standard of living. It produces over one third of the world's food supplies, enhances productive capacity in otherwise harsh environments, and reduces the need for a horizontal expansion of rain-fed agriculture onto marginal lands. However, these benefits often come at an environmental price and the impacts of intensive irrigation are not exclusively positive. Contrary to those who would negatively influence decision makers and financing agencies, environmentally sound irrigation projects are feasible.

First and foremost, irrigated agriculture must be geared, in harmony with nature, to increased production to overcome the drudgery, poverty and harrowing shortages of food which are major obstacles to sustainable development. Sustainable irrigated agriculture, while integrating the needs of future generations, should not divert attention from the threats to the present generations, whose needs are far from being met.

2. Concepts of Sustainability

Interest in sustainable development has arisen as a consequence of national, regional, and, subsequently, global concern about the environment. The concept of sustainability is not new, but has recently received considerable interest, especially when comparing the irrigated agricultural production practices between the developed and the developing countries of the world. The FAO defines sustainability as: "Sustainable development is the management and conservation of the natural resource base and the orientation of technological change to ensure the attainment and continued satisfaction of human needs–food, water, shelter, clothing, and fuel–for present and future generations. Such sustainable development, including agriculture,

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 291–307.

forestry, and fisheries, conserves genetic resources, land and water resources, is environmentally non-degrading, is technically appropriate, is economically viable, and socially acceptable" (FAO 1992).

While sustainable agriculture is inspired by considerations of human needs, poverty alleviation, and the creation of production incentives, it also recognizes the crucial role of human resources. Natural resources are used and managed by people to safeguard their well-being, not simply for the sake of conservation. Hence, the conservation of natural resources is not just a technical issue: it has important economic and social dimensions. Access to inputs, improved land tenure conditions, economic motivation, equitable distribution of income, development of human resources, and sound agricultural policies are crucial in ensuring the sustainable management of the natural resource base.

If irrigated agriculture is to be sustainable, then the status and role of farmers in our societies must be commensurate with these responsibilities (FAO 1992). The terms of trade between agricultural producers and those who process, market, and consume agricultural products–urban dwellers in particular–must be modified to more equitably distribute the cost born by farmers and other rural people for enhanced natural resource conservation and environmental protection.

The concerns of sustainability differ markedly between developed and developing countries. In developed countries they may arise from over-use of agricultural inputs, improper tillage, or continuous mono-cropping, among others. In developing countries, however, they are usually related to lack of agricultural inputs, the low productivity of manual labor, and reduced production. In developing countries environmental damage is often due to low-intensity agricultural practices which require horizontal expansion of cultivation on to marginal areas prone to degradation. Sustainable development in developing countries should therefore be sought within an overall framework of growth, so that the development measures adopted can maintain a momentum towards the goal of a more effective, stable, and productive agricultural sector (FAO 1992).

Renewable water supplies are essential for sustainable irrigated agricultural development. While inputs such as pesticides, fertilizers, and better quality seeds are important, reliable water availability and control are commonly critical prerequisites for the profitability of such input use and for the enhancement of agricultural production on a sustainable basis. Thus, the interrelationship between water and sustainable agricultural development is a direct and vital linkage: the latter is not possible without the former.

Scarcity of water is a major constraint for further agricultural development of arid and semi-arid countries. In many countries, all available water sources which can be economically used have already been developed or are in the process of development. As the demand for water continues to increase, it is imperative that this limited resource be used efficiently for agricultural and other uses.

2.1. POPULATION AND FOOD DEMAND

The essence of the concept of sustainability is the legacy that the present generation will leave for future generations. This immediately raises the questions of what population one needs to consider when exploring the future and from what base level one begins. The projections of population in the world as made by the United Nations are presented in Table 1. The most striking fact is that, of the projected world population growth for the year 2000, about 90% will take place in the developing countries.

TABLE 1. Projection of Population and Growth Rates. Source: United Nations (1991)

	Population (million)				Growth rates, % per annum		
	1985	1990	2000	2025	1985-90	1990-2000	2000-2025
World	4851	5292	6260	8504	1.87	1.86	1.54
Developing countries	3677	4086	4996	7150	2.26	2.21	1.76
Africa	553	642	866	1597	3.05	3.13	2.87
Latin America & Caribbean	404	448	538	757	2.14	2.01	1.65
Asia	2605	2981	3420	4569	2.05	2.04	1.42
Middle East	115	132	172	288	2.91	2.86	2.46
Developed countries	1174	1206	1264	1354	0.60	0.60	0.53

To feed this uncontrolled growing population, food production must be increased by enlarging the area served by irrigation, or by intensifying agricultural production on the existing irrigated and rain-fed lands. Irrigated agriculture has expanded horizontally into areas where conditions for production are less favorable, and vertically by increasing production per unit area of land through intensification.

Much of the additional agricultural production has been achieved through the development of new irrigation products and the use of high-yielding varieties, which require optimum management of land and water. Two major questions remain: Will the newly developed projects be sustainable, and what other potentials are there for development?

These trends point to the danger of a decline in per capita agricultural production, which will become even more dramatic with the increasing world population. Hence, the world food and water problems may worsen with time.

A broad indication of the relation between the demand of basic needs and the production of agriculture for the 93 developing countries is shown in Table 2 (FAO 1988). The growth in demand exceeds that of production, and this spread may increase when accounting for the increased expectations of future generations. Food self-sufficiency is a concept closely linked to that of independence, a term whose meaning is changing in today's world.

TABLE 2. Demand for and Production of Agricultural Product 1985—2000 in 93 Developing Countries (% per annum). Source: FAO (1988)

	DEMAND		PRODUCTION	
	Total	Per Capita	Total	Per Capita
93 Countries	3.1	1.2	3.0	1.1
Africa (Sub-Saharan)	3.5	0.2	3.4	0.1
Near East/N. Africa	3.1	0.6	3.1	0.5
Asia	3.1	1.6	3.0	1.5
Latin America	2.8	0.7	2.7	0.6
Low income countries	3.1	1.4	3.1	1.3
Middle income countries	3.0	0.8	2.9	0.6

2.2. IRRIGATION DEVELOPMENT

During the past four decades, development of irrigated agriculture provided a major part of the increase in production necessary to meet population demands. By the mid-1980s, 36 percent of the total crop production came from less than 15 percent of the arable land which was irrigated (FAO 1992). On a global basis, the average rate of irrigation expansion was about 1 percent per year in the early 1960s and reached a maximum of 2.3 percent per year from 1972 to 1975. The rate of expansion began to decrease in the mid 1970s and is now less than 1 percent per year (FAO 1990).

The reasons for this decrease in expansion are many. One of the most commonly cited causes is the high cost of irrigation development, and the decline of the world price for major cereals. Further, and perhaps most important, as much of the suitable land for irrigation development and available water supplies have already been developed, progressively more expensive and socio-economically less favorable areas are left for further expansion.

Of major concern is the continuing decrease in the rate of expansion of irrigated land in developing countries while population growth rates are greater than 2 percent per year. The FAO (FAO 1990) projections of expansion of irrigated land to the year 2000, based on previous trends modified by land, capital, and inputs required to meet future needs, was 2.25 percent per year from 1982/4 to 2000; however, the projections appear to be overly optimistic. Clearly, the needed increases in production cannot be achieved only from expansion of irrigated land. Rather, production increases must be achieved from both rain-fed and irrigated agricultural lands.

3. The Irrigation Design and Management Process

3.1. IRRIGATION SYSTEMS AND SCHEMES

The term "irrigation system" is often used to describe anything from a small-scale water supply and application system to an entire agricultural scheme serviced by a single large-scale or multiple small-scale water supply systems. Following Keller (1992), the term irrigation system can be defined as the capture, delivery, application, and removal of water from agricultural land. Further, the irrigation scheme is defined as an entire agricultural production system served by an individual or group of irrigation systems along with the associated watershed.

3.2. IRRIGATION INPUTS AND OUTPUTS

In addition to water and other natural resources, a number of institutional, financial, and production inputs from sources external to an irrigation scheme are essential for its implementation and success (Keller 1992). A list of such inputs that should be included in the selection process and design of irrigation systems includes:

- labor, techniques, and technical skills;
- information about crop selection, husbandry, protection and management;
- management assistance in all three domains;
- capital (money) and credit;
- irrigation system and farming equipment, technologies and supplies;
- power and fuel (energy) to operate the irrigation system and farming equipment;
- transportation and communication devices; and
- other needed infrastructure.

In developed countries there is a relative abundance of such inputs and their availability can usually be taken for granted. But this is not often the case in developing countries. Thus, many irrigation projects in the developing countries have yielded disappointing results because it was assumed the needed inputs would be available, but they were not.

For irrigation to be a commercial and economic success, there must be ample marketable production to recover the capital costs as well as the recurring operational and maintenance plus the periodic rehabilitation costs of the irrigation system. However, if the purpose of the enterprise is not purely commercial, i.e., there are political or other societal benefits, covering these costs may not be required.

Some beneficial social, economic, and environmental effects of irrigation development are (Keller 1992):

- labor benefits;
- increased tax returns;
- new fisheries;
- recreational opportunities;
- reduced flooding and erosion;
- more stable groundwater and downstream irrigation water supplies;
- improved domestic water supplies;
- more people having reliable and nutritious food supplies, better incomes, and improved living standards; and
- increased commerce and incomes in adjacent regions, etc.

Unfortunately, as identified by Keller (1992), irrigation development may also create several adverse effects. These include:

- waterborne diseases;
- health hazards related to chemical (such as insecticide) inputs;
- displaced farmers from the submergence and canal right-of-way areas;
- loss of recession agriculture lands and the related silt deposits which improve the soil;
- destruction of traditional river and estuary fisheries;
- salt water intrusion in estuaries;
- labor shortages in adjacent areas;
- depressed local commodity prices due to excess production;
- social conflict and political corruption;
- increased inequities in income distribution due to uneven access to water; and
- real estate windfalls and excess speculation in the areas commanded by the irrigation project, etc.

3.3. INTEGRATION OF RESOURCES

3.3.1. *Water Resources*

It is obvious that sustainable irrigation is not possible without a reliable source of water of suitable quantity and quality which allows for continued cropping. With growing populations, improved standards of living, urbanization and industrial development, the demand for water is steadily increasing. Easily available water sources have already been developed and the water competition between sectors and between countries is becoming more severe. Because agriculture is the largest consumptive user of water, improved irrigation management should be a major future conservation option. There is considerable opportunity for improvement in water conveyance and application efficiency. Furthermore, if the projected contribution of irrigated agriculture to food production is to materialize, alternative irrigation methods are required.

The quality of water available to agriculture is as important as the quantity. Poor quality water not only reduces crop yields, but can also cause environmental hazards and a decline in land productivity. Excessive use of fertilizers has led to surface runoff and deep percolation of nutrients, both of which have contributed to water pollution, particularly to high levels of nitrates in groundwater. Contamination of waters with pesticides and human and animal wastes also seriously affect the quality of waters.

Even the best irrigation water contains salts. Without proper drainage, the salt load or the water table gradually builds up. Eventually, the land may become unusable. The answer is to use limited quantities of water with proper drainage. However, water is often treated as a free or unlimited resource, and there may be insufficient financial incentive for improved water management. Thus, there is little reason for carefully managing irrigation flows and applications, or building and maintaining drainage works, although this may be essential to the sustainability of the irrigation system.

Irrigation return flow results from reservoir spills and releases plus channel seepage, operational losses and excess irrigation applications. Return flow may be good or bad, depending on its quality as well as temporal and spatial quantity. Therefore, before making system changes designed to reduce water losses from a mature gravity-flow system, the benefits being derived from conjunctive use within the system and from return flow should be carefully considered.

Introducing enforceable water legislation for surface water is difficult and for groundwater, it is even more so. This situation should change when the users understand the hydrological issues and become participants in the development planning process.

3.3.2. *Land Resources*

Is there enough land available globally to produce the food that will be needed by future populations? Is there enough land available at national level to allow all countries to attain self-sufficiency in the production of food? As stated in FAO (1992): If the people of the world were to live in harmony, if resources were shared, if cultivable land were used in an optimal way, and if there were unrestricted movements of produce, there would be food for all for many years to come without undue stress to the natural resource base. The reality, however, is very different.

When planning for a higher degree of self-sufficiency, it is essential that differences in crop production potential are fully appreciated and that land degradation hazards are identified. In some countries, land reserves are such that cultivation can be expanded to meet national requirements and even beyond. In other areas, the limits of cultivable land have already been reached or are about to be reached, and most of the necessary increased production will have to come from the intensification of agriculture on land already cultivated. Certain countries with unfavorable soil and climatic conditions may not be able to meet the food requirements of their population, even if the level of inputs were to be optimized. A national assessment of the available land resources is a prerequisite for determining appropriate food policies, and development decisions must be based upon reliable knowledge of what is possible and what is not!

With the existence of critical areas in various parts of the world, it is clear that food security will also depend on areas with different food-production capabilities complimenting each other–a clear indication that the problems of land use and food supply must be tackled at national, regional, and global levels–not just within the context of individual countries.

By far the most quoted drawback of irrigated land-use is waterlogging and salinity (Dudal 1992). Irrigated agriculture is often blamed, in its entirety, for salinization hazards which occur essentially in arid and semi-arid areas (Table 3). However, waterlogging and salinity are not a fatality. They can be avoided and prevented by judicious water use and drainage.

TABLE 3. Irrigated Land Damaged by Salinization, Top Five Irrigators in the World, Estimate, Mid-1980s. Source: Rydzewski (1992)

Country	Area Damaged (million hectares)	Share of Irrigated Land Damaged (%)
India	20.0	36
China	7.0	15
United States	5.2	27
Pakistan	3.2	20
Soviet Union	2.5	12
Total	37.9	24
World	60.2	24

3.3.3. *Plant Nutrients and Plant Protection*

Agriculture requires a number of inputs in order to achieve sustainability. At the very least, it is necessary to replace the nutrients removed by harvested crops. However, even this basic requirement is not being met in many developing countries.

Environmental effects of fertilizers may be both beneficial and hazardous, and their actually impact depends less on the fertilizers themselves than on the amounts and on the way they are applied. Where detrimental effects are observed, they are usually due to over-application or to improper timing, which may be corrected by improved management practices. It must be noted that the amounts of fertilizers, both mineral and organic, used in developing countries are relatively low.

While recognizing the widespread benefits derived from the Green Revolution, it should be recognized that the rapid increase in yields was also accompanied by a massive increase in the use of agricultural inputs. Pesticides in particular were indiscriminately used in many countries, with widespread negative impacts on the environment, the health of farmers and consumers, production costs, the ecological balance of pest populations, and the resistance of pests to pesticides. This situation led to the development of alternative and more sustainable pest management strategies, which included the "best mix" of natural control measures (resistant varieties, cultural practices, biological control, etc.) and a need-only-based use of selective pesticides.

3.3.4. *Energy*

With irrigation, energy is used to pump water, to manufacture fertilizers and, locally, to fuel mechanical power. Obviously, measures should be taken to conserve energy, not only from an environmental point of view, but in terms of economics. However, pleading for low energy consumption in areas where the level of inputs is already low–often below a bare minimum–is unjustified. The synergy between different inputs greatly enhances yield levels. Energy inputs increase the productivity of human labor and widen the access to water resources. Energy use in agriculture is a minor fraction of total energy consumption at the country level.

Pumping, where needed, requires energy and reduces profitability. Unfortunately, it is required for most of the modern irrigation systems. The exceptions are gravity-fed surface systems and pressurized systems where the water supplies are high enough above the irrigated land to produce the necessary pressure by gravity. Energy required to pressurize most sprinkler systems ranges between 0.9 and 2.1 kilo-watt-hour (kWh) per hectare-millimeter (ha-mm) of water applied.

3.3.5. *Economics*

Implicit in any benefit/cost analysis or irrigated agriculture is the assumption that someone will benefit from the costs incurred. In many cases, this leads to the feeling that those who benefit should contribute to the costs through some form of water charge. If these charges do not cover the whole project cost, then other sectors of society are subsidizing irrigation farmers. Whether this is right or wrong is a socio-political question and is the subject of much debate.

At the farm level, improved efficiency and better management can lower production costs and projects can be designed to have greater control of water. However, many problems lie beyond the farm level. The success of agriculture in terms of increased production and sustained rural income depends to a very large extent on appropriate government policies. They determine, for instance, whether agriculture prices should favor producers or consumers, whether food deficits will be remedied through imports of food or agricultural inputs, whether the cost of construction of irrigation schemes will be partially defrayed by the government or will be charged entirely to the farming community, whether small-scale irrigation will be encouraged versus large-scale systems, whether economic performance will take into account the consumption or degradation of non-renewable natural resources.

Sustainability implies that economic motivation encourages the farmer to produce on a continuing basis and that this work allows him to improve his standard of living. If the price of food does not include the cost of conserving the land on which it is produced, then the natural resource capital is being depleted. On the other hand, limitations of land use on environmental grounds may threaten the income of rural communities–for example, by restricting the use of inputs through the elimination of price supports. Both degradation and protection have a price, not only in monetary but also in terms of socioeconomic tradeoffs. The economic aspects of sustainable irrigated land-use are as important as improved management and advanced technology.

4. Irrigation System Design Considerations

NOTE: Much of the material in this section was taken from Keller, (1992).

Modern on-farm irrigation techniques have been developed to improve the productivity of and sustain, as well as extend the land area under irrigated agriculture. The technological changes involve both discoveries of whole new irrigation concepts as well as refining or improving the adaptability of existing ones.

4.1. IRRIGATION SYSTEM SELECTION AND DESIGN

Technical or physical suitability of an irrigation system is obviously essential for the appropriate selection of modern irrigation techniques. Usually there are a number of irrigation system types which can be selected and designed to fit almost any physical land area and set of crop requirements.

The engineering and agronomic aspects of modern irrigation systems in terms of technical selection and design are almost fully transferable. However, the more perplexing problems are related to the human interface with irrigation systems. All irrigation systems must be maintained and operated within their socioeconomic and institutional environments by the people who live there. It is this socio/technical interface where the experience and knowledge for transferring modern irrigation technologies is most lacking (Keller 1992).

Insightful selection of the system type and layout that best meet the goals and objectives of an irrigated agricultural development is of primary importance in the overall design process. The practically obtainable efficiencies of the various modern irrigation technologies are similar, at least under optimum conditions. Therefore, the final choice of system type, from the ones that are physically applicable, is reduced to a socioeconomic decision dependent on the expected probability of satisfactory cultural fit and economic as well as technical sustainability.

4.2. SYSTEM COST AND IRRIGATION EFFICIENCY

A list of various types of modern irrigation water application systems that might be considered is given in Table 4. To achieve the listed efficiencies, surface irrigation systems require precision land leveling; however, this is difficult to do without using laser leveling equipment. The current problem is not a lack of effective irrigation technologies, but the proper application and management of each of them.

4.2.1. *Cost Factors*

The initial capital investment, economic life, expected annual maintenance cost, and attainable application efficiencies for each type of system are given in Table 4. The on-farm cost interrelationship among irrigation techniques is an important criteria for system selection. Since the focus is at the water application level, it makes no difference whether the water is delivered by private pump or via a giant public system. However, the dependability of the supply at the individual or group outlet level and whether it is a continuous or period flow does affect the economic relationships and the suitability of various types of systems.

The Initial Equipment Cost ranges given in Table 4 are in U.S. dollars based on mid-1980 prices. The costs are for systems already in place and ready to operate on fields large enough (typically 65 ha for the mechanized sprinkle systems) to gain the full economy of scale for each particular type of system. The costs are based on having a surface water supply available at the edge of the field, and include the cost of a mainline and pumping plant, if needed.

The values given for the Economic Life of each system are reasonable life-cycle values for economic planning, but not necessarily the maximum full life of all the equipment involved. The double values presented for the economic life reflect the life of the above ground laterals and the buried supply network, respectively.

4.2.2. *Irrigation Efficiencies*

The irrigation efficiencies should not only be considered in the traditional water use efficiency terms of uniformity of water application and losses, but also in terms of ease of scheduling and timing of irrigations. The efficiency values in Table 4 represent practical seasonal values that are considered to be attainable with good design when fully irrigating to meet all crop water requirements on approximately 90% of the field. The range of values given for each system represent a combination of management levels from good to excellent and various site/design conditions. However, during peak water use periods, individual irrigations may be at the high end of the ranges, with only average management.

The surface systems are assumed to have lined canal or piped distribution systems and precision leveled fields. However, this is not often the case in many surface water delivery projects. The range of values reflects the effects of high and low infiltration rate soils and management differences. The higher efficiency values can only be obtained with excellent management and optimum designs for the specific site conditions.

The lower values for the sprinkler systems reflect appreciable wind or evaporation. The higher values require excellent management with calm wind conditions and the use of alternate sprinkler positions between lateral moves.

The water requirements of localized systems may be 10% to 30% less than the requirements for other systems with identical application efficiencies. This is because of the reduced evaporation and consumptive use by vegetation resulting from only wetting a small portion of the soil surface and profile.

4.3. IRRIGATION SYSTEM SUSTAINABILITY - CONCEPTS

The various application techniques should be selected in terms of their physical suitability, costs, efficiencies, and yield/profit potential (Table 4). However these are not sufficient; they should also be considered in terms of their divisibility, organizational requirements, sustainability, risk, required management effort and complexity, and layout flexibility (Table 5).

Many small-scale systems and most very small irrigation systems require lifting water from wells or surface sources. The lifting devices and fuel required to operate them add considerably to the complexity and out-of-pocket expense of operation. Furthermore, serving energy, repair and maintenance requirements for many small lifting devices may also require a complex network, such as an electric grid or liquid fuel delivery system and engine repair services. In addition, unlike gravity-flow systems, uninterrupted operation of irrigation systems relying on mechanized pumps requires disciplined systematic maintenance along with an almost continuous flow of fuel and other cash inputs.

In view of the above, once the decision has been made to use motor or engine driven pumps, it also makes sense to consider using pressurized distribution and application systems. Energy requirements for both lifting and applying the water may actually be reduced. This is because of the much higher efficiencies of such systems as sprinkle and trickle irrigation, as compared to traditional methods. Furthermore, once the complexity of operating pumping plants has been taken on, the addition of pipe and hoses and emitters to deliver and apply the water adds relatively little more to the complexity.

4.3.1. *Physical Suitability*

Physical suitability is obviously essential for the appropriate selection of modern, and typically mechanized irrigation techniques. Usually more than one type of system can be selected and designed to fit most any physical site condition and requirements of the selected crops.

4.3.2. *Other Selection Factors*

Divisibility: The three categories of divisibility used in Table 5 are: **Total**, for techniques that can be economically fitted to any size of plot; **Partial**, for techniques that can be divided with difficulty or at high expense; and **No**, used for techniques that realistically are only suitable for large fields.

TABLE 4. Costs and Efficiencies of Different Types of Modern On-Farm Systems. Source: Keller (1992)

Irrigation Method and Type	Equipment Initial Cost $U.S./ha	Economic Life yr.	Annual Maintenance % of Cost	Efficiency %
SURFACE (Precision)				
Basin (level)	370—1,085	Con	1	70—90
Border	370—1,085	Con	1	70—85
Furrow	150—750	Con	1	65—85
Conveyance				
Lined	400—1,250	15	3	———
Piped	800—2,500	20	1	———
Automation	300	10	5	———
SPRINKLE				
Lateral				
Hand-Move	450—675	15	2	65—80
End-Tow	600—950	10	3	65—75
Side-Roll	800—1,100	15	2	65—80
Side-Move	950—1,350	15	4	65—80
Hose-Fed	450—675	5/20	3	60—80
Traveling Gun	950—1,200	10	6	55—70
Center-Pivot				
Standard (400m)	1,100	15	5	70—85
w/Corner	1,200	15	6	65—85
Long (500m)	700	15	5	65—85
Linear-Moving				
Ditch-Feed	1,100—1,300	15	6	65—85
Pipe-Feed	1,600—2,050	15	6	65—85
Solid-Set				
Portable	2,700—3,250	15	2	65—75
Permanent	2,300—3,500	20	1	65—75
LOCALIZED				
Orchard				
Drip/Spray	1,500—3,500	10/20	3	75—90
Bubbler	2,500—4,000	15	2	60—85
Hose-Pull	1,200—1,800	5/20	3	65—90
Hose-Basin	1,500—1,800	7/20	2	55—80
Row-crop				
Reusable	2,000—5,000	10/20	3	65—90
Disposable	1,650—3,000	1/20	20	60—80

TABLE 5. Factors Affecting the Selection of Different Types of Modern Irrigation Systems for Use in Developing Countries. Well adapted for irregular shaped fields. Source: Keller (1992)

Irrigation Method and Type	Factors Affecting System Selection					
	Divisibility	Maintain By	Risk	Mgmt. & O&M		Layout Flexibility
				Skill	Effor t	
SURFACE (Precision)						
Canal-Feed						
Basin	Total*	Grower	Low	Master	5	Restricted
Border	Total*	Farmer	Low	Master	6	Restricted
Furrow	Total*	Farmer	Low	Medium	10	Restricted
Pump/Pipe-Feed						
Basin	Total*	Shop	Med	Master	3	Full
Border	Partial*	Shop	Med	Master	3	Restricted
Furrow	Partial*	Shop	Med	Master	6	Full
SPRINKLE						
Lateral						
Hand-Move	Total	Shop	Med	Simple	9	Restricted
End-Tow	Partial	Shop	Med	Medium	5	Restricted
Side-Roll	Partial	Shop	High	Medium	6	Restricted
Side-Move	No	Agency	High	Master	5	Little
Hose-Fed	Total*	Farmer	Med	Simple	10	Full
Traveling Gun	Partial	Agency	High	Master	4	Restricted
Center-Pivot	No	Agency	High	Complex	1	Little
Linear-Moving	No	Agency	High	complex	2	Little
Solid-Set						
Portable	Total*	Shop	Med	Medium	5	Restricted
Permanent	Total*	Farmer	Med	Medium	1	Full
LOCALIZED						
Orchard						
Drip/Spray	Total*	Grower	High	Complex	2	Full
Bubbler	Total*	Grower	Low	Complex	4	Full
Hose-Pull	Total*	Farmer	Med	Simple	9	Full
Hose-Basin	Total*	Farmer	Low	Simple	10	Full
Row-Crop						
Reusable	Total*	Grower	High	Complex	5	Full
Disposable	Total*	Grower	High	Complex	3	Full

Systems with **Total** divisibility can be operated independently by each private farmer. Totally divisible application systems supplied by a shared pump or distribution network should be considered as being only partially divisible. With **Partial** divisibility, group (or cooperative) effort is usually required. The direct operational assistance of an agency such as a large cooperative or irrigation department is usually needed to manage and operate an application system with **No** divisibility.

Maintain By: This category provides an estimate of the complexity of the technologies in terms of overall physical sustainability. **Farmer** is used for equipment that can be rather easily maintained and fixed by the ordinary farmers who raise traditional crops. **Grower** is used for equipment that can be maintained at the farm level, but requires advanced skills normally associated with producers of high value crops. **Shop** is used to indicate the need for typical local merchants having some special but limited facilities and technical capacity to repair the equipment. **Agency** is used to indicate that very specialized equipment, facilities, and skills are needed to keep the equipment in operation. Irrespective of who maintains the application equipment, shops or agencies are normally required to maintain engine driven pumps.

Risk: This category addresses the issue of potential crop loss due to equipment "breakdown." The **Low** risk category is used for surface systems that are not vulnerable to breakdown at the field level. **Medium** is used for all pressurized systems where parts of the water application equipment can break or malfunction without jeopardizing the rest of the system. **High** is used for both localized irrigation systems require micro filtration and irrigation machines.

Management, Operation, and Maintenance: These factors are closely linked for the various irrigation techniques. They should be considered together in terms of: management difficulty; what must be available and known; the nature of the skills needed for operation and maintenance; levels of support services required for service and spare parts; and what other agricultural technologies will be needed in order to make irrigation cost effective and sustainable.

The management complexity categorized according to the Skill level necessary to realize the attainable application efficiencies presented in Table 4 are given in Table 5. It also relates to the skill and support services necessary to maintain and service the equipment to keep it operable for its anticipated economic life. **Simple** is used to indicate only elementary skills are necessary. **Medium** indicates considerable skill is needed to manage and operate the equipment properly. **Master** indicates that much hands-on field experience is needed to manage the flows, spread the water, and do the irrigating. **Complex** indicates sophisticated technical skills and reading ability (or hands-on training of farmers) are necessary to operate and service the irrigation equipment effectively.

Effort: The levels of 1 through 10 indicate the relative management time and labor required to manage, operate, and maintain the various types of irrigation application systems. The numbers give a fair quantitative indication of the average number of man-days/hectare per irrigation month required.

Layout Flexibility: This refers to the adaptability for various sizes and shapes of small farms, as well as mixed cropping layouts. Systems with **Full** flexibility can be easily tailored for any size of water supply and land area. They can be designed to accommodate mixed cropping patterns with minimum farm layout restrictions and used in conjunction with other types of irrigation application systems. Systems with **Restricted** layout flexibility are more difficult to tailor to the water supply and land area. Where they are to serve small land holdings with mixed cropping, the individual crop areas must be sized and laid out to fit the irrigation system. Systems with **Little** flexibility are difficult or impractical to tailor to fit small land holdings.

4.4. IRRIGATION SYSTEM SUSTAINABILITY - TESTS

The technical, economic, and cultural obstacles to transferring modern irrigation technologies to developing countries are often overlooked. Cultural fit as well as technical and economic sustainability tests are necessary for successful technology selection and transfer. The challenge is how to take advantage of the economies and benefits of modern irrigation delivery and application systems while preserving the vitality and human-initiative associated with privately operated small-scale irrigated farming enterprises (Keller, 1992).

4.4.1. *Technical Sustainability*

Matching the irrigation system technologies to the physical site conditions is usually less of a problem than matching them to the local social and institutional environment. For systems that can not be maintained by ordinary farmers or those who possess the complex skills required to manage, operate, and maintain them, then achieving the high efficiencies presented in Table 4 is problematic.

At the onset there is usually an incompatibility with existing local management skills and a general lack of necessary commercialization for operating and maintaining each new technology. To assure technical sustainability the management skills and support infrastructure necessary for operating, servicing, and maintaining each new irrigation technology should be carefully considered and in place before attempting to employ it.

4.4.2. *Economic Sustainability*

Modern irrigation technologies require cash inputs to cover ongoing operation and maintenance costs even if the systems are given to the farmers. Furthermore, most of them require cash inputs for fuel, spare parts, or mechanical services during the cropping season. Therefore, they are only economically sustainable where cash flows generated by the new irrigation activities are timely and generously exceed the associated costs.

Two additional considerations should be kept in mind when considering economic sustainability: the necessity for or at least desirability of diversified agriculture on small landholdings should not be overlooked; and the lag time and effort required for local farmers, and the irrigation community, to learn how to best select, design, operate, manage, and maintain a new technology to attain the necessary performance.

In addition to the economic sustainability, there must be potential for having a "sufficient mass" of each particular type of system. The system can then become commonplace and justify or attract the needed supporting infrastructure for technical sustainability. However, the gestation period for success with a new technology is usually several years in each region. During this time the application of the technology will probably require considerable fine tuning to fit it to the local socioeconomic and physical environment.

4.4.3. *Cultural Fit*

The importance of cultural fit to the acceptance and consequent sustainability of modern irrigation technologies is usually overlooked when recommending them for farmers with small land holdings. There are two aspects of cultural fit: the degree to which the technology fits the social culture of the individual farmers or collective users if they must collaborate to efficiently utilize the particular technology, and the adaptability of the irrigation technique to fit each farmer's water supply, land area, and concept of a desirable cropping pattern and farm layout.

Furthermore, farmers prefer systems they can maintain themselves, that have medium to low risk, and that are relatively inexpensive to own and operate in comparison to the increased productivity and profitability.

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MICRO-IRRIGATION SYSTEMS AND FERTIGATION

I. PAPADOPOULOS
Agricultural Research Institute
Ministry of Agriculture, Natural Resources and Environment
Nicosia, Cyprus

1. Introduction

Drip and minisprinkler irrigation systems have experienced an enormous increase in commercial significance and research interest in the past three decades. Both systems as they are known today became practical with the development of plastics that were inexpensive, durable, and easily moulded into the variety and complexity of shapes required for pipe and emitters. The earliest systems were made up of small-bore (1-2 mm ID) plastic microtubes (emitters) inserted into larger-diameter plastic pipe. Water emission rate was controlled by friction in the microtube, producing irrigation rates of 2 to 6 litres per hour per emitter. Operating pressures were low, often around 103 kPa, necessitating careful system design to offset effects of small elevational changes on internal system pressure and emission rate. Emitters have since evolved into a number of forms, from discrete emitter units to various types of porous hose, and more recently to pressure-compensating types that regulate flow over a range for pressures, permitting higher pressures to be utilized in drip irrigation lines.

Recent innovations designed to adapt drip irrigation to different conditions include moving units, simplified bubbler systems, and the promotion of spitters or micro sprinklers rather than drippers. Perhaps the most significant trend has been toward greater control and automation of the frequency and amount of water application, using programmable computer-based systems and including such devices as sequential metering valves and sensors to monitor weather and soil moisture variables. More recently, new drip-irrigation systems have been introduced for use with wastewater in both agricultural and garden settings. The rubber tubes of these pipes have a labyrinth "toothed" water passage which facilitates superior filtration. Chemigation and particularly fertigation are yet other developments of major importance.

Drip irrigated area has been expanded rapidly. The first international survey by Gustafson *et al.* (1974) indicated that about 56,000 ha were under drip irrigation in the world, with approximately half that area in the U.S.A.. A recent survey (Abbott 1988) indicated that only with drip irrigation the area was expanded to 1,081000 ha (Table 1). In Cyprus, drip and minisprinklers are covering today more than 95% of the irrigated land. The bulk of this expansion has taken place in orchard and vegetable

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crops as opposed to field crops, primarily because of the higher unit-crop value of those crops and excessive irrigation system cost factors associated with drip irrigation for crops.

TABLE 1. Area irrigated with micro - irrigation systems adapted from Abbott, (1988)

Country	1981 (ha)	1986 (ha)
USA	185300	392000
Israel	81700	126810
Spain	N.A.	112500
South Africa	44000	102250
Egypt	N.A.	68450
Australia	20050	58758
France	22000	50953
Portugal	N.A.	23565
Italy	10300	21700
Brazil	2000	20150
Mexico	2000	12684
Jordan	1020	12000
Taiwan	N.A.	10005
China	8040	10000
Cyprus	6600	10000
Other Countries	29750	49806
Total	412760	1081631

In spite of its recent beginnings, drip irrigation has been the subject of a number of reviews. Early reviews focused on specific developments or practices in different countries. The development for subsurface drip irrigation has been retarded by problems of plugging, which are more difficult to diagnose, accumulations of salt at the soil surface when saline water is used, and other difficulties that offset the benefits in water savings from reduced evaporation. More recently, the topics of drip irrigation design, soil-water relations and infiltration phenomena, and salt movement under drip irrigation have been subjected to detailed mathematical analysis.

2. Advantages of Micro-Irrigation Systems

The advantages of the micro-irrigation systems can be summarized as follows :

- Significant water saving. Since conveyance losses are eliminated and soil surface area wetted is restricted efficiencies higher than 80% can be achieved ;
- Increased yields. The root-zone of the crops with the modern irrigation methods remains continuously moist and the plant is not, therefore, subject to stress cycles;
- In addition, the required fertilizers can be applied with the irrigation water (fertigation), whenever and where they are exactly needed by the plant ;
- The area between plant rows of trees remains free and dry enabling spraying and harvesting to be done even during water applications ;
- Utilization of steeper slopes and problem soils otherwise unsuitable for irrigation

with the conventional methods of irrigation ;

- Poor quality saline water can be used with the drip and minisprinkler irrigation methods, because by maintaining high moisture in the soil with frequent irrigations the salt that is being added with the irrigation water is diluted and remains acceptable ;
- They can operate with a limited flow rate at a relatively low pressure head. One bar for drippers and 2 bars with minisprinklers. This means savings in the cost of the pump, fittings, lines, energy and labour ;
- They require limited labour. They can be automated by using automatic metering valves, electronic tensiometers, time switches, etc.

3. Problems and Drawbacks of Micro-Irrigation Systems

- Relatively high investment is required for the installation of the modern irrigation systems, ranging between $ 2,200-7,000/ha. Economic incentives to the farmers can help in this respect. Usually the cost of drip irrigation systems is higher than low capacity sprinklers and minisprinklers ;
- Toxicity problems: They are associated mainly with sprayers and minisprinklers due to high bicarbonate, sodium and chloride concentration in the water.. Wetting of foliage with water high in bicarbonates causes white deposits on leaves which reduce drastically plant photosynthesis. In addition, high sodium or chloride concentrations of irrigation waters, exceeding 3 meq/L, create problems to sensitive crops if their foliage is wetted by the irrigation water. With such waters low angle minisprinklers kept close to the ground may reduce wetting of the foliage and therefore, may help overcome the problem in orchards ;
- Emitter clogging: The load of suspended matter, chemical precipitates and biological slimes may cause emitter clogging, particularly in drip irrigation.The plugging potential of irrigation water when emitters with small nozzle openings are used is presented in Table 2.

TABLE 2. Plugging potential of irrigation water in drip irrigation systems (Bucks *et al.*, 1979)

Type of problem	Restriction on use		
	Little	Slight to moderate	Severe
Physical			
Suspended Solids (mg/L)	<50	50 - 100	>100
Chemical			
pH	<7.0	7.0 - 8.0	>8.0
Dissolved solids (mg/L)	<500	500 - 2,000	>2,000
Manganese (mg/L)	<1.0	0.1 - 1.5	>1.5
Iron (mg/L)	<0.1	0.1 - 1.5	>1.5
Hydrogen sulphide (mg/L)	<0.5	0.5 - 2.0	>2.0
Biological			
Bacterial populations (maximum number/mL)	<10,000	10,000 - 50,000	>50,000

4. Components and Design of Irrigation Systems

4.1. HEAD OF THE SYSTEM

The head of the system is similar to all micro-irrigation systems. The following fittings are indispensable: Vacuum valve, check or one-way valve, volumetric water meter,fertilizer injector, pressure control valve, and filters.

4.2. MAIN AND SUB-MAIN SUPPLY LINES

Plastic pipes, usually of black polyethylene of high or low density and PVC ranging in diameter from 40 to 90 mm outside diameter (O.D.) are used. They are manufactured to withstand a pressure of 4 to 6 bars.

4.3. IRRIGATION LINES

The diameter of the piping to be installed depends on the length of lateral line and flow rate. For the drip systems 12 to 25 mm O.D. black-polyethylene piping usually of low density is used, for the minisprinkler systems between 20 and 32 mm O.D. and for low capacity sprinkler systems between 25 and 32 mm O.D. The pressure loss in the irrigation lines must not in general exceed 20% of the minimum pressure required by the orifice. They are manufactured to withstand a pressure of 4 bars.

4.4. MICROIRRIGATION SYSTEMS

4.4.1. *Drippers*

Different types of drippers are available; vortex type, labyrinth type, long path microtube drippers, self regulated drippers, etc. The flow rate of the individual nozzle ranges between 2 and 10 l/h at the recommended operational pressure, which is usually 1 bar. Drippers are mainly used to irrigate vegetables grown in rows spaced at relatively great distance in the row and between rows. One outlet is usually installed to deliver water to each plant. They find also application in permanent tree plantations. One or two lateral lines are usually installed per tree-row or a feeding line with a loop around each tree on which the drippers are installed. The dripper spacing on the irrigation line in the orchards may range between 40-150 cm. It is closer in light (sandy) soils and with small dripper discharge rate, while it is wider in heavy (clay) soils and with increased dripper discharge rate.

4.4.2. *Minisprinklers (spitters)*

Different types are available. Their flow rate at 2 bar operational pressure ranges between 30 and 150 l/h and the corresponding wetted area between 2 and 6 m in diameter. During the first years of tree growth minisprinklers with the least flow and wetting diameter are recommended to avoid water losses and excessive weed growth. With tree growth the orifice of the nozzle is changed to increase the flow and the wetted area. Recently, nozzles of up to 250 l/h were manufactured but their use is not recommended, because tree performance is not further improved and the installation cost is higher. Nozzles wetting a full circle, half-circle or a quarter of a circle are available. The part circle nozzles are used in cases where moistening of the trunk favours disease attack. Various micro-jet systems are also successfully used in orchards.

4.4.3. *Low Capacity Sprinklers*

They are plastic rotating sprinklers of low discharge rate, ranging between 120 and 250 l/h at 2 bar operational pressure. They are used to irrigate densely spaced vegetable crops like potatoes, carrots, beans, etc. They are permanently attached to polyethylene pipes of 25-32 mm in diameter and the recommended spacing in the field is 5x5m. The best operational pressure ranges between 2 and 3 bars.

5. Fertigation

The application of chemicals through the irrigation system became a common practice in modern irrigated agriculture (Bresler 1977, Elfving 1982, Hairstone *et al.* 1981, Phene and Beale 1976, Papadopoulos 1986b; 1987a; 1988).

Application of chemicals, especially fertilizers, through irrigation systems is a practice of relatively long standing. However, fertigation-chemigation research and practical applications coupled with advances in irrigation system design, led recently to a rapid expansion of both fertigation and chemigation. Fertilizers were probably the first chemicals injected into modern irrigation systems. Since these initial applications many types of chemicals have been injected into irrigation systems, including herbicides (Phene *et al.* 1979), fungicides and insecticides (Phene *et al.* 1979), nematicides (Chesness *et al.* 1976), growth regulators, fumigants (Goldberg and Uzrad 1976, Overman 1976), and chlorine, acids and other chemicals to control clogging (Bucks *et al.* 1979, Ford 1976, Nakayama *et al.* 1977).

Drip irrigation system, which is highly efficient for water application, is also ideally-suited for fertigation and is practical to chemigating certain applied chemicals (Goldberg *et al.* 1976, Papadopoulos 1985). In this way, water soluble fertilizers at concentrations required by crops are conveyed via the irrigation stream to the wetted volume of soil. Thus the distribution of chemicals in the irrigation water will likely place these chemicals in the desired location, the root zone (Papadopoulos 1985, 1986a and b, Gerwing *et al.* 1979). Furthermore, with drip irrigation, the application of herbicides and pesticides for soil-borne diseases and pests due to the localized application in the wetted area only, results in the chemicals being more effective at lower concentrations (Gerstl *et al.* 1981). In contrast to drip irrigation systems, sprinkler irrigation systems are exceptionally well suited to spray chemigation.

Some potential advantages of fertigation are: improved efficiency of fertilizer recovery (Miller *et al.* 1981, Phene and Beale 1976), minimal fertilizer losses due to leaching (Bresler 1977, Klein *et al.* 1989, Papadopoulos 1985, Stark *et al.* 1983), control of nutrient concentration in soil solution (Bar-Yosef 1977, Papadopoulos 1986 and b; 1987b), control of nutrients form and ratio of the various forms particularly for N-fertilizers and flexibility in timing of fertilizer application in relation to crop demand based on development and physiological stage of crops (Bresler 1977). Advantages of scheduling fertilizer applications on the basis of needs are potentially reduced nutrient-element losses associated with conventional application methods that depend on the soil as a reservoir for nutrients. In addition, fertigation reduces fluctuations of soil solution salinity due to fertilizers (Papadopoulos 1985), thereby improving soil solution conditions particularly for salt sensitive crops (Papadopoulos 1986b, 1987c). In general with fertigation, protection of soil and water from fertilizers on a sustainable basis can be achieved.

Possible disadvantages include unequal chemical distribution when irrigation system design or operation is inadequate, over-fertilization in case that irrigation is not based on actual water requirements, or leaching if rainfall occurs at the time of fertilizer application, and chemical reactions in the irrigation system leading to corrosion, precipitation of chemical materials, and/or clogging of outlets.

5.1. FERTIGATION SYSTEMS AND EQUIPMENT

The fertigation unit (Fig.1) is composed of a fertigator (fertilizer injector, metering pump), a fertilizer tank for the concentrated stock solution, a non-return valve, a main filter and a water meter. Depending on the model of the fertigator additional equipment (valves, pressure and flow regulators) may be required. The metal tanks may corrode and, therefore, plastic containers are preferred. Flushing after fertigation reduces both the corrosion hazard and microbial growth.

Chemical injection can be accomplished in four main different ways:

5.1.1. *Venturi Pumps*

A constriction in the main water flow pipe causes a differential pressure ('vacuum') which is sufficient to suck chemical solution from an open reservoir into the water flow. The rate of flow can be regulated be means of valves. This is a simple and inexpensive method of chemical application, but it has some disadvantages; the pressure loss across a Venturi valve is high (about 1/3 of the operating pressure) and precise regulation of flow is difficult because the rate of injection is very sensitive to the pressure and rate of flow in the system. Recently, it has been suggested to install the Venturi valve on a by-pass of the total irrigation flow. In this way, the head loss decreases considerably, the capacity of the system increases substantially, and the chemigation system can be disconnected and moved easily. The apparatus is quite simple, relatively inexpensive easy to install, does not have moving parts, and is particularly convenient for small fertigated areas. The suction is from an open plastic container; the dilution ratio does not fluctuate. Among its limitations are relatively large head loss in the direct connection and sensitivity to changes in pressure and discharge rate. However, installation of a pressure regulating valve will enable constant injection rate (Eliades and Hadjiloucas 1985).

5.1.2. *By-Pass Flow Tank*

This method employs a tank into which the dry or liquid chemical is placed. The tank is connected to the main irrigation line by means of a by-pass so that some of the irrigation water flows through the tank and dilutes the chemical solution. This by-pass flow is created by a pressure gradient between the entrance and exit of the tank caused by a permanent constriction in the line or by a control valve. The concentration of chemicals in the tank decreases gradually.

Some of the advantages of the system are its simplicity in construction and operation and its low cost. There is no need for an external power supply, and it is not very sensitive to changes in pressure or flow rate. The disadvantages of the system are: the varying concentration of nutrients causes the bulk of the chemical to be applied at the beginning of the irrigation cycle; the tank has to be refilled with solution at each irrigation. This system is not suitable for automatic or serial irrigation. This system because of its simplicity and low cost is the most common fertigation system in use in semi-automatic drip installations.

5.1.3. *Pressure Differential System*

This is a variation of the above flow by-pass system. The tank is fitted with a rubber diaphragm to separate the fertilizer solution from the irrigation water. The rate of flow of the solution is determined by the difference in pressure between the inlet and outlet points and is monitored by a flow meter. This technique ensures a relatively constant rate of supply of fertilizer to the irrigation water, provided the flow rate of the chemical solution is adjusted to the flow rate of the irrigation water.

The main advantages of by-pass systems are their simplicity to operate, the absence of moving parts, and the fact that they do not require electric, fuel or water pumps. They can operate wherever water is flowing and pressure drop is present. The primary disadvantage, on the other hand, is that concentration is not uniform but changes continuously with time.

A modification of the pressure differential system is a tank that contains a collapsible plastic bag into which the chemical is added. Water is admitted to the area between the tank and the bag, which forces the chemical compound from the bag into the system.

5.1.4. *Injection Pumps System*

With this method a pump is used to inject chemical solution from a tank into the irrigation line. The solution is normally pumped from an open unpressurized tank, and the choice of type of pump used is dependent on the power source. The pump may be driven by water flow, by an internal combustion engine, by an electric motor or by a tractor power take-off. The electric pump can be automatically controlled and is thus the most convenient to use. However, its use is limited by the availability of electric power, and is therefore, more suited to greenhouse than to field cultivation. With these injection devices, chemicals may be supplied to the irrigation water at a more of less constant rate. The pumping rate and the concentration of the stock solution can be adjusted to attain the desired level of chemical to be applied. However, the water flow and the chemical flow are independently controlled. The dilution factor, therefore, is necessary to be estimated directly in the field, and after being estimated be checked periodically. Changes in water flow, power failure or mechanical failure, may cause serious deviation from the planned concentrations. The use of pressure regulators may help overcome the problem. Another disadvantage of this system is the need for an external power source and the relatively high cost of the system.The use of a hydraulic motor, operated by the line flow, avoids these difficulties. This device requires a minimal pressure (1.5-2.0 Bars) to operate. At each stroke of the pump a certain predetermined volume of chemical solution is injected into the irrigation system. The number of strokes can be adjusted accordingly. The hydraulic motor may be activated by a pulse-generating water meter so that the injected chemical it is proportional to the water flow and a constant concentration is maintained. Automatic computerized control systems are also available to provide proportional injection of chemicals into the water flow.

The general advantages of the injection pump system are: the high degree of control of dosage and timing of chemical application, centralized and sophisticated control, portability, no serious head loss in the system, labour-saving and relatively cheap in operation. On the other hand, the installation is more complex and costly compared to other applications, and outside power sources may be needed.

5.2. DISTRIBUTION OF FERTILIZERS UNDER DRIP FERTIGATION

The fertilizer application through drip-irrigation systems is the most common application of the chemical injection techniques. Drip fertigation is an attractive concept, as it permits application of nutrients directly at the site of a high concentration of active roots and as needed by the crop.

However, following application through drip irrigation, mineral nutrients move into the wetted volume in a manner consistent with the flux of the water in the soil, their solubility and/or reactivity with constituents in the soil solution, and their interaction, if any, with the exchange sites of the soil. Since chemical characteristics of fertilizers differ, mineral nutrients are differently distributed in the soil when applied by drip irrigation (Bar-Yosef 1977, Papadopoulos 1985). The nitrate form of nitrogen does not react with the soil exchange sites and is not held in soils. Nitrates move with other soluble salts to the wetted front. This is of particular interest since NO_3-N should always be applied with every irrigation and at that concentration needed by the fertigated crop, is to satisfy its requirement in N from one irrigation to the other (Papadopoulos 1988a). Under irregular NO_3-N application the fertigated crops might be under the over-fertilization stress at the day of fertilizer application and under deficient stress due to leaching following the irrigation without fertilizer. The same applies, although at a lower degree, and for other nutrients that are not reacting with soil, and almost with all nutrients under pure sandy soils (Papadopoulos 1991, 1992). The ammonium form of N derived from ammonium or urea fertilizers is not nearly so subject to immediate leaching losses because temporarily may be fixed on exchange sites in the soil.

Potassium (K) is less mobile than nitrate (Goode *et al.* 1978), and distribution in the wetted volume may be more uniform due to interaction with soil binding sites (Kafkafi and Bar-Yosef 1980, Uriu *et al.* 1980). Drip-applied K moves both laterally and downward, allowing more uniform spreading of the K in the wetted volume of soil.

Phosphorus (P), contrary to N and K, is readily fixed in most soils (Kafkafi and Bar-Yosef 1980), although movement of applied P differs with soil texture. Commercial standard P-fertilizers may also precipitate in the irrigation lines in reaction with ions in the irrigation water such as Ca or Mg. Due to soil fixation of the applied P and the problem of low solubility and precipitation of P in the irrigation system, it has been suggested that under such conditions P not be applied through irrigation systems. However, such an approach reduces the availability of P with consequent significant reduction in the yield. The phosphoric acid is a useful source of P and in recent years widely used particularly in minisprinkler and drip fertigation.

5.3. FERTIGATION PRACTICES AND RECOMMENDATIONS

In fertigation both irrigation and fertilization affect plant behaviour, and adjustments in one factor can lead to limits imposed by other. For optimum plant performance under fertigation, all fertilization-irrigation input factors must be balanced so that none is imposing a significant limit.

However, the actual water and nutrient requirements of the crops, together with a uniform distribution of both water and nutrients, are important parameters in practising meaningful fertigation. In this respect, extensive research in developing fertigation recipes has been undertaken and some tentative recipes developed in Cyprus and elsewhere (Table 3). Evidently, the real crop water requirements, particularly under plastic and greenhouse production, is the most critical link between irrigation and sound fertigation. In this respect, research priority should be attached.

The recipes as suggested in Table 3, although they may be adjusted according to the soil fertility, are not based on physiological growth stages of crops. In this respect, substantial research is in progress since the crop demand to nutrients is dynamic, where not only the amount but also the form of the same nutrient and the ratio between the nutrients is changed.

6. Economic Benefits of Microirrigation and Fertigation Systems

Modern irrigation systems, including a fertigation unit, represent a substantial investment for the farmer. Therefore, the potential use of the fertigation technology is directly related to the extent to which the farmers are financially rewarded by using this technology. The level of increase in production, improvement of quality of produce, efficient use of inputs and saving in energy and labour are the main factors which are directly related to the acceptance of the fertigation approach by the farmers.

TABLE 3. Recommended concentrations of nutrients in the irrigation water ($g\ m^{-3}$)

Crop	N	P[1]	K
Cucumber	150 - 200	30 - 50	150 - 200
Eggplant	130 - 170	50 - 60	150 - 200
Bell pepper	130 - 170	30 - 50	150 - 200
Tomato	150 - 180	30 - 50	200 - 250
Potato	130 - 150	30 - 50	120 - 180
French beans	80 - 120	30 - 50	150 - 200
Strawberries	80 - 100	30 - 50	150 - 200
Lettuce[2]	100	30 - 50	150
Iceberg lettuce[3]	100	18	120
Shamouti oranges[4]	35	3 - 5	8 - 10
Banana[5]	15	---	45
Cotton	40 - 60	20 - 30	100
Sunflower	40 - 60	20 - 30	100

[1] P can be less than $30 g/m^3$; more research is needed
[2] Papadopoulos, I., 1987a
[3] Bar-Yosef and Sagiv, 1984
[4] Dasberg *et al.*, 1983
[5] Israeli *et al.*, 1985

In this respect, Table 4 indicates the striking increase in yield obtained in open field and greenhouses with modern irrigation systems by the same farmers before and after introducing fertigation in Cyprus. The results obtained under experimental conditions are even more striking and it is expected that the progressive farmers will achieve comparable yields in the near future.

Beside the increase in yield with the fertigation, by providing carefully balanced nutrient solutions to suit particular growth stages of the crop, fertigation has been also established an effective means which potentially may improve the quality of yield Tables 4, and 5. It has been experimentally found that fertigation is an effective way for increasing yield of vegetables and to maintain the NO3-N level in produce at low and acceptable levels for even the most demanding consumers in Europe.

TABLE 4. Yields (kg/ha) of some crops irrigated with modern irrigation systems as influenced by fertigation and traditional fertilization

Crop	Fertigation	Traditional fertilization
Potatoes	70000	37000
Carrots	54000	42000
Tomatoes (greenhouse)	350000	150000
Tomatoes (open field)	180000	55000
Cucumber (greenhouse)	300000	140000
Watermelon (open field)	115000	60000
Strawberries (low tunnels)	48000	20000

TABLE 5. Specific gravity, dry matter and starch in % and NO_3-N in mg/kg DM of potato tuber as nfluenced by fertigation and traditional fertilization

Characteristic	Fertigation	Traditional fertilization
Specific Gravity	1.073	1.064
Dry Matter	19.00	17.06
Starch	13.20	11.38
NO_3-N	141	290
Yield (kg/ha)	70000	37000

In Cyprus the area covered by modern irrigation systems accounts more than 95% of the total irrigated area. In this way the water application efficiencies achieved at the farmers level is 75-80, 80-90%, and 85-95% by conventional sprinkler, minisprinkler and drip irrigation systems, respectively, provided that the farmers follow the recommendations and irrigate according to the crop water requirements. This application efficiency, as compared to the traditional surface irrigation that has been practised some years ago, with water application efficiency ranging 40-50%, is substantially improved. The saving of water enabled further expansion of irrigated agriculture in Cyprus. With such high levels of water efficiency achieved, no further significant improvement of application water efficiency due to the irrigation system is expected. However, the yield per unit of water applied may be further increased by improving other limiting factors. In this respect fertigation has been found to be one and probably the most important single factor for such further improvement. It is estimated that the yield obtained by fertigation per unit area with the same amount of water applied increases by 2 to 3 times (Table 6). However, further research is in progress to study whether with such substantial increase in yield the widely accepted crop water requirements under fertigation should be reconsidered.

It has been found that more fertilizers are needed per unit area with fertigation, although the fertilizer efficiency is very high. This increase is needed to satisfy the higher yield obtained, although variable for different crops, roughly ranges between 30 and 50%. However, fertilizer amount per unit of water applied and per unit of yield obtained, decreases substantially indicating rational and efficient use of fertilizers. Experimental results and monitoring the fate of the fertilizers applied by fertigation at the farmers level, suggest that with appropriate fertigation recipes, adjusted to soil fertility, the fertilizer efficiency, particularly of N, can reach 80-90%. Evidently, the water allocation should be based on actual crop water requirements. With excess irrigation, since water is enriched with fertilizers, substantial loss of fertilizers particularly of nitrogen, is expected to occur deeper in soil. This is particularly important in sandy soils with low water holding capacity and very poor retention capacity for most of the fertilizers. The increase in yield and quality together with the improved water and fertilizer efficiency, make fertigation an attractive technology in modern irrigated agriculture. Adding to this that modern irrigation systems are expanded rapidly and have already been established in most countries as main irrigation systems, the additional cost for introducing fertigation is not a real constraint. However, the most important benefit of a sound fertigation programme is that agriculture could be based on a sustainable basis aimed at high yield and quality and yet protecting the environment from further pollution due to fertilizers.

TABLE 6. Yield of lettuce as influenced by continuous fertigation and soil application of two slow release fertilizers and a solid fertilizer

Treatment	Yield (5.4 m^2) in g	Wt/lettuce in g
Fertigation	76.8 A*	1066 A
Solid-powder	25.3 B	351 B
Paste I	26.8 B	373 B
Paste II	26.8 B	372 B

* Column means followed by the same letter are not significantly different at the 1% level.

7. Conclusions and Recommendations

Modern irrigation technology has mooved very rapidly from an experimental technique to a commercially significant method of irrigation. The ability to carefully control water application not only offers improved efficiency in the use of an increasingly scarce natural resources for agriculture, but opens the door to new and more efficient ways to manage fertilizers and other agricultural chemicals. However, future potential of modern irrigation/fertigation as means for sustainable agriculture on environmentally sound bases depends on a number of factors to which particular attention should be placed.

a. Availability and cost of micro-irrigation/fertigation systems. This should not be considered any more as a real constraint since in most countries reliable and relatively cheap equipment is available.
b. The micro-irrigation systems must operate properly, since any failure and/or losses of water also cause losses of fertilizers and of other chemicals applied with the irrigation water. In this respect, design and operation of the micro-irrigation systems must be proper to ensure uniform water distribution without losses.
c. Background on water requirements. Sound irrigation based on modern irrigation

technology requires sufficient background on crop water requirements. Under micro-irrigation systems, however, there are indications that the crop water requirements are changing. Therefore, research on this aspect could be of particular help to further improve water application efficiency.

d. In order to expect the highest possible benefits out of the use of modern micro-irrigation technology fertigation should be considered as an indispensable component of the system.
e. Research on fertigation should be intensified since the application of nutrients through the irrigation water not based on nutrients crop requirement might create serious environmental problems.

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DRAINAGE OF IRRIGATED LAND

S. BOUARFA*, B. LESAFFRE*, L. SMEDEMA**, D. ZIMMER*
**CEMAGREF*
Parc de Tourvoie, B.P. 121, 92185 Antony, France
***IPTRID Office*
World Bank, Washington D.C. 20433, U.S.A.

1. Introduction

The increase of the world population challenges the institutions involved in the agricultural development and in particular those in charge of water resources management. The sustainability of the agricultural system and its ability to respond to that challenge has become a major concern. Among the reasons for this are the ever increasing competition for water as well as the land degradation due to erosion and salinization. As pointed out by many authors, this calls for integrated land and water resources management policies to improve the efficiency of their utilization.

Irrigation has up to now played a major role in the increase of the world agricultural production: it is estimated that over one half of that increase over the past 25 years has come from expansion of the irrigated area and that 60% of the production of major cereals in the developing world derive from irrigation. The productivity of irrigated agriculture is however increasingly hampered by waterlogging and salinity problems induced by the combination of (1) increasing water application by irrigation, (2) low water use efficiencies and (3) poor natural drainage conditions. Improved drainage plays therefore an important role in the maintenance of the productivity of irrigated agriculture. This role is examined in the present paper which does not aim at reviewing all drainage aspects.

The paper includes four parts. The present situation of drainage and irrigation in the world is examined firstly. In a second part, the interactions between drainage and irrigation in the agricultural development are analysed. The third part focusses on the human, institutional and technical qualities a drainage project should comply with to adequately play its role toward sustainability. In the last part, general recommendations about engineering research needs and engineering priorities are presented.

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2. Drainage and Irrigation in the World

Irrigation facilities throughout the world are fairly well documented. The present extent of irrigated land is about 270 Mha and its annual growth rate is about 2 Mha (Smedema 1993a). A general overview of the global distribution of irrigated areas and of irrigation technologies is presented by Field (1990). The area provided with drainage (Table 1) is estimated to amount to about 170 Mha (Field 1990); out of this about 50 Mha benefit from pipe subsurface drainage (Lesaffre *et al.* 1992). The available statistics do not allow estimation of the area of drainage directly associated with irrigation nor of the annual growth rate of drainage construction in irrigated land.

An important difference between drainage and irrigation is that, whereas two-thirds of the drainage have been constructed in developed countries, two-thirds of the irrigated area are located in developing countries (Field 1990). As developing countries are mainly located in arid, semi-arid or semi-humid zones, it is likely that at least one third (about 50 Mha) of the drained land is irrigated. The applied drainage techniques are mainly open drainage by ditches with a rather low technological input.

Salinity problems are estimated to affect at least 20-30 Mha severely and 60-80 Mha moderately. The annual growth of the affected area ranges between 1 and 2 Mha (FAO 1990) and is comparable with the annual irrigated area growth rate. The problems are mainly located in developing countries.

TABLE 1. Global distribution of irrigation and drainage (adapted from Field 1990, Schultz 1990, Lesaffre *et al.* 1992)

Continent	Irrigation Mha	Drainage Mha	Subsurface drainage Mha
Africa	12	3.0	1.4
America	40.1	67.6	17.7
Asia (with ex-USSR)	161.6	44.9	13.8
Europe	37.8	51.1	20.5
Oceania	1.8	1.0	0.05
Total	253.3	167.6	53.45

Climate to a large extent determines the sustainability concerns regarding drainage and irrigation. Three climatic zones are considered in the following, each having its specific problems. These zones are:

- the *humid temperate zone*, where drainage is installed to prevent winter and spring waterlogging and to improve root zone aeration and trafficability;
- the *arid and semi-arid zone*, where the drainage role is to prevent or combat irrigation-induced salinization;
- the *semi-humid area*, where the drainage role includes both aspects of root zone aeration and salinization control.

These zones do not precisely correspond to classical climatic zones. The rainfall limit between semi-arid and semi-humid zones ranges between 500 and 600 mm per year.

In the **humid temperate regions**, drainage provides satisfactory root aeration during the rainy and cold season as well as adequate trafficability to farmer machinery. In these regions drainage has played an important role in agriculture intensification. Its contribution however is nowadays regarded as rather negative since its detrimental effects on natural resources and on water quality appear greater than its positive impact on food production. Controlled drainage and subirrigation provide a way to optimize the use of water resources and to reduce the leaching of pollutants to surface waters.

The increase of water available for crops after drainage installation (due to the better root development) provides another example of the interaction between drainage and irrigation. In regions where the summer water shortage is not severe every year, questions arise about the economic justification of irrigation. Conceivably, drainage could be a more appropriate and more economical way to improve crop water use and agricultural production, especially in deep soils with a high water storage.

In the **semi-arid and arid regions** prevention of irrigation-induced salinization is the main concern. These regions suffer from water scarcity due to the competition of several uses for water. The problem is increasing fast as these countries are mainly developing countries with high population growth rates. Drainage can be seen as a waste of water and the technical choice between an increase of irrigation efficiency and an improvement of drainage is of major importance.

Semi-humid regions are characterized by annual rainfall more than 500-600 mm and high evapotranspiration rates. With this amount of rainfall, there is generally enough natural leaching to maintain a low salinity in the rootzone in areas with good natural drainage. Among these regions are some mediterranean regions and regions with a monsoon type of rainy season. An important difference between these two types of climate is that in mediterranean climate the rainy season corresponds to the cold season whereas in monsoon climate the rainy season occurs during the hot season which is in general the major cropping season. In the first type of climate, the leaching properties of rainfall are therefore likely to be more effective.

The peculiar problem of these regions is to cope with both waterlogging in rainy seasons and irrigation induced salinization in medium or poorly drained areas. The combination of both problems is a technical challenge: the corresponding drainage design rate as well as the suitable drainage techniques, generally combining surface and subsurface techniques, have not been investigated extensively up to now (Smedema 1994).

3. Which Irrigation and Drainage Strategy?

3.1. DRAINAGE AS PART OF THE MANAGEMENT OF AN INTEGRATED SYSTEM

Drainage is a component of an integrated production system which includes: social and political aspects, economical and agricultural development, technology and techniques, environment. The waterlogging condition of the land is usually not the only constraint, and agricultural production may be restricted by many other factors: land tenure, farm size, farmers' education, farmers' organization, soil agricultural potential, irrigation and farming practices.

The drainage process must be considered in its entirety, at the project level as well as at a regional or even a national level and from technical as well as organizational and institutional standpoints. As a consequence, the interrelations between drainage and all these aspects should be considered. During the preparation of drainage project plans, these interrelations must be analysed and discussed. Planning decisions cut across all these aspects in the formulation of drainage plans and it is critical to understand the effect of each of them on the total system.

In the following, the physical aspects of the interrelations between both irrigation and drainage systems will be detailed in order to illustrate the complexity of the drainage problem in irrigated areas.

3.2. IRRIGATION AND DRAINAGE INTERACTIONS

All factors have to be considered for the determination of the need for drainage, and for the design and the planning of a drainage project. However, due to the complexity of the waterlogging and salinization processes, the interactions between all influencing factors for the definition of a proper irrigation and drainage strategy are difficult to take into account.

3.2.1. *Mechanisms and Factors of Irrigation Induced Waterlogging Salinization*
The occurrence of excess salt and water is to be expected in many areas of the irrigated semi-arid and arid zones. The major factors and processes of salinization have been widely investigated and documented. The problem results from a positive balance between salts deposited by irrigation water or by groundwater upward fluxes due to evapotranspiration and the salts leached by irrigation or rainfall waters. The water balance is of major importance for the process: a combination of low irrigation efficiencies (very often as low as 50%) and of poor natural drainage conditions inevitably results in waterlogging which in turn increases the groundwater contribution to evapotranspiration and the salt deposit. Depending on the amount of rainfall during the rainy season, a fraction of this salt will be leached.

The salinization of the irrigated lands of the Indus plain in Pakistan may serve to illustrate this (Table 2). These lands have been irrigated for centuries but the volumes of applied irrigation water were limited and an equilibrium existed between the recharge and the natural drainage of the groundwater, with watertables mostly being maintained at 30m or more below soil surface. Recharge of the groundwater increased considerably after the plain was equipped with irrigation, due to seepage from the canals and to field deep percolation (Mohtadullah 1990, Smedema 1993a). As a result watertables started to rise and they are now close to the soil surface in many areas despite the development of drainage systems (Aklilu and Hussain 1992).

TABLE 2. Water table rise in Indus plain from 1961 to 1981 (from Aklilu and Hussain 1992)

Year	Percentage of Indus Plain with water table depth:			
	0-3 ft	3-6 ft	6-10 ft	>10 ft
1961	2	11	23	62
1981	7	15	20	55

The same history applies to many other areas in the world. The time lapse between project construction and the first large scale appearance of waterlogging and salinization ranges from less than ten years to 50 years (Table 3). The range of variation accounts for different initial water table depths and for different irrigation efficiencies and canal losses. The salinization process itself results from climatic factors as indicated above. It is also influenced by several physical and technical factors (Figure 1) among which irrigation water quality and soil texture, which governs the upward capillary rise and the difficulty to remove salt; medium textured soils are more sensitive to salinization. Cropping system and cropping intensity also play a major role in (i) controlling the water table depth and (ii) limiting the rise of salts.

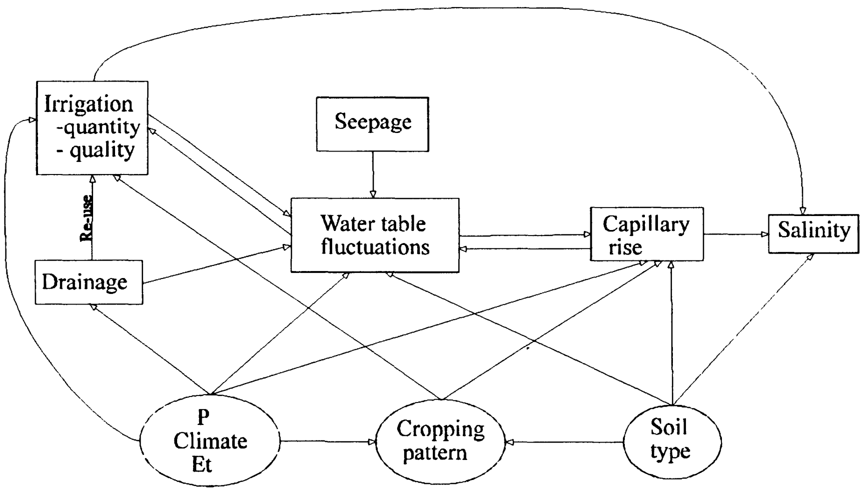

Figure 1. Interactions between physical and technical factors in an integrated drainage and irrigation system

TABLE 3. Time lapse between project construction and first large scale appearance of waterlogging and salinization (from Smedema 1993a)

Project	Time lapse (years)
Rajasthan Canal Project (India)	< 10
Western Desert Project (Egypt)	< 10
Amibara Project (Ethiopia)	10 to 20
State Farm 29, Xinjiang Province (China)	10 to 20
SCARP VI Project (Pakistan)	40 to 50
South West Punjab (India)	50 to 70

Non technical factors like water price, land tenure and investment policies also have a major indirect influence on the development of waterlogging and salinity in an area.

It can be concluded that, as pointed out by many authors (Gates and Grismer 1989, Smedema 1990, Abu-Zeid 1993), drainage of irrigated land aims at an integrated multi-objective water table management (salinization prevention, soil aeration, reuse and disposal of saline effluent).

3.2.2. *Drainage Needs and Planning in Irrigated Lands*

Artificial drainage of irrigated land is technically needed when either the leaching requirement or the rainfall recharge during critical periods exceeds the natural subsurface drainage capacity. However, there are many intermediate situations where the technical need for drainage is difficult to determine. In these situations the debate "improvement of irrigation efficiency" versus "improvement of drainage efficiency" is crucial as well as difficult to solve.

The adequate control and management of irrigation water, both at scheme and farm level, play a crucial role in determining the efficiency of water use and the extent of water losses. Water regulation, distribution plans and canal modernization at scheme level have to be studied as part of the project planning. Efficiency at the farm level starts with adequate water volumes received at the farm intake at the appropriate time; irrigation practices and scheduling should be continuously improved; appropriate technologies (modernized surface irrigation, development of sprinkler and micro-irrigation) should be transferred to farmers.

From examples from Pakistan, Brazil and Peru (Mohtadullah 1990, Prieto-Celi 1990) it has been shown that better irrigation water management always results in reduced drainage requirements. But since some loss of water is unavoidable, drainage is still needed above a certain level of water supply and cropping intensity. From its experience in Pakistan projects, Mohtadullah describes in non quantitative terms the relation between irrigation and drainage for an individual project (Figure 2):

- as water supplies increase, the cropping intensity increases but at a decreasing rate as farmer use more water per unit area of crop;
- as water supplies increase without drainage, the watertable rises to a new level, which causes loss of yield due to waterlogging and salinization;
- the increase in production due to the extra irrigation, and the decrease in production, due to the increased waterlogging, together mean that without drainage

extra water gives less and less benefit and eventually actually causes a loss in total production;
- for low to medium water supply and agricultural production, better irrigation water management is more beneficial than artificial drainage which is no longer true for higher production objectives.

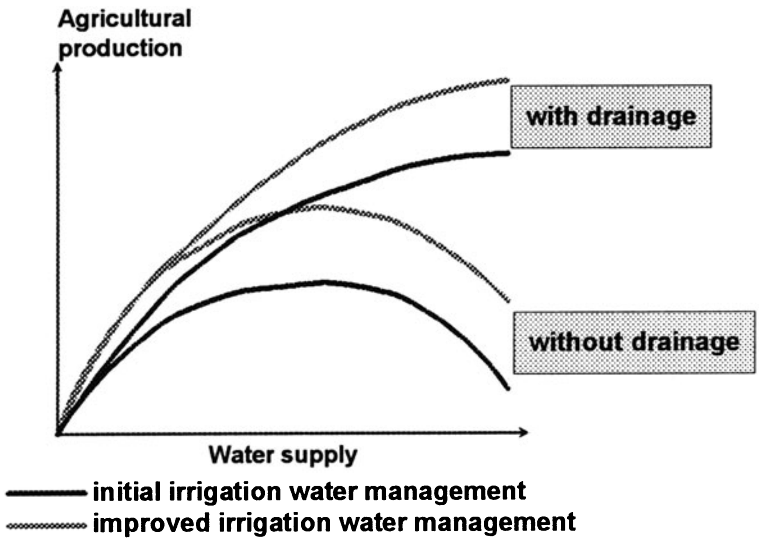

Figure 2. Agricultural production potential versus water supply (qualitative relationship adapted from Mohtadullah 1990)

As pointed out by Prieto-Celi, the drainage requirements ought to be determined and taken into account from the beginning of an irrigation project. For a proper drainage design, the impact of the change in the water balance induced by irrigation development should be determined early by means of hydrological and hydrogeological simulations. Irrigation and drainage should also be planned concurrently for the following reasons:

- coordinated planning of irrigation and drainage canal systems offers possibility to minimize crossings between the two systems and to include appropriate hydraulic structures; this results in better system design as well as a reduction in cost (Prieto-Celi 1990);
- besides the effect on the layout of the systems, simultaneous planning permits construction of both systems during the same period, thus avoiding extra costs that occur when one of the systems is built before the other is planned;
- if the construction of the drainage system is delayed, the place and location of the future channels and hydraulic structures is reserved, so that the execution of the drainage systems will not be hindered when it is decided.

3.3. WHAT DRAINAGE TECHNIQUES IN IRRIGATED AGRICULTURE?

Various means and methods of land drainage including surface drainage (furrows, land forming), horizontal subsurface drainage (open ditches, pipe drains), and vertical subsurface drainage (tubewells) have been developped in irrigated areas. Just like the evaluation of drainage needs, the choice of one of these techniques is mainly determined by economical, institutional, physical and environmental factors.

Surface drainage is much more prevalent than the two other methods. It presents the advantage of low costs and easy to use. However, to reach high levels of crop production, it is necessary to increase irrigation intensities, which results in an increase of losses, and may call for the installation of more efficient drainage systems. In most cases, the choice is between deep or shallow horizontal subsurface drainage and vertical subsurface drainage. The decision depends on the following factors:

- *the cropping intensities* determine the existence of fallow periods which induce a high salinization risk in case of shallow water tables; a deep horizontal drainage below the "critical depth" will be preferably chosen when cropping intensities are low and long fallow periods exits; a shallow horizontal drainage is more appropriate for high cropping intensities; a downward water flux through and beyond the root zone can in that case be maintained all over the year (Abu Zeid 1993);
- a *relatively high transmissive aquifer* is required for the installation of vertical drainage;
- *the environmental issues* of *disposal* and *reuse* of saline drainage water are crucial points which usually condition the choice of the drainage system; as a general rule, the utilization of tubewells is recommended when the salinity of the aquifer is not too high to jeopardize the reuse of drainage effluent in irrigation or to induce disposal problems; Hillel (1990) stresses the hazard of vertical drainage in shallow coastal aquifers which can cause an intrusion of saline water which is very difficult to drive back;
- *the scale of the problems and the origin of financements* may condition the choice; horizontal subsurface drainage is more area specific and has an action limited to the field level whereas vertical drainage operates at a larger scale; pipe drains will be in priority adopted in localized problems, especially when private sector has a share in the installation of drainage systems (Mohtadullah 1990);
- *the cost of the system* depends on many local factors; it is however estimated that the cost of vertical drainage, including power cost, is often less than horizontal subsurface one including gravel envelopes and power in flat regions (Mohtadullah 1990).

That combination of factors results in a great variability of situations. Wahab and Sheikh (1992) mention the examples of Nile Delta of Egypt, Mesopotamian Plain of Iraq and Indus Valley in Pakistan which concentrated the drainage activity of the Middle East during the last decade. These three regions are irrigated and have comparable climate, land slope and irrigation water quality. However, according to their soil conditions and agricultural practices, different methods of drainage have been chosen (Table 4).

TABLE 4. Drainage systems in relation to soils nature and agricultural conditions in three irrigated areas (from Wahab and Sheikh 1992)

Country	Soil conditions/ Agricultural practices	Drainage technique
Egypt	Heavy and poorly permeable soils. High cropping intensities (about 200%) which includes rice-growing. No secondary salinization.	Shallow horizontal subsurface drainage between 1.2 to 1.5 meters depth.
Irak	Medium to heavy soils. Low cropping intensities with fallow periods resulting in a salinization process by capillarity rise.	Deep horizontal subsurface drainage between 1.8 to 2 meters depth.
Pakistan	Medium textured and well permeable soils. Semi intensive cropping intensity. Fresh groundwater.	Tubewells drainage + deep horizontal subsurface drainage.

The combination of both systems may also be a solution in certain situations. Ansari (1992) describes the case of a vertical drainage in SCARP North Rohri in Pakistan where the recharge water is through seepage from canal system and drainage water. The quality of drainage water is poorer than the canal water one due to its storage which cause an increase of its concentration in salts by evaporation. The utilization of this water induces an increase of the general salt balance. To equilibrate groundwater salt balance, it is necessary to install surface or horizontal subsurface drainage to reduce drainage water deep percolation and thus to increase the dilution effect of canal seepage.

China provides a good illustration of an adaptation of an irrigation/drainage system. To face salinity and waterlogging problems in a semi-arid/semi-humid region, under the monsoon climate in the northern part of the country, the "Four Waters" concept has been developed (Shen and Wolter 1993). It involves a comprehensive control and management of groundwater, surface water, soil moisture and rainfall all over the year. Its basic innovation is to use a dense network of shallow tubewells for conjunctive use of drainage and irrigation and to consider the aquifer as a dynamic reservoir.

The validity of presently used steady-state methods for the design of horizontal subsurface drainage systems in irrigated areas is not yet clearly established. There is also a lack in knowledge concerning the criteria which have to be used to design vertical drainage. In addition, the currently allowed assumption that the water coming from horizontal subsurface drainage is fresher that the one from vertical subsurface drainage remains to be empirically verified (Smedema 1993b).

3.4. REUSE AND DISPOSAL OF DRAINAGE WATER

In irrigated lands, the aim of drainage is, to a great extent, to remove the salts deposited by irrigation water to ensure the sustainability of agriculture. However, the role of drainage does not end at the edge of the field and it is essential that the salt balance be maintained *both at field level and at basin level* (Smedema 1993c); to be effective, the drainage design should prepare a safe oultlet for the disposal of the drainage effluent.

The problems of disposal of saline water began in irrigated areas in United States (St Joaquim Valley) and in Australia (Murray river); various countries having recently developed drainage systems such as Egypt, Pakistan, Iraq, China, India are now confronted with this problem (Smedema 1993c). In some cases, the quality of the drainage water may allow its *reuse* for irrigation, but in many other cases the drainage effluent is too saline or polluted to be suitable for irrigation and has to be *disposed* safely. Moreover, presently, no economical solution exists to effectively treat the large volume of polluted drainage water, especially in low income developing countries.

3.4.1. *Reuse Potential and Strategies*

When it is not too saline (less than about 6 g/l in total disolved salts), or too polluted, reuse of drainage water in irrigation is obviously the most interesting solution in some situations. It presents the double interest to reduce (1) the irrigation water requirements in the various regions where water resources are limited; and (2) the volumes of drainage water and disposal problems. However, in low-rainfall areas e.g., India, Isarel, and California, various studies indicate that reuse of saline drainage water may be feasible only if others sources of irrigation water were available within the season; in humid and semi humid climates, large amounts of fresh water are applied each year, and make supplemental irrigation with saline water more feasible.

According to Grattan and Rhoades (1990), three principal strategies exist for conjunctive use of saline drainage water with irrigation water:

- *subirrigation* consists in managing the shallow groundwater depth so that crops can use this water directly; this method is technically difficult to implement since it requires the control of the water table at the right level for the crop; it may also result in increased salt concentrations in the root zone (Kruse et al 1990);
- *cyclic strategy* involves using alternatively fresh water to irrigate moderately salt-sensitive crops and establish salt-tolerant crops and saline water to irrigate the salt-tolerant crops during later growth stages; advantage of this technique is that more salt-sensitive crops can be included in the rotation; however, since the amount of drainage water does not coincide in time with crop water demand, it often requires to build costly surface storage reservoirs;
- *the blending strategy or conjunctive use* consists in mixing two waters of different qualities in order to obtain water suitable for agriculture; this strategy requires that a facility for blending the water supplies be built in the system.

In many cases, if the cost of drainage water disposal is not too high, the cyclic strategy is preferred against the two others due to the flexibility of this technique. However, uncertainty still exists about the long term effects of these practices on the physical characteristics of the soil. In irrigated areas where the reuse of drainage water in irrigation is considered, careful studies, such as field experimentations and modelling are strongly needed to evaluate the specific conditions of the area, and the long term impact of such methods.

3.4.2. *Disposal of Drainage Water*

In case drainage water cannot be reused due to a very poor quality (which may content, in addition of salts, elements such as fertilizers, pesticides, selenium, boron, arsenic etc...) or due to a lack of financial resources to undertake it, few solutions are possible for a proper disposal.

Discharge to surface waters is the most widely used practice today. The best solution consists in disposing the drainage effluent in the sea via specific conveyance system (Hillel 1990). However, too frequently, raw effluents are directly exported into the hydrographic network which may induce the salinization downstream to the point of discharge and cause hazards for the population. Wetlands can also be used as outlets with the risk of damages for these sensitive ecosystems. Water quality standards should be established at the national level for all receiving waters to protect beneficial uses, and determine the engineering design, dilution factors, and installation of conveyance and disposal facilities (Lee 1990).

Evaporation ponds are recommended when physical factors preclude discharge to surface waters. However, they also pose a risk to groundwater and environment. Thus evaporation ponds must be designed and operated with care in relation with the salinity and the toxicity of the drainage water (Lee 1990). Deep-well injection may be an other solution to dispose water drainage, but probably too costly for many of the countries.

Clearly, all options pertaining to the disposal of drainage water are likely to impact the larger environment and therefore requires careful studies considering the specific conditions of the region and comprehensive long-term considerations.

4. Key Factors for Drainage Sustainability

Four particularly important keyfactors may be emphasized for the achievement of a sustainable drainage project: organizational and institutional aspects; drainage project planning and implementation; field experiments and investigations; quality control of drainage systems.

4.1. ORGANIZATIONAL AND INSTITUTIONAL ASPECTS

It is of major importance that all organizations required, whether they already exist or not, should be identified at the planning stage and that funding for each activity should be adequately allocated. This includes not only the stages of the project itself, but also all the activities that are necessary for the project to progress properly. In preparing drainage project proposals, all partners involved in the drainage process (farmers and their representatives, surveyors, consultants, administrators, donors) must be associated. The participation of farmers long before the works are executed is critical for proper operation and maintenance. Overall management should be considered to start as soon as the objectives for drainage are set, including the role of organizations and individuals, and relating drainage to other main aspects.

From the analysis of existing organizations, both in drainage (Bos 1986) and in irrigation (Cernea and Meizen-Dick 1992), the following recommendations may be given. Designers of new projects should build upon existing organizations, provided that equity goals are not seriously compromised by maintaining the traditional arrangement. Indeed, where organizations exist (such as irrigation water user associations or polder associations), they can be expected to have legitimacy and a certain level of expertise.

The principle of working with existing organizations may seem obvious. Its implementation is not necessarily easy (lack of official recognition, improper functioning, overloaded capacity). Where no apropriate farmer organizations are preexistant, drainage projects must initiate the creation of new organizations.

Farmers' participation will usually be achieved through the formation of associations which will assume responsibility for operating and maintaining drainage systems to the *field level*. The associations should not be too large: too many members would have difficulties to meet; the costs of maintaining an organization, particularly in terms of conflict resolution and information management, will increase with size. Another major point is that farmers' associations must be viewed as belonging to the members, not as unpaid extensions of the government.

As regards drainage at *scheme level* (main drainage, hydraulic structures, pumping plants if any), larger organizations should be established: they may be associations' federations, borough syndicates, regional authorities. These organizations can also act as service organizations, when they render services to the farmers in order to secure optimum and sustained agricultural production.

4.2. DRAINAGE PROJECT PLANNING AND IMPLEMENTATION

Since drainage involves heavy long term investments and operational costs, the proper planning and implementation of drainage systems, both at field and scheme level, is essential. Well-planned and implemented drainage systems ensure a more efficient use of resources.

Some prerequisites are required for an adequate drainage project preparation. The need for drainage and for economic objectives should be defined; it should be specifically determined if other investments and practices resulting in extra costs are needed. Water master plans, with due consideration to adequate outlets and disposal works, flood control, interrelation with groundwater use and managements should be elaborated. Land reclamation and consolidation, in areas where farms are small and fragmented, should be developed; the lengthy process of land consolidation (a few years) should systematically be carried out ahead of drainage (and irrigation) works construction, otherwise the start of drainage projects may be delayed, and sometimes jeopardized.

Drainage projects require survey and investigations of site conditions and study of various data to determine their feasibility and to design the systems. Three stages of drainage investigations are usually distinguished (Lesaffre et al 1992): reconnaissance, semi-detailed, and detailed surveys. Existing data are collected and the survey is supplemented by field inspection and discussions with all people involved. The existing investigations should be reported and mapped (scale of 1:50,000 to 1:250,000) and additional investigations should be defined and funded.

The primary objective of the semi-detailed or preliminary survey is to provide a preliminary plan of the future drainage systems (scale of 1:10,000 to 1:25,000) and a rough estimation (to an accuracy of some 10 to 20 percent) of the costs. The soil map should not be conventional but should give information related to waterlogging and drainage operation. At the end of this stage, the drainage techniques and criteria for the various soils should be known or, if not, subject to continuous investigations such as field experiments.

The extent of this preliminary survey and the number of field experiments depend upon the existing knowledge, upon the size of the project area and upon the complexity of problems. For large areas where drainage systems are to be constructed within a rather limited period, surveys should cover the whole area. For smaller areas or agro-climatic areas where the need for drainage is not systematic or where drainage systems will be installed over a long period, investigations should focus on a limited area representative of the whole area (pilot or reference area). For small projects involving individual farmers, the survey may begin at the detailed stage, provided that there is no feasibility problem.

Detailed surveys (scale of 1:2,500 to 1:5,000) should accurately delimite the soil units, the sources of excess water and salt and the recommended drainage techniques. They are required for design of construction plans and specifications, which will be the basis or the call for tenders.

4.3. FIELD EXPERIMENTS AND INVESTIGATIONS

Field experiments, pilot testing and monitoring of existing drainage systems have proved to be very effective at project levels as well as at national levels.

Surface and subsurface drainage is not an exact science, but depends on many more or less advanced disciplines. A lot of skill is still needed, and drainage specialists are not only excellent scientists, but they are also experts with much field experience. Present drainage criteria and technologies are *semi-empirical* and, whatever the progress of knowledge, formulas will never be sufficient for decision making. Local specific criteria and technologies have to be developed, modified and checked using monitored systems like field experiments or pilot testing. Scientific investigations on existing drainage systems should be carried out in order to determine how appropriate the previous recommendations were and to possibly improve the present state-of-the-art.

Field experiments may have five basic functions, most often combined within a given experimental site:

(a) creating *awareness on drainage* and demonstrating effective techniques;
(b) evaluating *drainage system ageing* and determining factors affecting the *sustainability* of drainage systems;
(c) assessing the *cost* and *benefit* of drainage;
(d) testing *drainage criteria,* related to design (e.g. drain spacing or depth), construction (e.g. type of envelope) or operation (e.g. farming practices);
(e) evaluating the *impact of drainage* on environment, on river flooding, and on water quality.

These functions will not be thoroughly discussed here, as much literature is available on the subject (for instance see the proceedings of International Drainage Workshops edited by Wesseling 1979, Ochs and Willardson 1983, Smith and Rycroft 1986, Saavalainen and Vakkilainen 1986, Nolte 1987, Daniane 1990, Lesaffre 1990, Vlotman 1992).

Functions (d) and (e) are best fulfiled using models calibrated versus field data. Present scientific debates mainly focus on topics related to these functions and to the use of models. Some agreements have been reached within the scientific community:

- various types of models have to be developed according to different objectives;
- increase in knowledge on fundamental mechanisms require laboratory experiments and data;
- for management purposes, it is recommended to use field data measured at a scale which should be consistent with the size of the hydraulic systems so as to obtain field effective values;
- as regards drainage criteria, investigations on agronomical input data are less developed than on hydraulic input data.

Fewer scientific investigations deal with functions (a), (b) and (c). Nevertheless, there is much experience developed by actors involved in the drainage process. This knowledge is seldom widely shared, mainly due to a scarcity of publications; even in developed countries, technology transfer to users is critical and should be done through national and international networking (IPTRID 1993).

Field experiments and research have to be performed in close relationship not only with research institutes and academic research in universities but also with drainage managers and users. For this purpose, field adaptive research projects should be linked to a country investment Programme. This has three main advantages:

- funds can be more easily allocated to a research component of a large investment project;
- people in charge of the investment project are more eager to incorporate the research findings to the design, construction and operation of the drainage systems;
- dissemination of the results to the users and to the decision markers is made easier.

4.4. QUALITY CONTROL AND MAINTENANCE OF DRAINAGE SYSTEMS

To meet the expected performance and economic criteria, installed drainage systems should be of good quality. This applies especially to the used materials and construction methods.

Nowadays almost all the countries use plastic pipes made from PE (polyethylene) or PVC (polyvinyl chloride); clay and concrete pipe are still used, but mainly for the larger diameters. The quality control of material is thus concentrated on the manufacture, carriage, stocking, and installation conditions of plastic pipes. Several countries have very detailed quality standards; an International and an European standards are also currently in preparation. Based on them, some general applicable guidelines regarding corrugated plasic pipes are recommended for the most places where no real quality standards exist (Summers et al 1990).

Due to the development of mechanized drainage execution works, it has become necessary to establish construction standards. Several standards have been developed in different countries. To reach a good quality of pipe laying, the combination of the pipe laying tool with the grade control equipment and command should be thoroughly tested and harmonized in the factory (Westland 1990). Several grade control systems are currently used for drainage installation. Manual systems continue to exist, such as the use of boning rods, where the driver manually maintains the slope of the pipe. However, the recent grade control systems, like laser command which is directly linked to the machine hydraulics, allow considerable improvement of the quality of the pipelaying.

The poor performance of drainage systems, as well as of irrigation systems, is often attributed to the low level of maintenance of ditches and canals. The main problems are due to aquatic weeds which infest many watercourses all over the world. When their growth are not adequately managed, plants clog intakes, reduce conveyance capacity, increase evapotranspiration and harbour the vectors of waterborne desease. Due to the increase of the maintenance cost with the frequency of interventions, the key to cope with the problem is to use a maintenance plans which incorporate regular weed management (Brabben 1993).

Clogging hazards of horizontal pipes should be, especially in unstable soils, avoided by the use of envelopes. Gravel envelopes are currently used and provide and adequate protection when it is well graded and properly installed; otherwise, synthetic envelopes may be a solution (Dierickx 1992). The long term viability of the drainage systems also depend on bank stability of ditches and on the control of tubewells performance which should be regularly carried out.

As a well-functionning drainage system in irrigated areas is of first importance to conserve soil productivity, continuous monitoring is necessary. A specific authority, which should dispose of the appropriate means, should assumed this task (Dierickx 1992).

5. General Recommendations

1. Information regarding drainage in the world in agricultural land are presently missing. A survey of the drainage extent and its relationship to irrigation should be regularly carried out by ICID (International Commission on Irrigation and Drainage).
2. Technical references for drainage in semi-humid regions are missing. They could be acquired and exchanged between countries belonging to these areas. This task could be supported by IPTRID (International Programme for Technology Research in Irrigation and Drainage).
3. Drainage in irrigated land should always be planned concurrently with irrigation. The required drainage efficiency is related to the irrigation efficiency and both efficiencies should evolve interactively according to the state of agricultural development.
4. The sustainability of any technical innovation relies upon the active involvement of the ultimate users. Farmers' participation and organization should consequently be paid special attention at all stages of implementation of any drainage scheme in irrigated areas.
5. Field investigations and experiments should be developed together with modelling and long term monitoring at scheme level to assess the impacts of waterlogging and salinity and to check the efficiency of the drainage technique to achieve favourable root zone conditions. To help implementing them, it would be useful that the FAO Irrigation and Drainage Paper Number 28 on drainage testing (Dieleman and Trafford 1976) be updated. At the project or country level, investment programmes should include a research and development component. 1 or 2 % of the total works cost for this component may reduce by 10 to 20 % the investments cost and improve the operation and maintenance.
6. The data provided by the above monitoring should also aim at providing guidelines and criteria to properly design the drainage systems and may allow to update the FAO Irrigation and Drainage Paper Number 38 on drainage design criteria (Dieleman 1980).

7. Research on water reuse and on the impact of drainage on water quality and quantity should be developed.
8. The viability of drainage systems should be paid more attention. Maintenance of systems is of major importance for their sustainability; clogging hazards of horizontal pipes, bank stability of ditches, and tubewells performance should be investigated.

6. Conclusion

Drainage of irrigated land is expected to increase in the near future to prevent and combat irrigation-induced salinization and therefore improve the sustainability of the farming systems. In many developing countries however, policy formulation and project preparation is severely handicapped by lack of reliable information on the nature and extent of the affected area and therefore on drainage needs.

Drainage and irrigation should follow a common development strategy since both techniques are interrelated. Methods to achieve this common strategy are still to be developed; they require interdisciplinary approach to take account of the variable social, physical and technical factors involved. Research and development play an important role to develop these strategies: long term monitoring, field experiments and modelling at different scales should in particular be emphasized.

In terms of research and development, the suggested priorities are: (1) groundwater management at basin level to properly evaluate drainage needs and propose suitable drainage techniques; (2) development of suitable drainage technology and design methods in semi-humid areas facing both salinity and rainfall induced flooding and waterlogging; (3) development of conjunctive use or reuse water management strategies as well as suitable techniques for drainage water disposal, and (4) development of adequate institutional arrangements to ensure proper maintenance of drainage systems.

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PART V

WATER QUALITY MANAGEMENT

SALINITY MANAGEMENT IN IRRIGATED AGRICULTURE

N.K. TYAGI
Principal Scientist
Central Soil Salinity Research Institute, Karnal, India

1. Introduction

Salinity is one of the most serious problem faced by the world irrigated agriculture. Recounting the damages inflicted by salinity Hall (1974), writes that "History is on their (forces of degradation) side, as are the laws of physics, chemistry and biology. Today, every arid land region of the world is in some immediate or final stage of this process". But there can be no doubt that our long term economic survival depends upon how we come to terms with the problem raised by soil and water salinity.

The increase in salinity levels, be it in the crop root zone or in the ground water, appears to result from disturbances in hydrologic ground water balance which is influenced by the land and water management practices carried out over a period of time. If the assumption, that emerging hydro-salinity problems in a given region are the consequence of water management practices, is accepted, then it would be logical to postulate that prevention and control of salinity can be effected through manipulation of water management activities. Assuming that it is technically possible to evolve a system of water management that would keep hydro-salinity regime under control, the next question is the associated costs that determine economic feasibility. Embedded in management schemes are the alternatives and their trade-offs. In this paper we discuss the process of salinity development in different forms, their extent and distribution and approaches to problem solving. Also discussed are the research and development issues looking for solution.

2. Nature, Extent and Distribution

2.1. NATURE AND PROPERTIES

Salinity is defined as the concentration of salts present in soil and water per unit volume or weight. Two categories of problems can be roughly identified: (1) presence of excess soluble salts that interfere with plant growth due to increased osmotic effect, and (2) presence of excess exchangeable sodium that creates problem of poor permeability and tilth. Sometimes a combination of both, excess salinity and sodicity

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may be present. Excessive presence of certain trace elements like boron, selenium and cadmium etc., also interfere with plant growth. A combination of factors which are mainly geological, climatic and hydrological in nature are involved in formation of salt affected soils. Critical mineralization and critical depth of mineralized ground waters were considered important by Kovda (1961) in describing secondary salinization. Evaporation, capillary rise of mineralized waters in the presence of high water table, mineral weathering and addition of salts by irrigation water are the major processes involved in salinization. The chemical exchange reactions involved in formation of alkali soils are given in Kelley (1951) and Kovda (1961).

Saline soils (soils with high electrolyte concentration) have normal physical properties. But the presence of excess exchangeable sodium in alkali soils induces poor physical properties resulting in compaction of top layer, destruction of soil structure and extremely low transmission characteristics. The affected soil properties that have influence on soil-water behaviour are infiltration, hydraulic conductivity, soil moisture retention and storage. Due to the dispersed soil structure, the infiltration rate of alkali soil is very low as compared to normal soil. The breakdown of aggregates and consequent dispersion of the soil particles in the presence of water, causes a surface seal, which greatly impedes water intake by the soil. As a result, the moisture extent in the alkali soil is considerably less as compared to normal soils . It seems that the total water storage is effectively reduced due to restricted entry from the surface layers (Abrol and Acharya, 1975). Since plants take water from the soil in the root zone, the availability of water to plants is considerably reduced.

2.2. EXTENT AND DISTRIBUTION

Soil salinity is of common occurrence in arid and semi-arid regions wherever irrigated agriculture has been practised. Reports indicate (Brinkman, 1980) that out of the total area of 985.7 million hectares occupied by problematic soils, nearly 322.9 millions hectares is accounted for by saline and sodic soils (Table 1). This constitutes nearly 5 percent of the total geographical area of the earth and about 23 percent of presently cultivated land in the world. Tanji (1990) estimates that the area under saline soils is 340 million ha and that the area under alkali soils is 560 million ha . Szabolcs (1989) estimated that 10 percent of arable land is on saline alkali soils spread over 100 countries.

Salinity is a major problem in India, Pakistan, China, USA, Soviet Union, Australia, Iraq, Hungary and UAR. Irrigated area damaged in the top five irrigated countries in the world is given in Table 1.

3. Management of Salinity

Salinity management is a problem of multiple dimensions and includes different aspects of agriculture, engineering and economics. Broadly salinity management can be considered a two stage problem: (1) root zone salinity management, and (2) regional or project level salinity management.

TABLE 1. Irrigated land damaged by salinization in top five irrigator countries

Country	Irrigated area damage (Million ha)	Share of irrigated land damage (percent)
India	5.4	10
China*	7.0	15
USA*	5.2	27
Pakistan*	3.2	20
Soviet Union*	2.5	12
Total	23.3	

* Source: Postel, 1989

3.1. ROOT ZONE SALINITY MANAGEMENT

The engineering and agronomic practices for management of saline or sodic soils and waters at field level are as follows.

1. Using chemical amendments to improve physico-chemical properties.
2. Land preparation methods that facilitate uniform infiltration of water.
3. Following irrigation procedures that maintain sufficient soil moisture and cause periodic leaching.
4. Adopting irrigation methods that permit frequent, uniform and efficient water application with as little percolation loss as possible without curtailing essential leaching requirements.
5. Using planting procedures that minimize salt accumulation around seed.
6. Avoiding use of saline or sodic waters at sensitive stages.
7. Practising conjunctive use.
8. Providing leaching and drainage to take care of excess salt and water.

These practices will be discussed here after:

3.1.1. *Common Amendments And Their Quantities*

Unlike saline soil and waters, alkali soil and waters respond to chemical amendments. Materials that directly supply the soluble calcium for replacement of exchangeable sodium are called amendments. The choice of an amendment and the quantity required for reclamation depends on the physico-chemical properties of the soil, the amount of exchangeable sodium to be replaced, the desired rate of improvement, the quantity and quality of water available for leaching and the cost of the amendment. The usual amendments are given in Table 2.

Prather *et al.* (1979) have reported the advantages gained by using the different amendments in combination. The quantity of amendment needed to reclaim an alkali soil is determined as a product of gypsum requirement (the equivalent amount of exchangeable sodium to be replaced in the soil) which is multiplied by a factor (1.2-1.3) to compensate for the inefficiencies. Based on pH value of soil in 1.2 soil water suspension, Abrol *et al.* (1973) have developed a graphical relationship to determine the gypsum requirements of light, medium and heavy alkali soils (Fig.1). The assessment of gypsum requirement is based on cation exchange capacity (CEC) of different types of soils. The quantities of gypsum computed by this method are, however, approximate.

3.1.2. *Precision Land Levelling*

Land formation which is accomplished through levelling is the most important practice for improving irrigation efficiencies. What is required is not to make the land level but to grade the surface to a uniform slope. The degree of levelling is generally expressed in terms of levelling index (Tyagi 1984) or the topography index (Khepar *et al.* 1982). The levelling index may be defined as the average deviation in elevation from the elevations required to achieve a planned grade. Precision land levelling benefits the crop by permitting application of smaller irrigation depth at more frequent intervals. Field investigations were made at CSSRI, Karnal to evaluate the effect of precision levelling on application depth, irrigation efficiencies and crop yield (Tyagi 1984).

The relationship between system application depth, and levelling index for a typical alkali soil of the Indo- Gangetic plain is shown in Fig. 2. It is seen that the average system application depth increases with increase in the levelling index. As the depth per application increases the application efficiency decreases (Fig. 2). Since for a given seasonal irrigation depth, the depth per application and the number of irrigation in a season will be fixed. If the depth of irrigation per application is low, the number of irrigation and hence the frequency would be high. But, if the depth per application is high the number of irrigation would be less and frequency would also be low.

TABLE 2. Gypsum equivalent of different amendments

Amendment	Amount equivalent to gypsum
Gypsum ($CaSO_4 . 2H_2O$)	1.00
Sulphur (S)	0.19
Sulphuric Acid (H_2SO_4)	0.57
Lime Sulphur (24% S)	0.77
Calcium Carbonate ($CaCO_3$)	0.58
Calcium Choride Dehydrate ($CaC1_2 . 2H_2O$)	0.85
Ferrous Sulphate ($FeSO_4 . {}_7H2O$)	1.61
Aluminum Sulphate ($A1_2(SO_4)3 . 18H_2O$)	1.29
Iron Pyrite ($FeS_2 .$ 30% S)	0.63

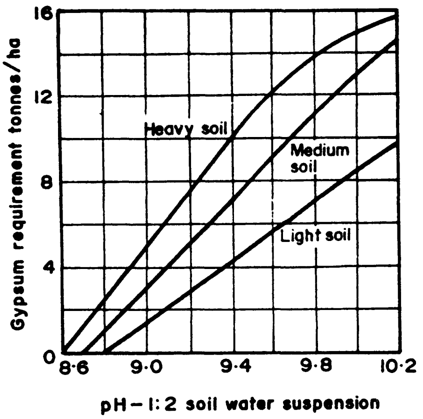

Figure 1. Nomogram for calculating gypsum requirement in alkali soil
Source: Abrol *et al.* (1973)

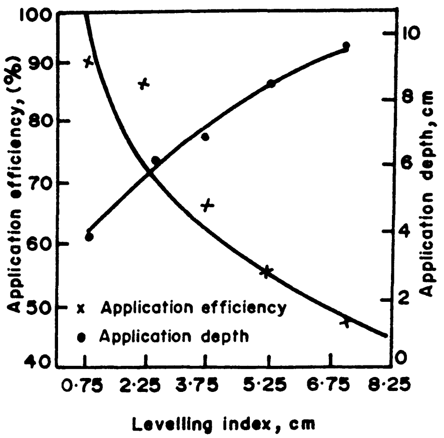

Figure 2. Relationship between levelling index, application efficiency and application depth
Source: Tyagi (1983)

3.1.3. *Water Application Methods*

Proper choice of the application method greatly facilitates reduction in drainage volume, uniform leaching and use of poor quality water. There are a number of irrigation methods through which water is applied to crops. These are broadly classified as gravity flow and pressurized systems. Excess water through different methods of irrigation may be applied because of: improper design of the system; improper choice of the method of water application; lack of control of water application depths during the process of irrigation,and non-uniform application resulting from non-uniformity in soil infiltration rate or irrigation system or both.

Border strips, furrows and level basin are the commonly used surface methods of water application. In alkali soils where uniform leaching and downward movement of salt and water flux are the primary considerations, the use of furrows and subsurface methods is precluded. The preferred cropping pattern during the initial years being rice during summer and wheat, berseem and barley during winter, the use of sprinkler has also not been found beneficial (Pandey and Singh 1976). Tyagi (1983) studied the relative performance of level and graded borders in alkali soils and found that graded borders were efficient by as much as 30 percent. Surge method is also being advocated in areas where infiltration rates are high (UC Committee of Consultants on Drainage Water Reduction, 1988). This method reduces the water lost due to deep percolation and thus decreases ground water recharge.

In micro-irrigation which includes several pressure system like drip, trickle, bubbler and miniature spray, irrigation efficiency varies from 75-85 percent while the distribution uniformity is between 80-90 percent. The salinity hazards in highly efficient system are of utmost concern. As matching between irrigation application and evapotranspiration is very precise, a higher degree of salinity management is needed. Due to frequent irrigations, soil plays much less important role as moisture storage reservoir as compared to surface irrigation. Drip irrigation is most suitable for applying saline water in row crops. The system can be planned to operate at low leaching fraction and still ensure uniform distribution over the entire field. The efficacy of the drip system in using saline water has been tested over the world. In India also the experiments with drip irrigation at several locations have shown that it is possible to maintain higher water use efficiency and low salt accumulation when saline water is applied by drip system (Singh and Singh 1985, Gupta and Tyagi 1985).

Pitcher irrigation technique which uses earthen pots buried in soil also offers scope for saving water in irrigation of horticultural crops like grape, watermelon and gourds etc. The technology being simple and available at village level has its own advantages. The irrigation requirements and irrigation schedules with different quality waters were investigated (Dubey *et al.* 1991). Results in case of grapes indicated that water salinity even up to 8 dS/m did not have any significant effect in fruit yield in case of daily filling. But drastic yield reductions occurred in the third day filling as compared to the daily filling when the salinity of water exceeded 4 dS/m (Table 3). Studies on salt tolerance of various crops as influenced by pitcher irrigation have also been conducted. It was observed that some vegetable crops, when irrigated by pitchers, were able to tolerate much higher salinity water (Cabbage : 9.75 dS/m, Brinjal : 9.8 dS/m and Ridge gourd : 9.2 dS/m).

TABLE 3. Effect of pitcher irrigation interval on growth yield and chemical composition of grapes

Applied water salinity EC DS/m	Yield/pitcher (kg)			Chemical composition of fruit juice	
	Irrigation interval			EC dS/m	pH
	Daily	Second day	Third day		
0.4	5.4	4.5	3.8	1.75	3.59
2	4.5	4.8	5.7	1.29	3.39
4	4.4	4.6	5.6	1.37	3.35
6	5.9	3.9	3.0	1.44	3.31
8	4.5	3.9	1.5	1.60	3.47

(Dubey *et al.*, 1991)

3.1.4. *Leaching of Salts*

Leaching is practised for reclamation as well as for maintaining salt balance during the process of irrigation over a season. Leaching may be practiced by ponding water continuously or by intermittent ponding. In milder climates where evaporation rates are low, intermittent leaching is more efficient. In monsoonal climates as it prevails in India, leaching by ponding, which occurs naturally during periods of heavy storm, seems desirable. Normally leaching curves are prepared to determine the amount of water that may be actually required to reduce the initial salinity by a certain percent. A saving in fresh water (Fig. 3) can be effected by performing part of the leaching with saline water which is less saline than the soil to be leached (Gupta and Pandey 1983). It is important to establish the threshold salinities of water draining from the root zone to determine leaching requirements. Such limits for important crops are given in Table 4 (Anonymous, 1989). There is a need to consider the effect of irrigation system nonuniformity and soil spatial variability effects on leaching.

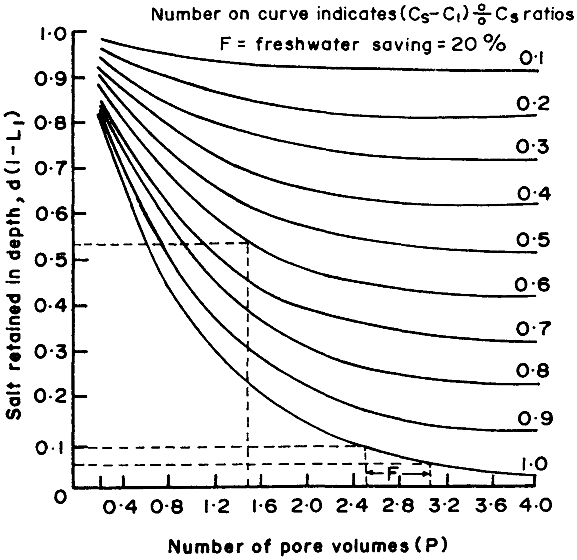

Figure 3. Correlation diagram for evaluating freshwater saving during reclamation (Gupta and Pandey, 1983)

3.1.5. *Drainage*

Like irrigation, drainage is a moisture control system that is required to maintain moisture and salt balance in the root zone. Problems of surface water inundation, that are more severe in alkali soils, are mostly taken care of by surface drainage which is accomplished by land grading. Naryana (1980) proposed a three tier surface drainage system for alkali soils. The important features of this system were: collection of part of the rainwater in crop land till such a time and extent that it was not harmful to crops; collection of the excess water from the crop land into farm ponds in low lying areas and its utilization during dry spells, and drainage of excess water from farm ponds into regional drainage system.

Subsurface drainage is accomplished through vertical and horizontal drainage. Technological options to provide vertical drainage include several variations of shallow wells including: common filter and cavity tubewells, single skimming wells or tubewells and multiple well points. For designing skimming wells the important points of consideration are: thickness of relatively fresh water aquifer; well penetration depth, and pumping rates. Vertical drainage has been used with considerable success for reclaiming alkali lands in India (Abrol *et al.* 1988) and China (You and Wang 1983). Well points are being used successfully in Australia for skimming relatively fresh water in salinity affected area.

TABLE 4. Salt tolerance of important crops as function of electrical conductivity of soil saturation extract (C), where relative yield Yr is in percent = 100 - S(C - Ct)

Crop		Electrical conductivity of saturated soil extract	
Common name	Botanical name	Salt tolerance Threshold (CT) dS/m	% Yield decline (S) (% per dS/m)
Barley	Hordeum vulgare	8.0	5.0
Bean	Phaseolus vulgaris	1.0	19.1
Corn	Zea mays	1.7	12.0
Cotton	Gossypium hirsutum	1.7	5.2
Rice, paddy	Oryza sativa	3.0	12.0
Sorghum	Sorghum bicolor	6.8	16.0
Soybean	Glycine max	5.0	20.0
Sugarcane	Saccharum officinarum	1.7	5.9
Wheat	Triticum aestivum	6.0	7.1
Bean	Phaseolus vulgaris	4.0	9.0
Potato	Solanum tuberosum	1.7	12.0
Tomato	Lycopersicon lycopersicum	2.5	9.9

* Percent yield decline is the rate of yield reduction per unit increase in salinity key and threshold.

Source: Mass and Hoffman, 1977

Horizontal subsurface drainage primarily means keeping watertable under control and taking care of leaching waters where water table remains above a given depth for a considerable length of time. Large scale horizontal drainage programmes are underway in Egypt and Pakistan for providing horizontal drainage to reclaim land and maintain salt balance. In U.S. which had large scale horizontal drainage for salinity control, it is not finding favour now because of environmental concerns; discovery of selenium in drainage waters has been major cause for reversal of the drainage policy. In India horizontal drainage has been limited to a few pilot projects. Results of one such pilots study indicated (Table 5) that horizontal drainage restored productivity by lowering water table and removing salt in a very short span of time (Rao *et al.* 1986). Experiences in India show that there is a need to revise the drainage criteria for drainage of saline lands. It should be based on seasonal salt balance rather than lowering watertable at a given rate.

TABLE 5 .Yield (1000 kg/ha) of crops and salt removed under sub-surface tile drainage system at Sampla (Haryana) in 1985

Crop	Drainage spacing (m)		
	25	50	75
Wheat	4.94	4.08	2.50
Barley	4.20	2.96	2.09
Cotton	1.80	1.64	1.60
Salt removed (mg/ha)	38.05	35.50	39.08

Source: Rao *et al.* (1986)

3.1.6. *Conjunctive Use*

Conjunctive use not only facilitates the use of poor quality water to increase area under irrigation but also minimizes drainage water disposal problems. The important issue related to conjunctive use of saline and fresh water is the mode of application. Saline or sodic waters could be applied to crops in three possible ways: application of saline water alone; application after blending fresh and saline water, and cyclic use of fresh and saline waters. The choice of an application mode depends on the quantity and quality of fresh water available from different sources, on soil texture, on crops to be irrigated and on the climate. Recently considerable research on technical aspects of dilution process (mixing different kinds of water into a single distribution system) within the water distribution network have been developed (Jury *et al.* 1980, Tyagi and Tanwar 1986). Water blending can be done in the main canals and distributaries or in the watercourses. Farmers in Haryana (India) have installed shallow tubewells along the canal watercourses to blend the saline water with canal water. A mixing distance of 15-20 m is generally allowed before using the water.

The advantage of cyclic application is that use of saline water can be avoided at the sensitive stages. Work at CSSRI and at several other locations has shown that avoiding saline water application as presowing irrigation would enable the user to minimize yield losses (Minhas *et al.* 1988). Based on field studies at some locations in India, the recommended cycles of saline and fresh water application for different crops are given in Table 6 (Anonymous 1989). It may be added that, as compared to blending, cyclic application is more common and has certain advantages over the former (Rhoades 1984).

TABLE 6. Cycles of fresh and saline water irrigation

Crop	Location	Soil type	Irrigation mode
Soybean	Agra	Sandy loam	2C:1T; 1C:1T
Jowar	Agra	Sandy loam	2C:1T; 1C:1T
Sorghum	Agra	Sandy loam	2C:1T; 1C:1T
Cabbage	Agra	Sandy loam	2C:1T; 1C:1T; 1C:2T
Summer	Dharwad	Black soil	2C:1T; 1C:1T
Cowpea	Dharwad	Black soil	2C:1T; 1C:1T
Maize	Bapatla	Black soil	2C:RTS; 1T:RTC
Wheat	Agra	Sandy loam	2C:1T; 1C:1T

Note: C = Canal water irrigation,
T = Tubewell (saline) water irrigation,
RTC = Rest of irrigation with canal water,
RTS = Rest of irrigation with tubewell water.
Numerals before C or T refer to number of irrigations by canal or tubewell water.

Source: Anonymous, 1989

3.2. REGIONAL SALINITY MANAGEMENT

The regional or project level salinity management is built around objectives related to environmental quality and regional and national economic development. Whereas root zone salinity management may help in coping up with the problem on short term basis, long term solutions have to keep in view that in a drainage basin, human beings, animals and plants share a common water supply. The water needs in respect of quality and quantity for all the users have to be fulfilled on a sustained basis. In regional salinity management the three important activities are: determination and implementation of optimal mix of irrigation system improvement interventions and their priorities; taking care of environmental problems arising from drainage effluent disposal and reuse; and enforcement of rules, regulations and incentives promoting use of environment friendly technology.

3.2.1. *Optimal Mix Of Irrigation Return Flow Minimizing Interventions*

Salinity management at project level is the outcome of judicious choice of irrigation system improvement interventions and their proper implementation in order to improve the system efficiency. To arrive at optimal plan it is necessary that the decision maker is able to: forecast with reasonable accuracy the response of aquifer system to changes imposed on the hydrologic system, and select the best management practices consistent with the hydraulic, hydrologic and socio-economic restrictions.

Considerable attention has been given to the development of optimal strategies for salinity control by working out the cost effectiveness of different alternatives (Evans *et al.* 1983, Tyagi 1986, Gardner and Young 1987). Recently Tyagi *et al.* (1993) proposed a method to provide decision support to irrigation system improvement programme. The two important components of the method were: (1) simulation of ground water behavior which was accomplished through a two dimensional finite difference ground water model and (2) development of appropriate irrigation system improvement (ISI) plan through a multi-objective optimization model that would minimize ground water accretions. The methodoloy was applied to a part of Lower Ghaggar Basin (LGB) in India to determine optimal activity levels with minimum cost and maximum benefits (Fig.4). The area has been divided into a number of polygons. The improvement activities (ISI) included: precision levelling and introduction sprinkler at farm level (A), lining conveyance system (C) and lining of distribution system (D). The level of activity was measured interms of reduction in ground water recharge by way of improved efficiencies. The degree of improvement represents the reduction in ground water accretions from after implementing the system intervention with zero level representing no reduction while 100% representing maximum possible reduction in ground water accretions. The results of the study indicated that under financial constraints the priority of interventions should be improvement in application subsystem followed by distribution and conveyance system.

3.2.2. *Hydro-Salinity Modelling For Regional Salinity Management*

In the past, provision of drainage and leaching were considered adequate for reclamation and management of waterlogged saline lands. However, growing concern for environmental protection of surface and ground water bodies has, under certain situations, put question mark on the sustainability of drainage system itself. Under these situations the study of salt and chemical balance through hydro-salinity modelling appear to be essential.

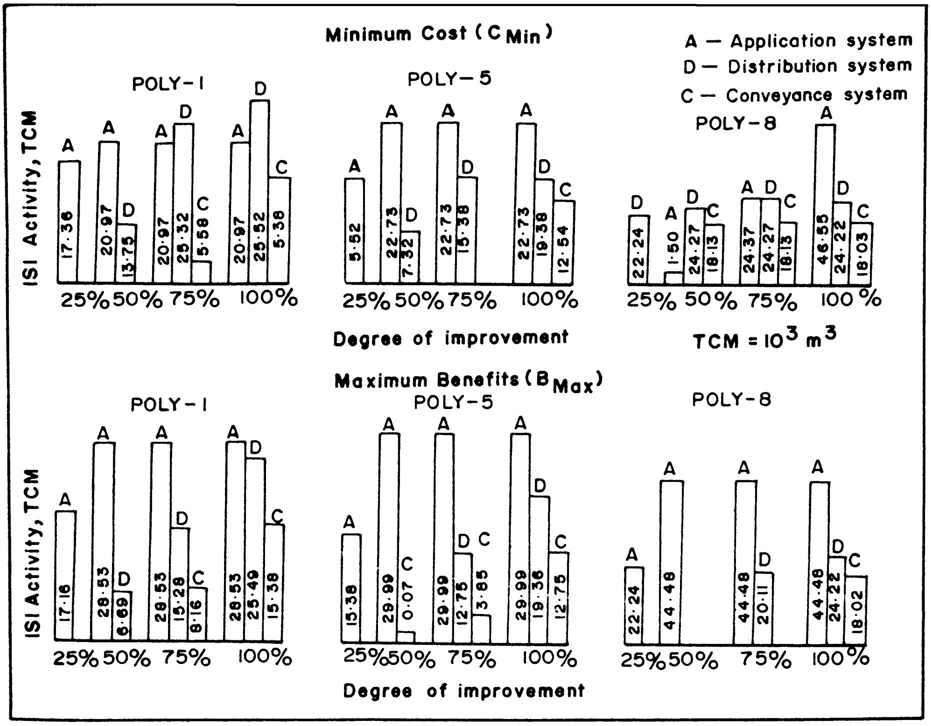

Figure 4. Optimal mix of irrigation system improvement activities for (a) minimizing cost of improvement and (b) maximizing benefits - Source: Tyagi, N.K., (1983)

The hydro-salinity models are used to study: environmental issues related with disposal of drainage effluents; impact of fertilizers/pesticides and other chemicals on stream/ground waters, and to understand the processes related with genesis of salinity.

Hydro-salinity models are likely to play an increasing role in management of irrigation and drainage systems. But the main problem with these models is the data requirement. It is because of the nonavailability of data that properly calibrated and verified models are very few. The only model that has been actually used is the one by Tanji (1977). The conceptual hydro-salinity model developed by Tanji has been used with good results in Glenn-Colusa and Panoche Irrigation Districts in USA. A modified form of Tanji's model (Aragues *et al.* 1985) was applied to Violada Irrigation District (VID) in Spain.

3.3. INSTITUTIONAL AND ECONOMIC MEASURES

Both degradation and protection of agricultural land have a price in monetary terms as well as in terms of socioeconomic trade-offs. These aspects are as important as the advanced technology. Successful programmes for prevention of waterlogging and salinity must have a large number of institutional and economic incentives to accommodate the large diversity of circumstances. These programmes include items such as water pricing, subsidies on technology upgradation, drainage taxes, output prices, banking institutions and government regulations etc..

3.3.1. *Water Pricing*

The response of the water users to changes in water conservation practice depends upon the cost effectiveness of the improvement. If the cost of improvement is more than the amount spent on reduction in water use, the practice is unlikely to be followed. To ensure efficient water use, the water charges should reflect the shadow price of water. A tiered pricing structure with increasing tariff for water use beyond certain level may provide incentive for increasing water conservation.

3.3.2. *Drainage Tax*

Water lost to irrigation on basin-wide scale becomes drainage water that has to be disposed off the area. Since surface run-off or ground water recharge from deep percolation become common property, individual user does not feel immediately concerned about such losses. When such a problem is resolved by governmental action, it implies social cost to be shared by efficient as well as inefficient users. One of the methods to minimize the problem could be imposition of drainage tax. It would be difficult to measure the drainage effluent produced by individual farmer. An indirect method of assessing could be the area irrigated by the farmer by a given discharge or volume of water supplied. It is possible to develop standards of area irrigated by a unit discharge over a growing season and crop under given agro-climatic conditions. The drainage tax can then be levied on the area falling short of the standard norms.

3.3.3. *Incentive For Technology Upgradation*

The success of a salinity control programme, to a large extent, depends on appropriate governmental policies. The term policies covers a wide range of subject matters which are important for the national economy as a whole. These may cover issues such as: prices of agricultural produce, partial defrayment of the cost of irrigation facilities and subsidies on high irrigation technology. A good example of incentives for use of high irrigation technology is the subsidy on purchase of drip and sprinkler systems in India. Hundreds of thousands hectares of land has been brought under drip and sprinkler after adoption of this policy. This policy is likely to give better results if water pricing is also done at realistic levels. The current water charges in India are rather low.

4. Future Research Needs

Salinity is not the property of irrigated agriculture but occurs in response to the kind of management imposed on the system. Management of salinity is a multidimensional problem requiring the understanding of the genesis, and the development of appropriate technology which is socially acceptable and economically viable.

Irrigation technology developed so far has considerably enhanced our capacity to manage land and water salinity problems. But, as the concern for protecting the natural environment grows, the need to refine the technology and shift emphasis on drainage volume reduction and reuse will also increase. The future research in land and water salinity management will have to give more attention in the following areas.

- Irrigation systems and procedures should be developed to increase the efficiency and uniformity of water application.
- Procedures should be developed to incorporate the effect of irrigation system nonuniformity and soil spatial variability in leaching requirements.
- Low volume and localised water application methods like sprinklers, drip and earthern pitchers can considerably reduce the drainage volumes. Pilot projects need to be established in saline groundwater areas having a rising watertable trend to evaluate the efficiency of such methods.
- In the past leaching and drainage were considered the ultimate solution for resolving salinity problems. The growing environmental concerns have put question mark on the sustainability of drainage system itself. There is a need to study the trade-off between provision of full drainage and drainage volume reduction.
- The ground water flow models should incorporate salinity component to predict the development of not only waterlogging but also of soil water salinity. Regional agro-hydro-salinity models should be used in planning appropriate water management strategies.
- The subsurface drainage design criteria for salinity control should be modified to base it on seasonal or annual salt balance.
- The emphasis so far has been on development of technology hardware. The role of policies and institutions in creating demand for technology has not been fully appreciated. Adequate attention should be given to this very important aspect, so that sustainability of irrigated agriculture in saline environment be ensured.

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USE AND MANAGEMENT OF SALINE WATER FOR IRRIGATION TOWARDS SUSTAINABLE DEVELOPMENT

A. HAMDY
Director of Research
Mediterranean Agronomic Institute of Bari
Via Ceglie 9
70010 - Valenzano (Bari)
Italy

1. Introduction

The goal of sustainable development should be to make sure that natural resource will be available for future generations. This applies to the use of water resources in such a way that renewable water does not diminish over the long term.

Worldwide, agriculture is the major consumer of water supplies, accounting for about 69% of the total. In arid and semi-arid regions, particularly the Mediterranean, the limiting water resources, on one hand, and the relatively high rate of population growth (3.5%), on the other hand, will be the major constraint for future agriculture and socio-economic development. An increasing number of countries are now approaching full utilization of their surface water resources. The quantity of good quality water supplies available to agriculture is diminishing, thus requiring the use of marginal quality waters.

In this regard, the question which yet remains to be answered is : can the use of marginal water be technically sound, economically viable and environmentally non-degradating? In other words, is it viable to propose the use of marginal water for agriculture production?

This paper discusses the options and main guidelines of which are necessary towards sustainable utilization of low quality water particularly the saline one.

2. Assessing the Suitability of Saline Water for Irrigation

Quality of irrigation water is an important consideration in any appraisal of salinity or alkali condition in an irrigated area. Many problems associated with irrigated agriculture arise from the chemical composition of water applied. The use of various water qualities for irrigation, as well as the advantage of predicting problems that

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might develop when different quality of irrigation water is being used, created the need for a system of water quality classification that is completely different from the system in use for geochemical, industrial, aquatic life, recreational and sanitation purposes (Frenkel 1984).

Much work has been done for classifying waters with respect to their suitability for irrigation (U.S. Salinity Laboratory Staff 1954, Rhoades and Bernestein 1971, Rhoades and Merill 1976, Ayers and Westcott 1985). Although the methods of classifying irrigation waters differ somewhat, they agree reasonably well with respect to criteria and limits. However, in all these criteria proposed, much emphasis has been placed on an attempt to answer the question: "How good is the water?" rather than "what can be done with these waters?" (Hamdy 1989).

It is difficult to define absolute standards of irrigation water quality as the relationship of the composition and concentration of the soil solution to those of the irrigation water is both complex and dynamic, being dependent upon a large number of factors that may be difficult to quantify. Soils and plant responses are not necessarily related to the properties of the soil solution.

The actual suitability of a given water for irrigation depends very much on the specific conditions of use and on the relative economic benefit that can be derived from irrigation with that water compared to others. However, for assessing the suitability of saline water in irrigation we are in need to establish new criteria that must be related to other territorial components including soils, climate, plants and management factors and to quantify this relationship in a relevant practical way.

Therefore, in assessing the suitability of water for irrigation due consideration should be given to the followings:

- cropping system: crop tolerance to salinity must be known on a quantitative basis for all specific ecological conditions of concern;
- prevention of salt accumulation in the soil: the dynamics of salts in the soil must be quantitatively known for all specific soils, climatic and hydrological conditions of concern. Furthermore, the interrelationship of leaching to crop response must also be understood;
- use of advanced irrigation and drainage technology: Irrigation methods must be adjusted to the use of brackish water and must be very efficient, technically as well as economically; a drainage system must be provided when necessary.

The sustainable use of saline water for irrigation requires that our research programmes should be modified from the individual to the integrated ones where crop rotation, water management and soil amendments are all combined. In addition, more emphasis should be given to the development of appropriate models, criteria and standards under non steady state conditions.

3. The Potential for Using Saline Water in Irrigation

Although the number of documented reports on successfully using brackish water for irrigation is relatively limited, enough exist to support the premise that water, more saline than conventional water classification schemes allow, can be used for irrigation. Recent research development on plant breeding and selection, soil, crop and water management, irrigation and drainage technologies enhance and facilitate the use of saline water for irrigated crop production with minimum adverse impacts on the soil productivity and the environment (Hamdy *et al.* 1993, Shalhevet 1994). At Bari Institute, studies were conducted for about 15 years and produced evidence that using water with salinity up to 6 dS/m for major cereal crops may be technically feasible (Hamdy 1989).

Jury *et al.* (1978) grew wheat in lysimeters with water up to 7.1 dS/m without deleterious effects on yield. Shalhevet and Kamburov (1976) suggested that water with up to 6000 mg salt/l were often classified as acceptable and used indeed. Other evidence of the potential to use saline water for irrigation successfully under hot dry (arid) climate was demonstrated by Ayers and Westcott (1985) and Rhoades (1988). The experience of Israel (Pasternak *et al.* 1984, Shalhevet 1984, 1994) supports the potential for using relatively high saline water for irrigation under arid conditions for variable crops such as: wheat, sorghum, sweet corn, sugarbeets, cotton, tomato, asparagus, broccoli, beets, celery, melons and lettuce.

O'Leary (1984) has shown that several halophytes have potential use as crop plants and can be grown under field irrigation with very saline water. Yields have been achieved under high salinity conditions which exceed the average yield of crops, like alfalfa, irrigated with fresh water. These yields amounted to 0.6 to 2.6 times of protein per hectare as compared with alfalfa. The use of drainage waters for the growth of such crops would facilitate the disposal of drainage waters as proposed by Van Schilfgaarde and Rhoades (1984).

The use of water with higher salt levels including that of sea water for irrigation of various food, fuel, and fodder crops has been reported by many researchers including Aronson (1985); Epstein (1983, 1985), Gallagher (1985), Glenn and O'Leary (1985), Lyengar (1982), Pasternak and De Malach, (1987), and others.

The assessment of saline water suitability for irrigation, combined with these latter cited worldwide references, indicate that waters of much higher salinities than those customarily classified as suitable can be used effectively for irrigation of selected crops under the right conditions.

4. Management Practices under Saline Irrigation Water

Damage caused by irrigation with waters either containing high total salt content (total salinity) or the soluble composition (specific ion effects) or both, depends to a large scale on management. Therefore, management practices must prevent excessive salt and sodicity building up and accumulation in the soil surface and in the root zone, and control the salt balance in the soil-water systems.

There is usually no single way to control salinity in irrigated land. Several practices can be combined into systems that function satisfactorily depending upon the economic, climatic, social, soil and hydrogeologic situation. Thus, management measures should not be considered in isolation but should be developed in an integrated manner to optimize water use, minimize drainage and increase crop yields within limits of the physical and social environment.

Three general management strategies seems practical: (a) control salinity within permissible levels, (b) change conditions to improve crop response, (c) change management to maintain yield at the field level when salinity causes damage at the plant level. All three can be used toghether, but the first one is the most commonly used.

5. Irrigation Practices

Irrigation practices which are important in the management of saline water are: irrigation scheduling (amounts and interval); leaching scheduling (amount and timing); irrigation method and management of multi-source irrigation water of different qualities (Shalhevet 1984).

5.1. IRRIGATION SCHEDULING

The irrigation scheduling should allow both good crop yields and adequate leaching of the soil when saline irrigation is practiced. Irrigation scheduling is complicated under saline water application mainly due to: i) information on consumptive use of many crops under saline water irrigation is not available, and ii) under saline water practices, the leaching requirements (LR) of the crops related to the salinity level of water must be calculated and included in the crop water requirements.

Different equations have been proposed describing the yield of several crops under saline water (Stewart *et al.* 1974, Shalhevet *et al.* 1983, Hanks *et al.* 1978, Frenkel *et al.* 1982, Parra and Romero 1980). The field and greenhouse results obtained by these authors offer convincing evidence of the unified relationship between yield and evapotranspiration (ET).

Successful saline irrigation requires new production functions that relates crop yield to water consumption with consideration of the irrigation intervals for the various crops. Several models to simulate crop-water production functions have been developed (Fienerman *et al.* 1984, Letey *et al.* 1985, Solomon 1985, Bresler 1987). The results of Bresler's model (1987) suggest full compensation between irrigation water amount and salinity for a relatively wide range irrigation water salinities. However, the results of the model of Letey *et al.* (1985) suggest that increasing the amount of irrigation water compensates only partially for the irrigation water salinities.

The dynamic models (Bresler 1987, Hanks *et al.* 1978, Van Genuchten 1987) can be used to simulate seasonal crop water production functions for various irrigation schedules, if appropriate input data for the given model is available. Solomon (1985) and Letey *et al.* (1985) presented seasonal water-salinity-production functions based on our current understanding of the response of crops to water, the salt tolerance of crops and the leaching process.

Both the dynamic models and the seasonal ones assume a unique relationship between yield and ET for a given crop and climate that is independent, regardless whether the water stress leading to the reduced ET is caused by deficit water supply, excess salinity or both. Beginning with this premise, Solomon (1985) stated that, for any given amount and salinity of irrigation water, there will be some point at which values for field ET, leaching and soil salinity all are consistent with one another. The yield at this point is the yield to be associated with a given irrigation water quantity and salinity.

There is no doubt that substantial progress has been made in developing empirical models that can be used to relate crop yields and irrigation management under saline conditions. However, further work is needed before these empirical models can be reliably applied under a wide variety of field conditions. Further work also is required on the relation of ET to soil and environmental conditions. Nonuniform applications of water and spatial variations in soil parameters significantly affect seasonal water production functions. Variations in the environment affect the growth of the plant, so random effects related to the weather need to be included in models of the growth of plants under saline conditions. To date, little or no work has been done to estimate transient production functions under non-uniform conditions.

5.2. IRRIGATION FREQUENCY

Plant growth is a function of the osmotic and matric potential of soil water; salinity can be controlled by leaching, whereas matric potential is controlled by adequate and timely water application. The question arises whether it is necessary to narrow the watering intervals to keep the soil solution concentration low (to diminish harmful effects of the salt), or whether it is possible to lengthen the interval and to apply large amounts of water.

Analysing the process that occurs when evapotranspiration reduces soil water content between waterings shows that as the soil dries, the matric potential decreases as well as the soil solute potential while the soil solution concentration increases. Thus, beneficial effects from decreasing the irrigation intervals as soil salinity increases could be reasonably expected (Allison 1964, Ayers and Westcott 1985).

This process is counteracted by the effect of irrigation intervals on the shape of salt distribution in the soil profile and on the overall level of salinity. Under steady state conditions, increased irrigation results in an upward shift of the peak of the salt distribution profile, thereby increasing the mean salt concentration in the upper root zone. Furthermore, ET increases as irrigation becomes more frequent, leading to additional (saline) water applications and an increase in the salt load (Van Schilfgaarde *et al*. 1974, Bernstein and François 1973a).

Singha and Singh (1976) showed that the soil solution concentration adjacent to roots growing in a saline soil was 1.5-2.5-fold higher than in the bulk soil. The larger the difference, the wetter the soil and the higher the transpiration rate. Thus, keeping the soil wet by increasing irrigation frequency may enhance, rather than decrease, the effect of salinity.

The effects of irrigation frequency on the final crop yield was studied by several workers (Hoffman *et al.* 1983, Hamdy 1991b). The data obtained indicated that increasing irrigation frequency did not significantly benefit crop production, despite the much larger fluctuations in soil matric potential in the long-interval-treatment as compared the short-interval-treatment. Detrimental effects of increased frequency on crop response were found by several authors namely Ayoub (1977). They attributed reduced yields to flushing salts accumulated near the surface into the root zone, causing osmotic shock, and the foliar damage occurring with more frequent irrigation. Recently, Hamdy (1990a) studied the influence of varying irrigation frequencies under saline water application on both corn yield and salt accumulation and distribution under variable soil textures.

It was concluded that: frequent irrigation led to much greater salt accumulation at the soil surface; such accumulation accounts for the less-than-proportional yield increase; and that increased irrigation frequency is not a good choice in saline water management. Thus the bulk of evidence does not support shortening irrigation intervals when saline water is used.

Most of the methods used to determine the onset of stress, including both direct and indirect measurements, suffer the limitation of needing an empirical determination of the set-point for irrigation. Furthermore, measurements of soil water content or matric potential cannot be used (at least not conveniently) to assess or control the leaching fraction as is required to prevent an excessive build-up of soil salinity. Saline water irrigation scheduling require some methods of assessing the water availability to the crop with sufficient lead time to provide for a water application before significant stress occurs (Fig. 1).

5.3. IRRIGATION METHOD

The method used for saline water irrigation may be guided by:

- the distribution of salt and water in the soil under different irrigation methods;
- crop sensitivity to foliar wetting and the extent of damage to yield; and
- the ease by which high solubility and matric potential can become maintained in the soil.

Under flood or sprinkler irrigation where water and salt transport is downward and away from the seedling, limited pre-planting leaching of the upper soil strata may take care of the germination and establishment inhibition (Rhoades 1989). Under furrow and drip irrigation there is a downward component of water and salt transport, but another component is lateral and upward in the spaces between furrows or laterals. With these methods the adjustment of the soil surface contour and seeding or planting position according to the expected salt distribution can limit significantly this damage. Most undesirable will be to plant at the mid distance between two wetting fronts that reach each other, and on the most elevated spots. Thus, planting near the water supplying furrow, using double row beds, irrigating alternate furrows, and planting on sloping beds, will all push away the salt from the seed or seedling (Fig. 2).

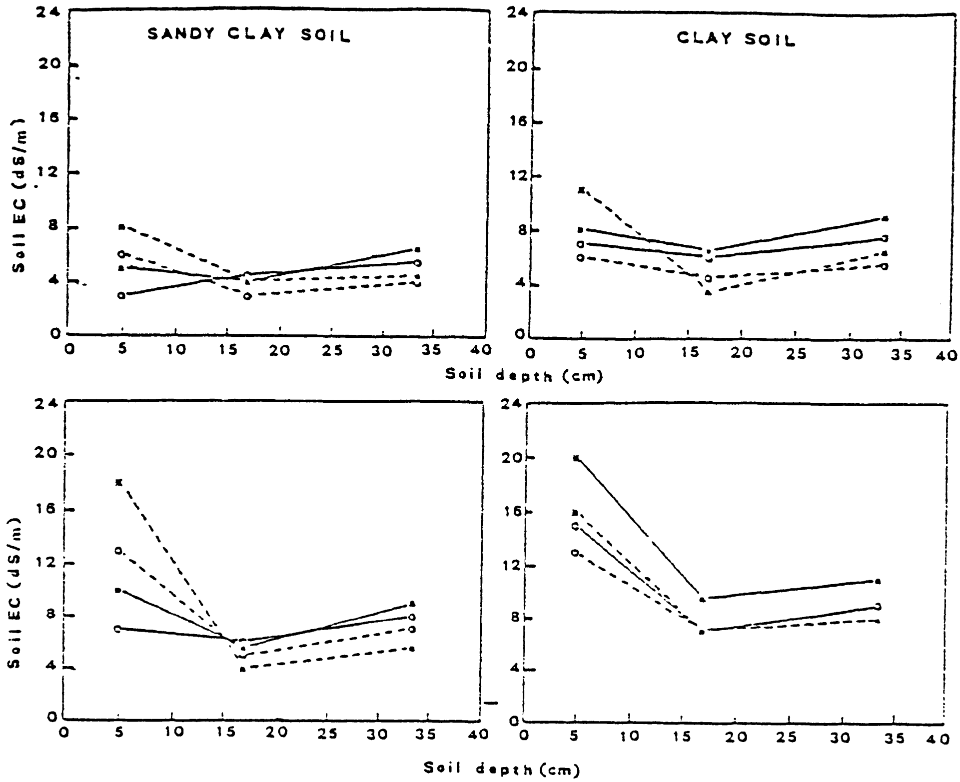

Figure 1. Salt distribution at different soil depths as a function of different irrigation intervals (x short; o long) and irrigation method (- surface irrigation; --- drip irrigation) at different EC : 4 dS/m above and 8 dS/m below

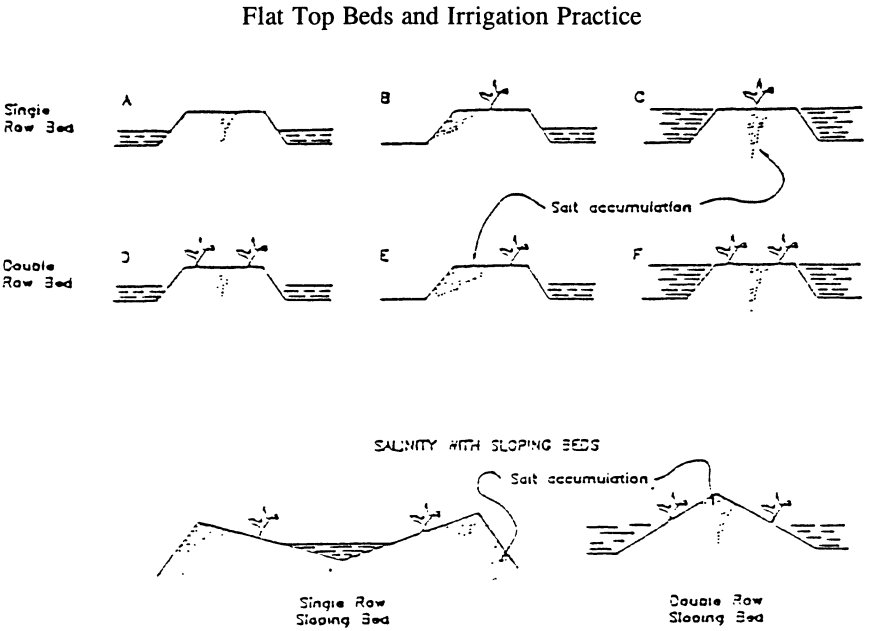

Figure 2 Typical salt accumulation patterns in ridge and bed cultivation (adopted from Bernstein *et al.*, 1955)

The principal problem encountered with sprinkler irrigation using saline water is wetting of foliage with consequent tip and marginal burning of the leaves, and ultimate defolation. Provided foliar burn is avoided (e.g.night irrigation), sprinkler irrigation has the advantege that salt-removal efficiency with sprinkler irrigation tends to be substantially higher than with flood or trickle irrigation.

Evaluating the ability of the irrigation method under saline water practice, the prevailing moisture conditions under the drip methods provide the best possible conditions of total soil water potential for a given quality of irrigation. The roots of the growing plants tend to cluster in the leached zone of high moisture near the trickles, avoiding salt that accumulates at the wetting front (Yaron *et al.* 1973, Shalhevet *et al.* 1983, Hamdy 1991a). Moreover, the drip system offers means of maintaining a low soil water tension within the root zone, thus enabling the use of higher salinity besides avoiding leaf injury.

Subsurface systems provide no means of leaching the soil above the source of water. Continuous upward water movement and evaporation cause salt to accumulate near the soil surface. Even under the most favorable circumstances, this method does not appear to be suitable for long-time use. Unless the soil is leached periodically by rainfall or surface irrigation, salt levels will certainly become toxic (Hamdy and Abu Zeid 1991).

6. Leaching Management for Salinity Control

Soil salinity control becomes more difficult as water quality decreases. Greater care must be taken to leach salts out of the root zone before they reach levels that might affect yields. Alternatively, steps must be taken to plant crops tolerant to the expected root-zone salinity. The frequency and amount of leaching depend on water quality, climate, soil and crop sensitivity to salinity.

For efficient leaching management, it is desirable to use extra water for every irrigation or for seasonal leaching. Leaching during a period of peak consumptive use means that not only greater amounts of water should be applied but also that greater amounts of salt are brought into the soil. So, this surplus amount of salt counterbalances to a certain extent the advantage of more leaching water. Moreover, permanent leaching means greater water applications, while increasing the risk of waterlogging and suffocation of the crops. On the other hand, seasonal leaching during a period of low consumptive use can also draw advantage from rainfall, at least in the Mediterranean area and the Middle East, where rainfall occurs during the winter.

The findings of Bernstein and François (1973b), François (1981) and Hamdy (1990c) support the idea that applying the seasonal leaching when salt accumulation becomes excessive rather than at every irrigation, is a better strategy for short-season crops. However, the point still needs to be settled: if leaching should be practiced periodically, at which growing stage should leaching be administrated and what is the appropriate leaching fraction?

Hamdy and Nassar (1994) concluded that, for maximum utility and better saving of fresh water and the achievement of satisfactory crop production, leaching should be carried out in accordance with the salinity tolerance of the growing stages. The leaching fraction should be established according to the salinity of the irrigation water as well as the degree of salt accumulation in the soils. The extent to which leaching can be minimized is limited by the salt tolerance of the crops being grown, salt content and composition of irrigation water, and soil characteristics including exchangeable cation composition (sodicity) texture, clay minerals, soil mineral weathering, salt dissolution and precipitation and structural stability.

Indeed, irrigation with saline water and leaching together with saline water is a complex issue. To increase the efficiency of leaching and reduce the amount of water needed, the following practices are suggested:

- leach during the cool season (rather than during the warm season) when ET losses are lower;
- use pre-planting sprinkling at lower application rate than the soil infiltration rate
- to favour unsaturated flow, which is appreciably more efficient for leaching than saturated flow;
- use more salt-tolerant crops, which require a lower leaching requirement and thus a lower water demand;

- use appropriate tillage to slow overland water flow and to reduce the number of surface cracks which bypass flow through large pores and decrease leaching efficiency;
- where possible, schedule leachings for periods of low crop water use, or postpone leaching until after the cropping season.

7. Management of the Multi-Quality Water Resources

Operation strategies that permit an optimal increase in cropped area and maximize the use of all available water of different qualities can be outlined under the following two major operational techniques :

A) Blending water (network dilution): different quality waters are mixed in the water supply permitting a predeterminated water quality for every field according to the tolerance of each crop to salinity, thereby either reducing the total salt concentration or changing the composition of the water reducing SAR. This procedure may increase the total quantity of water available for irrigation but at the same time will lower the quality of good water available.

B) Alternating between good and poor quality water (soil dilution):

i. crops are irrigated by alternating between water sources so that the dilution occurs in the root zone;

ii. sequential application: the water source is changed during the season according to the specific salt tolerance of the crops at each growth stage.

The management of the multi-source irrigation water is among the subjects which was argued by several investigators (Allison 1964, Ayers and Westscott 1985, Rhoades 1984a, 1984b, 1987, 1989, Van Schilfgaarde *et al.* 1974).

The practice of blending either increases the quantity of water resource or improves the relatively poor quality. This has shown in good performance many projects (Australia, Egypt, Israel, Pakistan and India). So far, results of studies show that this practice is easier to implement on large farms than other alternative uses of water. In addition, blending may be more practical and appropriate, provided the drainage or shallow groundwater is not too saline per se for the crop to be grown.

Nevertheless, an extensive reuse of saline water, on the long-term, applying this technique could lead to detrimental effects on both soil productivity and crop production. Consequently, the necessary precautions concerning drainage, leaching and crop selection should be taken.

In areas where mixing is not advisable nor technically feasible, there is the possibility of applying alternatively fresh and brackish water according to the varying tolerance of crops during growth stages. This reuse strategy that avoids blending has been demonstrated in field projects to be viable and advantageous in well-managed irrigation projects (Rhoades 1984a, 1984b, 1987, Rhoades *et al.* 1992).

Although cyclic strategy has more potential flexibility than the blending one, there may be a difficulty in adopting the cyclic strategy on small farms where the drainage water produced is too little or does not coincide with the peak crop water demand. To overcome this constraint, a surface storage reservoir has to be constructed to return the low water quality until its use is required. In addition, application implies a double distribution system of water -both saline and fresh- to farms.

An intensive 5 years research programme was carried out in the Bari Institute to evaluate the aforementioned water application strategies. The data and results obtained (Hamdy 1991b, 1993) favoured more the alternate water application than the blending one because of the following advantages:

- avoiding the deterioration of the good water quality. This water could be used at the time it is most needed, for instance at the germination and seedling stages which are very sensitive to the salinity level of irrigation water as well as to satisfy the leaching requirements which requires water of relatively good quality;
- with the plants which are sensitive to the salinity level in irrigation waters, satisfactory production could only be achieved with water of good quality through alternative application modes. The disadvantages appearing under mixing could be completely eliminated and offer a free-hand possibility in using the different water resources according to the prevailing conditions;
- the cyclic use of water of low and high salinity prevents the soil from becoming too saline while permitting, over a long period, the substitution of brackish water for a substantial fraction of the irrigation needs;
- cyclic strategy provides a vast choice of crops to be included in the crop rotation scheme as compared with the blending technique where crop selection is limited to the tolerant ones.

However, the matter is not simply the alternation of water resources. A suitable cropping pattern is also required that allows the substitution of saline water by normal water to irrigate certain crops in a suitable tolerant growth stage. Indeed, the timing and amount of possible substitution will of course, vary with the quality of the two waters, the cropping pattern, the climate, certain soil properties and the irrigation system.

8. Concluding Remarks

- World wide experience in the use of saline water for irrigation indicates that a high potential exist for using such waters.
- Research developments on salt tolerance of various crops, water, soil and crop management, irrigation and drainage methods and the reuse of drainage effluents, will enhance and facilitate the use of relatively saline water for irrigation.
- The use of low water quality for irrigation is a complex practice and its sustainable use requires great care, in considering agronomic as well as water management and economic factors, without neglecting the long term effects of this practice on the

physical and chemical soil properties, on crop yields and on the environment.

- Much work on potentials and hazards of the use of saline water, mostly done under controlled conditions in greenhouses, in small plots, is already available but hardly used in practice. Therefore, it is needed to test and demonstrate these practices under real world conditions by the farmers and the operational organizations (irrigation departments and water users associations).
- At present there are no clearly defined policies and strategies on the reuse of drainage water and on the mitigation of its adverse environmental impacts. To arrive at these policies and strategies, monitoring programs are required using both quantitative and qualitative approaches.
- Much important and useful research work has been carried out by a number of research institutes and organizations on problems related to saline water management, waterlogging and salinity. However, those activities were undertaken in relative isolation and no mechanism existed for coordinating the research work or for ensuring that the readily available research findings could be effectively utilized. In this regard it is needed:
  - to establish working relationships on national, regional and international institutions dealing with this subject through the formulation of net-works. This will allow to bring together the latest research experience for review and dissemination as well as identifying areas of needed research;
  - to conduct and foster a comprehensive multi-disciplinary basic and applied research programme in coordinating fashion on the sustainable use of saline water in irrigation and related problems;
  - to develop practical solutions to problems associated with the saline management aspects;
  - to provide facilities for research workers and to train associated personal in techniques and methods for dealing with saline water practices and related salinity problems.
- There are relatively few places where farmers are using successfully saline water for agriculture. Experience of those farmers need to be collected and documented.
- Farmers' participation and involvement in planning and management is the key point to overcome the gap between researchers and users.

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AGROCHEMICALS AND WATER MANAGEMENT

RAMESHWAR S. KANWAR
Professor of Agricultural and Biosystems Engineering
Iowa State University, Ames, Iowa 50011
U.S.A.

1. Introduction

Although population growth rates have been declining recently, by 2050 the planet could have 10 billion people, double the number of humans it has now. If we look at the global water resources, we see a frightening outlook. The impact of this increased population on the environment will be severe. While as much as 95 percent of the world population growth is projected in the developing countries where, by the year 2050, 87 percent of the world population is expected to live. This will add enormous stress on the available water resources for domestic, industrial, and agricultural use while maintaining environmental quality (Bouwer, 1993).

Maintaining a good standard of living for growing population will require a renewable water resources capacity of 1000 m^3 per person per year. China and India are developing future water resources management plans on renewable water supplies of 500 and 250 m^3 per person per year respectively to sustain their economies. Many other countries will have less renewable water resources for their economic growth. In contrast to population growth, water resources are finite. An increasing population will require more food and in many areas it will mean more irrigation. This might result in less water available for industrial and municipal demands. At the beginning of this century, 90 percent of all water used in the world was for irrigation, currently it is about 70 percent, and by the year 2000 it is expected to be about 60 percent (Bouwer, 1993). These data indicate that we must grow more food with less water using more intensive agriculture that uses fertilizers and pesticides. Farmers use pesticides to keep grasses and insects at bay and fertilizers to help crops grow better. For years it was believed that these chemicals would either remain on the top of ground surface of agricultural fields or would degrade before they could reach the groundwater and/or surface water. But recently, drinking water supplies have been found to contain nitrates, nearly all of which may have come from fertilizers. Many of these water supplies contained nitrate-nitrogen (NO_3-N) concentrations greater than 10 mg/l, a drinking water standard set by the U.S. Environmental Protection Agency (US EPA). Besides NO_3-N, some common pesticides have also been found in the water. Since the first discovery of a pesticide in the groundwater in 1979, 46

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pesticides have been found to contaminate groundwater as a result of normal agricultural use (Fairchild, 1987).

Contamination of surface and groundwater sources by N-fertilizers and pesticides has been well documented in the United States (Fairchild, 1987; Hallberg, 1989, Johnson and Kross, 1990). Pesticides were first discovered in groundwater in 1979. Prior to that time it was generally believed that they did not leach into groundwater as a result of normal agricultural use (U.S. GAO 1991). The detection of dibromochloropropane (DBCP) in groundwater wells in central California and aldicarb in wells in New York in 1979, has focused public concern on the vulnerability of groundwater contamination. Groundwater pollution is of increasing concern in the United States because about 40 percent of the people in the United States (approximately 100 million people) use groundwater for their drinking water source. In rural areas, the percentage is more than 90 percent (U.S. GAO 1991). People depending on groundwater for drinking water are those who could be affected most directly by contamination of pesticides.

Nitrogen and pesticide loss from agricultural lands is an important environmental concern in the U.S.A. relative to both surface and groundwater quality, because 60 percent of the pesticides and N-fertilizers used in the U.S.A. are applied to cropland in 12 midwestern states. The water management systems (surface and subsurface irrigation, sprinkler and trickle irrigation) also affect the movement of agricultural chemicals to groundwater. Because irrigation water provides a driving force for downward leaching of chemicals, the amount of irrigation water applied will potentially affect the movement of chemicals to groundwater (Bouwer 1987). The total irrigated area in the U.S.A. has dropped to 23.6 million ha in 1992. During the same period surface irrigated area decreased from 15.9 to 12.9 million ha and the area irrigated by other irrigation systems (sprinkler, pressurized systems, trickle/drip) increased from 8.9 to 10.7 million ha (Manges 1994). Several studies are currently going on in the U.S.A. to determine the impact of various irrigation systems on leaching of nitrogen and herbicides to groundwater (Fermanich *et al.* 1993, Kanwar *et al.* 1993ab, Watts *et al.* 1993) but some of the recent studies indicate that both amount and method of water application are important factors that determine pesticide movement to groundwater (Troiano *et al.* 1993).

More recent experiences, in the developed countries, have shown clearly that modern agricultural activities are contaminating the water sources because of the increased use of chemicals which are being found in the surface and groundwater sources (Spalding *et al.* 1989, Kross *et al.* 1993, Fairchild 1987). Groundwater is a major water resource and there is about 67 times more fresh water stored underground within drillable distance than in all the rivers and lakes of the world (Bouwer 1993). The increased use of agricultural chemicals has contributed significantly to the agricultural productivity but has been the source of much controversy recently because of the perceived health risks posed by the presence of nitrate, pesticide, and other compounds in drinking water. This has resulted in several groundwater quality legislation by several states in the U.S.A. High concentrations of nitrate-nitrogen

(NO_3-N) in well water was first recognized as a health problem in 1945 when two cases of infant methemoglobinemia (bluebaby syndrome - a temporary blood disorder that reduces the ability of an infant's bloodstream to carry oxygen through the body) were reported in Iowa (Comly 1945), and recently in South Dakota (Johnson *et al.* 1987). Some evidence exists that high NO_3-N ingestation is involved in the etiology of human cancer (Fraser *et al.* 1980, Foreman *et al.* 1985). The negative impacts of the use of pesticides to human health and the environment have been a source of concern. In addition to concern for the acute and chronic toxicity of pesticides, their potential as carcinogens and their presence in groundwater sources have raised questions about their continued use in agriculture. Therefore, a better understanding of groundwater contamination mechanisms is needed to develop better management systems to protect groundwater aquifer systems (Burkhart and Kolpin 1993). Research is needed to develop simple and rapid techniques to demonstrate how agricultural chemicals can move to aquifer systems. The purpose of this paper is to present summaries of various studies, including the ones conducted at Iowa State University, on developing best management practices to minimize the impacts of agricultural and water management systems on water quality and to recommend solutions to protect the environment.

2. Agrochemicals in the Environment

Nitrogen and water are probably two of the most critical factors influencing crop production. Nitrogen is generally the most limiting plant nutrient in soils. In 1945, less than 0.2 kg/ha of N was applied to Iowa's cropland as a commercial fertilizer and by 1985 that figure jumped to 160 kg/ha. Several studies have indicated that increases in NO_3-N concentrations in the shallow groundwater are related to the increased N fertilization rates in agricultural watersheds (Baker and Johnson 1983, Kanwar and Baker 1993). Similarly, the use of pesticides in the last 50 years have greatly increased the quality and quantity of food to feed the increasing world population. Today, more than 500 different formulations of pesticides are being used in our environment and agriculture holds the largest single share of pesticide use. Therefore, pesticide and N management practices are the key factors for controlling environmental pollution.

2.1. SOURCES OF AGROCHEMICALS IN WATER

It is extremely important to know the source of agricultural chemicals in the water. Sources of agrochemicals can be either point or nonpoint sources. Point sources of contamination are referred to a pollutant at a specific site whereas, nonpoint sources do not occur at a localized site but occur over a larger area.

2.1.1. *Nonpoint Sources of Nitrogen*

Most of the NO_3-N detected in surface or groundwater can be traced to nonpoint sources. The nitrogen in rainfall, manure and inorganic N-fertilizers, organic matter, crop residue, legume crops, and N-delivered in irrigation water are the main nonpoint sources of nitrogen in the surface and groundwater. The inorganic fertilizers applied to croplands are the single largest nonpoint source of nitrogen. In 1987, 9.39 million metric tons of nitrogen fertilizers were applied in the nation (NRC 1993). Corn crops receive the highest rates of fertilizer-N which increased from 67 kg/ha in 1965 to 157 kg/ha in 1985.

The amounts of nitrogen fixed by legume crops (like alfalfa and soybeans) could vary from 6.1 to 8.6 million metric tons. Alfalfa has been found to fix as little as 75 kg-N/ha and as much as 600 kg-N/ha (NRC 1993). Similar range for soybeans vary from 15 to 310 kg-N/ha. To minimize environmental losses a proper credit must be given to leguminous crops in a given farming system.

The nitrogen in crop residue eventually becomes part of the soil organic matter. The processes of mineralization (transforming the nitrogen in organic matter to ammonium ion) and nitrification (transforming the ammonium ion to nitrate) convert the organic form of N to available form of N. Nitrate is readily available for plant uptake or leaching through soil to groundwater. Another process of immobilization can again convert the NO_3-N and NH_4^+ back into organic -N. Denitrification can biologically transform NO_3-N into nitrate and then to N_2 and N_2O gases. These gases are of environmental concern because they contribute to the greenhouse effect and many affect the ozone layer.

The contribution of nitrogen from rainfall varies from storm to storm and from region to region. The total inorganic nitrogen deposited with rainfall as a nonpoint source varies from 3 to 7 kg/ha/yr in the eastern United States and 3.9 to 12.4 kg/ha/yr in the midwestern United States (NRC 1993).

Nitrogen can be lost to the environment through denitrification or volatilization of ammonia from fertilizers and manure. Nitrogen can also move through or over the surface with water to contaminate the surface and groundwater as a nonpoint source of pollution.

2.1.2. *Point Sources of Nitrogen*

The contribution of point sources of nitrogen do not play a major role in the overall contamination problem. Nitrogen can enter the surface or groundwater from a variety of point sources including municipal wastes, industrial waste water, animal feedlots, and local spillage from fertilizer tanks. In industrialized countries like the United States, the contamination potential from point sources is minimum because of the treatment requirements before waste water can be discharged to surface water.

2.1.3. *Nonpoint Sources of Pesticides*

Agricultural fields, receiving the application of pesticides to control insects, pests, and weeds from damaging the crops, are considered the main nonpoint sources of pesticides in the surface and groundwater. Soil erosion, infiltration recharge due to rain or irrigation water, and water runoff from agricultural field treated with pesticides are the major nonpoint sources of pesticide pollution. Volatilization of pesticides from the soil or plant surface and wind erosion of dust particles can carry pesticides into the atmosphere. These pesticide particulates will hang in the atmosphere until rainfall deposits these pesticides back on the land surface as a nonpoint source. Nations *et al.* (1993) have given a list of pesticides found in the rain water in Iowa. Obviously, the occurrence of pesticides in rain water affect the quality of surface water.

While atmospheric transport may add small amounts of pesticides to surface water, runoff water is still the largest nonpoint source of pollution.

In artificially drained areas, the movement of agrochemicals with subsurface drainage water is important and should be considered as sources of nonpoint pollution. Pesticide movement with subsurface drainage water is of minor importance compared to surface runoff (Baker and Johnson 1979, 1983).

2.1.4. *Point Sources of Pesticides*

Point sources of pesticide contamination will include pesticide mixing, storage, disposal, and manufacturing sites as well as accidental spills during transportation. Sometimes other kinds of point sources of pesticides will also be important like in-field mixing and rinsing of spraying equipment, and disposal of pesticide containers near the surface or groundwater sources. Some studies have found the evidence that more than 20 percent of the pesticide detects in the water were due to the carelessness associated with operating equipment adjacent to streams. Sometime the leachate from spray sites contributed directly to the contamination of surface and groundwater. Seepage from sites where empty pesticide containers were discarded after use were also a contributing factor.

2.2. SCOPE OF ENVIRONMENTAL CONCERNS

Pesticide contamination is affected by the local hydrologic and land-use factors. For example, about 310 metric tons of atrazine or 1.2 percent of the atrazine applied in 12 midwestern states that drained into the Mississippi River from April 1991 to March 1992 eventually ended up in the Gulf of Mexico based on USGS water tests. Three quarters of that loss occurred in April, May, and June when the median atrazine concentration was 1.1 mg/l (Baker 1992). Also after atrazine, alachlor, cyanazine, metolachlor, metribuzin and prowl were detected in 1.2 to 1.9 percent in groundwater in Iowa. The presence of NO_3-N in the drinking water has been related to the bluebaby syndrome and other forms of human cancer. Some pesticides have been labeled as potential carcinogens in addition to their chronic toxicities. A comprehensive analysis on human exposure of Ohio water supply sources indicated that over a 7-year period, about 0.05 and 0.06 percent of the population consumed water with an average concentration exceeding the MCL for atrazine and alachlor, respectively (Baker 1990).

2.3. SCOPE OF SOLUTIONS TO ENVIRONMENTAL CONTAMINATION

It is possible to reduce the environmental related health risks due to agrochemical contamination by using better management systems. There are three possible choices to reduce contamination of surface and groundwater due to pesticides (CTIC 1994). One approach would be to limit or ban the use of chemicals in agricultural watersheds. This approach, however, would put the farmers in the affected areas on a competitive disadvantage to other farmers who would still be using pesticides and would also eliminate the judious use of pesticides. Second approach could be the use of Best Management Practices which can reduce the leaching of chemicals to groundwater and pesticide loss to surface runoff. Success of these practices will depend upon several local factors. The last approach would be the use of site specific technology (like global positioning systems) in applying chemicals according to land use and site specific needs. The last two approaches may solve some of the environmental related problems and reduce the use of agrochemicals for our agricultural production systems.

3. Leaching Properties of Agrochemicals

It is extremely important to know the behavior of agricultural chemicals in the soil-water-air environment. The leaching of chemicals through the soil profile depends on complex interactions between the movement of water through the soil and the distribution of the chemical between the soil matrix and soil solution. Most of the agricultural chemicals can be divided into the three categories as (1) highly soluble but weakly adsorbed, these chemicals will be lost to groundwater with percolating water; (2) moderately adsorbed, these chemicals will leach to the environment mostly with runoff water; and (3) strongly adsorbed, these chemicals will be lost to the environment mostly with sediments or soil particles.

The highly soluble chemical, such as nitrate, could quickly leach into the soil with rain or irrigation water before they can become part of surface runoff. Subsurface drainage water can then transport these chemicals into surface and groundwater. Chemicals in the strongly adsorbed group include herbicides such as paraquat and trifluralin as well as many of the now banned insecticides (such as DDT, dieldrin, and heptachlor). The majority of herbicides used today fall into the moderately adsorbed group. Several studies have shown that herbicides such as atrazine, alachlor, and cyanazine are lost mainly in surface runoff (Baker and Johnson 1979, CTIC 1994) but have also been found in the shallow groundwater sources (Kanwar 1991, Kanwar *et al.* 1993a, Kalita *et al.* 1994).

3.1. PESTICIDE PROPERTIES

The fate and transport of pesticides applied to croplands require knowledge about their chemical properties, their transformation, and physical transport processes of site-specific conditions. Baker (1992) reported that four pesticide properties largely determine the tendency of pesticides to move once they are applied to the land surface. The most important properties are adsorption, persistence, vapor pressure, and solubility.

Persistence is pesticide's resistance to breakdown through chemical, photochemical (sunlight), and microbial degradation processes. Persistence is commonly evaluated in terms of half-life of the compound, which is the time it takes for 50 percent of the pesticide to breakdown or transformed to other products known as metabolites. Table 1 gives the estimated half-lives of some common pesticides (Baker 1992, Spalding *et al.* 1989). Pesticides that persist longer in the soil water environment are likely to move off-site because they remain at their original location. DDT and Dieldrin are very persistent insecticides with half-life in years. Similarly, atrazine is more persistent herbicide and is likely to be found in surface and groundwater. Pesticides are classified as nonpersistent if they have a half-life of 30 days or less, moderately persistent if they have half-lives longer than 30 days but less than 100 days, and persistent if they have half-lives longer than 100 days.

Sorption determines the relative distribution of the chemical in the vapor and solution phases, and bound to soil (solid) surfaces. Sorption is evaluated by partition coefficients (K_{OC}) based on the organic carbon content of soils.

Adsorption is the process that binds the pesticide droplets to the soil. The amount of soil adsorption determine the degree of pesticide loss to surface and groundwater. Strongly adsorbed pesticides are lost mostly with sediment. Weakly to moderately adsorbed are lost with runoff water. Many pesticides are moderately adsorbed, therefore, erosion control will have limited effect on their losses.

Vapor pressure of a pesticide is a measure of its tendency to evaporate or become a gas. Pesticide losses in excess of 50 percent have been observed on windy days as evaporation of pesticide can continue after application. Vapor pressure affects the post-application losses to the atmosphere, especially for pesticides applied to crop residue. Application and post application losses to the atmosphere may far exceed those moving with water (Baker 1992). For example in one study, about 5 percent of herbicide propachlor (Ramrod) escaped into the air within 24 hours of its application compared to 1 percent of cyanazine evaporated because propachlor has a vapor pressure 140,000 times greater than cyanazine.

Solubility is the tendency of a pesticide to move from the solid phase into solution. Solubilities vary be several factors. Pesticides that dissolve readily in water are highly soluble. These chemicals have a tendency to be leached through the soil to groundwater and to be lost with runoff from rainfall or irrigation practices.

All these properties give threshold values (Table 1) indicating the potential of a chemical for groundwater contamination. A pesticide is likely to contaminate groundwater if its sorption coefficient is low, its half-life is long, and its solubility is high although half-life values are difficult to predict because of its dependability on soil temperature, soil moisture, soil carbon, microbial population and soil types.

3.2. LEACHING POTENTIAL OF AGROCHEMICALS

The leaching potential of a chemical indicates the tendency of a pesticide to move in solution with water and leach below the root zone into groundwater. Various chemicals have been given leaching ratings from small to large depending upon their leaching potential. Similarly, the runoff potential indicates the tendency of the pesticide to move with sediment in runoff. A large runoff rating means that pesticide has a high tendency to move with sediment while a small rating means the pesticide has a low potential to move with sediment. Also, the soil sorption (measured by the K_{OC} values) indicates that the chemical has a stronger attachment to soil and a lesser tendency for the chemical to move except with sediment. The lower K_{OC} values will tend the chemical to move with water and have a greater leaching potential. Table 1 also gives the leaching potential of selected pesticides (between small to large) depending on pesticide properties.

The nitrate ion (NO_3^-) is the most water soluble form of nitrogen and the least attracted to soil particles and is lost mainly by subsurface drainage water. Highly soluble chemicals, such as nitrate, are not found significantly in runoff as they quickly leach into the soil before they can be carried off by overland flow. Subsurface flow and tile drainage can then carry these water soluble chemicals into surface water.

Pesticide manufactures are required by the U.S. Environmental Protection Agency (USEPA) to submit environmental fate and chemistry data needed to assess pesticides leaching potential. Table 2 gives the list of necessary environmental fate and chemistry studies that are required to determine the leaching potential. In addition, USEPA also requires data on pesticide's toxicity to people, wildlife, and effects on the ecosystem. Table 1 gives the data on health advisory levels in the water to avoid human toxicity and other data on selected pesticide properties.

4. Impacts of Water Management Systems on Water Quality

Irrigation practices can affect the movement of agricultural chemicals to groundwater. Rainfall and irrigation provide the driving force for chemical leaching. The type of irrigation system (surface methods like furrow irrigation, sprinkler, center pivot, subirrigation, drip), the amount of irrigation water, and timings of irrigations affect the movement chemicals through the soil profile. Ideally, the amount of irrigation water applied should equal the evapotranspiration losses if salinity control is not the objective. Sprinkler systems of irrigation often results in less movement of chemicals because of even distribution of water, whereas furrow irrigation might increase chemical leaching at the bottom of the furrow.

TABLE 1. Properties of some common pesticides at 20-25°C (Baker, 1992; Spalding *et al.*, 1989)

Pesticide	Leaching Potential	Soil adsorption (K)*	Half-life (days)	Vapor pressure (Lasso=1)**		Solubility (mg/L)+	K_{oc}	Health Advisory Level (ug/L)+
herbicides								
Atrazine (Aatrex)	L	2.0	60	$2.9x10^{-7}$	0.021	33		3
Cyanazine (Bladex)	M	3.8	14	$1.6x10^{-9}$	0.00011	170	160	1
Metolachlor (Dual)	M	4.0	90	$3.1x10^{-5}$	2.2	530	168	100
Alachlor (Lasso)	M	3.4	15	$1.4x10^{-5}$	1	240	200	0.4
Metribuzin (Sencor)	L	1.2	40	$<1x10^{-5}$	<1	1220	41	10
Prelude (Paraquat)	S	20,000	1,000	0	0	620,000	20,000	30
Imazethapr (Pursuit)	NA	0.2	90	NE–	NE–	1400	5	NE–
Propachlor (Ramrod)	S	1.6	6	$2.3x10^{-4}$	16	613	420	90
Trifluralin (Treflan)	S	160	60	$1.1x10^{-4}$	7.9	0.3	1400	2
2,4-D	S	0.4	10	$8.0x10^{-6}$	0.57	890	1000	70
insecticides								
Turbufos (Counter)	S	10	5	$3.2x10^{-4}$	23	5	3000	1
Carbofuran (Furadan)	L	0.4	50	$6.0x10^{-7}$	0.043	351	29	40
Chlorpyrifos (Lorsban)	S	121	30	$1.7x10^{-5}$	1.2	0.4	6070	20
Fonofos (Dyfonate)	M	17.4	40	$3.4x10^{-4}$	24	17	680	10
Phorate (Thimet)	M	20	60	$6.4x10^{-4}$	46	22	1000	NE–

* K = concentration in soil/concentration in water, for soil with 2% organic carbon.
** Vapor pressures relative to that of Lasso (arbitrarily chosen as a reference point).
\+ mg/L = parts per million, ug/L = parts per billion (or 0.001 parts per million).
_ NE = not established, K_{oc} = soil sorption index. Leaching Potential (L = large, M = medium, S = small).

TABLE 2. Data required to assess pesticides' leaching potential (USGAO, 1991)

Data requirement	Determination made
Hydrolysis	Breakdown of pesticide in water through chemical processes, specifically, the rate of breakdown and identity of breakdown products.
Photodegradation in soil and in water	Breakdown of pesticide by sunlight when pesticide is in soil and in water, specifically, the rate of breakdown and identity of breakdown products.
Aerobic soil metabolism	Breakdown of pesticide due to microorganisms in the soil and to physical and chemical processes that occur in soil, specifically, the rate of breakdown and identity of breakdown products.
Mobility in soil	Potential of pesticide to leach through soil or adsorb onto different types of soil particles.
Dissipation in the field[a]	Persistence and mobility of pesticide under actual use conditions in the field.
Water solubility	Tendency of pesticide to dissolve in water.
Vapor pressure	Tendency of pesticide to dissipate into the air, rather than enter soil
Octanol/water partition coefficient	Rough indication of tendency of pesticide to adsorb onto soil particles.

[a] EPA may also require a long-term dissipation study in some cases, depending on the results of certain other studies.

4.1. SURFACE IRRIGATION METHODS

Spalding *et al.* (1989) have reported that irrigating corn on well drained soils along the Central Platte River Valley have resulted in contaminating the groundwater where NO_3-N levels are one to six times the maximum contaminant level. They have also shown that groundwater beneath both gravity and sprinkler irrigated farmland contain atrazine but sprinkler irrigation is the better management option.

Bouwer (1987) compared the data from gravity irrigated fields and suggested that rapid downward movement of NO_3-N occurred at the upper end of a field where the vadose zone is at field capacity during much of the growing season and slower NO_3-N mobility on lower end side of the field where downward movement depended on rainfall or occasional excess irrigation. Preferential movement of herbicides was also possible under the excessive irrigated conditions.

Troiano *et al.* (1993) concluded that amount and method of water application are important factors that determine pesticide movement and must be considered as integral components of pesticide management in irrigated agriculture. Greatest movement of atrazine was observed in the furrow method where a greater flux of water was produced, and the sprinkler method resulted in the least water and atrazine movement even under more frequent irrigations. Weil *et al.* (1990) reported that the areas irrigated by center point irrigation systems resulted in NO_3-N concentrations in the groundwater in the range of 10-20 mg/l; the poultry manure resulted in significantly higher NO_3-N concentrations in groundwater under irrigated sandy soils compared to commercial N fertilizer.

Fermanich *et al.* (1993) compared the effects of three water management regimes on rate and amount of atrazine and nitrate movement through sandy soils of Wisconsin. Table 3 shows some of the data collected by Fermanich *et al.* (1993) in 1991. Atrazine concentrations ranged from 1 to 4 mg/l throughout the growing season in the solute water at 1.4 m depth. The results of this study indicated that amount of irrigation water has a significant impact on the movement of atrazine and nitrogen to the groundwater.

TABLE 3. Nitrogen and atrazine fluxes for three water management regimes (Fermanich *et al.*, 1993)

Irrigation				**Flux at 1.4 m**			
amount	**Rainfall**	**ET**	**Drainage**	**Atrazine flux**		**Nitrogen flux**	
mm	**mm**	**mm**	**mm**	**kg/ha**	**% applied**	**kg/ha**	**% applied**
0	452	312	102	.0019	0.22	12	6
215	452	371	254	.0048	0.55	20	10
272	452	380	297	.0065	0.75	58	29

Atrazine was applied at 0.87 kg/ha a.i.
Total nitrogen was applied at 198 kg/ha.

Watts *et al.* (1993) have compared the effects of three irrigation systems on NO_3-N leaching and uptake efficiency. Table 4 summarizes part of the data from their experiments. The results of their study indicate that improved center-pivot sprinkler system resulted in using 67 percent less water and 80 percent less nitrogen fertilizer and gave 91 percent of the grain yield compared to conventional furrow system of irrigation. Also, the residual N in 1992 spring was significantly lower under center-pivot system in comparison to other irrigation systems. Watts *et al.* (1993) found that the NO_3-N concentrations in the groundwater averaged around 26.1mg/l whereas, atrazine concentrations ranged from less than 1.0 mg/l to 3.5 mg/l. Studies by Watts *et al.* (1993) suggest that with better irrigation management we can minimize the impacts of irrigation on soil and water quality.

Ayars and Phene (1993) also have reported the preliminary results of their study comparing the effects of furrow and subsurface drip irrigation on groundwater quality. This research suggests that the electrical conductivity, boron, and chloride concentrations in the shallow groundwater were not influenced by the irrigation management whereas, the NO_3-N concentration in groundwater decreased during the growing season under subsurface drip system.

TABLE 4. Residual soil N and N uptake efficiency as a function of the irrigation practice (Watts *et al.*, 1993)

	Nitrogen use efficiency						
Irrigation System	**Rainfall**	**Amount of irrigation water**	**N-fertilizer applied**	**N with irrigation water**	**Residual Soil N**	**Total N* available**	**Yield**
1991	mm	mm	kg/h	kg/ha	kg/ha	kg/ha	Mg/ha
Furrow	75	940	201	301	106	608	12.53
Surge-Flow	75	450	123	144	173	440	12.33
Center-Pivot	75	340	33	109	95	237	12.17
1992							
Furrow	184	740	178	237	121	536	13.03
Surge-Flow	184	230	73	74	135	282	12.59
Center-Pivot	184	210	47	67	78	192	11.02

*does not include any mineralization or denitrification

4.2. SUBSURFACE IRRIGATION AND WATER TABLE CONTROL METHODS

Total water management, which includes both drainage and irrigation, can improve productivity and decrease the negative impacts of agrochemicals on groundwater quality (Kanwar *et al.* 1993b). Several studies are going on in the U.S.A. to determine the impacts of subirrigation and water table control on groundwater water quality. Kalita and Kanwar (1993) and Kalita *et al.* (1994) investigated the impacts of different water table management and subirrigation practices on the movement of NO_3-N and pesticides into the groundwater. Table 5 summarizes the data on NO_3-N, atrazine, and alachlor concentrations in the shallow groundwater as a function of the water table depth. These results show that NO_3-N and herbicide concentrations in the shallow groundwater can be reduced significantly by maintaining shallow water table depths in the range of 0.3 to 0.6 m during the growing season. They also concluded that water table management practices can be recommended with other sound agricultural practices to reduce the concentrations of NO_3-N, atrazine and alachlor in areas where the use of water table control or subirrigation systems is possible.

TABLE 5. Average NO_3-N, atrazine, and alachlor concentrations in the shallow groundwater under different subirrigation regimes when water table depths were maintained at 0.3, 0.6, and 0.9 m during 1991 (the third year of the experiment)

Groundwater sampling depth	**NO_3-N conc., mg/l**			**Atrazine conc., mg/l**			**Alachlor conc. mg/l**		
(m)	0.3 m	0.6 m	0.9 m	0.3 m	0.6 m	0.9 m	0.3 m	0.6 m	0.9 m
1.2	2.5	3.8	11.7	8.8	11.3	14.6	1.4	2.0	2.9
1.8	1.8	3.4	5.6	4.3	7.4	7.3	1.1	1.7	2.7
2.4	1.4	2.1	2.5	3.6	5.7	9.8	0.9	2.1	2.6

5. Impact of Agricultural Practices on Water Quality

It is important to identify the cause of agrochemicals in groundwater before the development of best management practices to control groundwater pollution. Many times the causes of groundwater contaminaton are not straightforward. Several studies have been conducted to determine the effects of various agricultural practice on groundwater quality. Kanwar *et al.* (1993a) have compared the effects of long-term tillage and crop rotation practices on groundwater quality. Table 6 gives data on average yearly NO_3-N concentrations in drain water, and total NO_3-N loss with drain water as a function of the tillage system and crop rotation. Table 6 shows that NO_3-N concentrations in the drain water were significantly higher under continuous corn in comparison with the corn-soybean rotation for all tillages. Three year (1990-92) average NO_3-N concentrations in drain water from moldboard plow plots were significantly higher in comparison to the no-till and ridge-till plots under continuous-corn. Of the concern was the fact that yearly NO_3-N concentrations of 10 mg/l (a drinking water standard in the United States) in tile flow was exceeded by nearly all the samples for each tillage system and crop rotation.

The yearly total NO_3-N losses with drain water ranged from 4.8 kg/ha in 1992 to 107.2 kg/ha in 1990. Three year average (1990-92) NO_3-N losses with drain water were much higher under continuous corn in comparison with the corn-soybean rotation for all tillages. Although NO_3-N concentrations were greater under conventional tillage (moldboard plow + disking) than under a no-till system, total NO_3-N losses with subsurface drain flow were higher under the no-till and chisel plow systems because of greater volume of water moving through the soil. The data on average monthly NO_3-N concentration in the individual plot piezometers indicate that under continuous corn NO_3-N concentrations at 1.8 and 2.4 m depths were higher in comparison with the corn-soybean rotation.

Table 7 gives the yearly total losses of herbicides with drain water as a function of tillage and crop rotation for 1990. These data indicate that atrazine losses were greatest in comparison with other three herbicides. Also, no-till and ridge-till systems gave greater losses of atrazine, cyanazine and metribuzin because of the preferential movement of these herbicides through macropores. The total yearly average losses for atrazine and alachlor ranged from 2.2 to 7.3 g/ha and 0.06 to 0.62 g/ha, respectively.

6. Best Management Practices for Environmental Enhancement

Best management practices (BMPs) are practices that can be used to minimize point and nonpoint source pollution and are economically, socially, and environmentally acceptable. A brief review of various BMPs is presented in the follow sections.

TABLE 6. Average yearly NO_3-N concentrations in drain water, and NO_3-N loss with subsurface drain water as a function of tillage and crop rotations

Year	Crop Rotation	Chisel	MB Plow	Ridge Till	No Till
		Average NO_3-N concentrations in subsurface drainage water, mg/l			
1990	Continuous corn	51.9	61.6	39.1	38.2
1991	-do-	21.7	27.3	14.4	14.6
1991	-do-	18.2	18.5	11.9	13.9
Average (1990-92)	-do-	30.6ab	35.8a	21.8c	22.2bc
1990	Corn-soybean	25.9	27.5	21.4	20.3
1991	-do-	13.8	15.3	11.4	11.1
1992	-do-	13.7	18.7	12.8	10.1
Average (1990-92)	-do-	18.5ba	19.0a	13.9ba	13.4b
		Average NO_3-N loss with subsurface drainage water, kg/ha			
1990	Continuous corn	100.0	58.1	83.4	107.2
1991	-do-	76.0	62.7	58.2	61.7
1992	-do-	17.0	16.6	10.2	14.9
Average (1990-92)	-do-	64.3a	45.8a	50.6a	61.2a
1990	Corn-soybean	52.4	38.0	30.3	36.5
1991	-do-	36.3	35.5	29.4	30.3
1992	-do-	15.3	9.1	11.2	4.8
Average (1990-92)	-do-	32.1a	27.5a	23.7a	23.9a

TABLE 7. Average herbicide loss with subsurface drain water as a function of tillage and crop rotation for three years (1990-1992)

Crop Rotation	Herbicide	Herbicide loss with subsurface drain water g/ha			
		Chisel Plow	MB Plow	Ridge-Till	No-Till
Continuous corn	Atrazine	4.4	2.17	5.9	7.3
	Alachlor	0.36	0.06	0.34	0.31
Corn-soybean	Cyanazine	0.10	0.25	0.19	0.16
	Alachlor	0.05	0.62	0.39	0.16
Soybean-corn	Metribuzin	1.7	1.70	3.4	2.5
	Alachlor	0.79	0.06	0.11	0.16

6.1. FORMULATION OF CHEMICALS

The changes in pesticide formulations may change the solubility, adsorption, and other properties. Pesticides are available in more than one formulation (i.e. wettable powders or flowable formulations). Wettable formulations have been found to have greater runoff losses than other formulations (Wauchope 1978, 1987). Emulsifiable concentrate and flowable formulations lost 4 to 8 percent of applied atrazine while wettable powder and granule formulation lost 9 to 12 percent with runoff water. One of the reasons for this difference may be the larger particle size of the formulation in the wettable powder form which may allow washoff of the particles with rainfall immediately after application. Encapsulation of pesticides may increase persistence and reduce the availability for leaching to groundwater, but could increase the potential for runoff loss.

6.2. CHEMICAL RATES AND METHODS OF APPLICATIONS

Reduction in the rates and total quantity of chemical applied could reduce the amount of chemical available for leaching to groundwater or for runoff. A computer simulation study indicated that higher NO_3-N losses were associated with high N application rates (Kanwar *et al.* 1988). Baker and Johnson (1983) have summarized the results of several field studies indicating higher NO_3-N leaching losses with larger N application rates. Hall *et al.* (1972) found a linear relationship between atrazine application rate and atrazine concentrations in the runoff water. For pesticides, rate of application has been found to be one of the dominating factors affecting pesticide losses with sediment and runoff water. If chemical application rates can be reduced it will reduce the contamination potential to water resources as well as save money and energy.

6.3. PLACEMENT OF CHEMICALS

One of the approaches to reduce the leaching of chemicals to groundwater and/or surface water would be to incorporate the chemical with soil. A chemical's location in the soil profile and/or on the surface affects its concentration in runoff and subsurface drainage water. If a chemical is broadcast applied, it will mix with the incoming rainfall or irrigation in a thin mixing zone (about 10 to 20 mm thick) and will either leach to subsoil layers or become part of the runoff water. If a chemical is incorporated it is less susceptible to runoff losses.

Another approach would be to apply the chemical on a partial area through the use of banding, where only the crop row area is treated as opposed to a broadcast application where the whole area in the field is treated. With banding practice, the rate of chemical application can be reduced to more than 50 percent or more. Kanwar and Baker (1993) have shown that banding of herbicides has a significant effect on water quality improvement. Last approach would be to have a spot treatment only which will result in much greater reductions in the use of herbicides. Placement of chemicals at an appropriate place is a good BMP to control groundwater pollution.

6.4. TIMINGS OF CHEMICAL APPLICATIONS

Appropriate timings of chemical applications can increase the efficient use of chemicals (especially N) and result in decreased leaching losses. Kanwar and Baker (1993) have shown that split-N applications resulted in lower residual N in the soil profile and NO_3-N concentrations in the subsurface drainage water were at or below 10 mg/l during the nine-year study period. Also, for certain situations, a pesticide can be applied as per-emergence versus post-emergence. But poor timings could result in increased pest damage or decreased environmental benefits. Hydrologic factors, primarily rainfall patterns, will have significant interactions with the timings of chemical applications.

6.5. CONSERVATION TILLAGE SYSTEMS

Any tillage system which leaves at least 30 percent of the soil surface covered with crop residue is defined as a conservation tillage system. Conventional tillage system (moldboard plow) disturb the soil surface and incorporates the crop residue. Also, conventional tillage system changes the infiltration characteristics of the soil by destroying the macropores. Several conservation tillage systems (namely no-till, ridge till, and chisel plow) are being used to reduce soil erosion and energy input costs, but these systems may require more pesticide use. Conservation tillage systems affect runoff volume and the chemical concentrations in the drainage water. Baker and Johnson (1983) and CTIC (1994) have reviewed the effects of various tillages on water quality. In recent studies conducted at Iowa State University (Kanwar *et al.* 1993a, Kanwar and Baker 1993) it has been concluded that conservation tillage systems increase infiltration, organic matter, adsorption, microbial activity, and chemical leaching to groundwater. Conservation tillage is an effective BMP for controlling groundwater pollution.

6.6. CROPPING SYSTEMS

Diverse cropping systems are currently being used in Iowa and in other U.S. watersheds. Narrow row width and densely planted crops, such as small grains and drilled soybeans affect infiltration and runoff volumes. These cropping systems seem to reduce the chemical concentrations in the runoff water. Crop rotations also affect the use of chemicals. For example, corn-soybean rotation will not use nitrogen fertilizer in the soybean years whereas continuous-corn practice will use nitrogen year after year. Also, crop rotations offer a greater diversity of pesticides being used within a watershed to control non-point source pollution. Kanwar *et al.* (1993a) have concluded that continuous corn practice receive higher N application rates and results in higher NO_3-N loss to the groundwater. Therefore, continuous-corn production is not an environmentally and economically sustainable management practice.

6.7. CONTOURING, TERRACING, FILTER AND BUFFER STRIPS, AND WELL BUFFER ZONES

Land topography and soil types add additional complications on the runoff volumes and soil erosion rates. Terracing and contour farming have been used widely for centuries to create better farming conditions, and control and conserve soil water. Contour farming can reduce soil erosion by as much as 60 to 80 percent compared to up and down method of farming. This reduction in soil erosion will result in reduced pesticide runoff losses. Terraces may reduce pesticide losses with runoff water whereas, tile outlet terraces may increase surface water contamination as tile water is discharged directly into streams.

Also, vegetative filter strips and waterways have been suggested as potential BMPs to control water quality problems. Several studies have shown that the potential exists to reduce soil erosion, soluble P and N, and pesticide losses to streams if vegetative filter strips or buffer strips are established at the edge of fields. Vegetative filter strips and grassed waterways have been found to reduce the pesticide loss from 19 to 22 percent with runoff water. Also, imposing buffer zones around shallow wells seems to correct some of the water quality problems. Prohibitive use of agricultural chemicals within a specified distance of drinking well may be an appropriate management practice.

6.8. IRRIGATION AND DRAINAGE SYSTEMS

Irrigation and drainage practices are typically considered as production practices rather than BMPs for water quality enhancement. Irrigation management is important in controlling water quality related problems. The rate, amount, and timings of irrigations are important considerations. Small amount of irrigation soon after herbicide application will move the herbicide into the soil and below the mixing zone. This will reduce the movement with later runoff producing rains. Also, many simulated rainfall (irrigation) studies conducted in Iowa have indicated that pesticide losses are greatest when heavy rains occur immediately after chemical applications (Kanwar *et al.* 1993a, Kanwar 1991, Everts and Kanwar 1994). Sprinkler irrigation is a better management option over gravity irrigation systems.

Several other irrigation systems that include consideration are surface flow, furrow diking, reuse pits to collect irrigation tail water for reuse, low-energy precision application method, drip and subirrigation methods, and use of chemigation. Local hydrologic and geologic factors must be considered before selecting the irrigation management practice.

Artificial drainage increases infiltration rates and decreases surface runoff. Baker and Johnson (1983) have reported several studies showing NO_3-N leaching was increased with subsurface drainage. Bengtson *et al.* (1989) have reported that subsurface drainage reduced atrazine and metolachlor losses by more than 50 percent and most of this loss occurred with surface runoff. The Iowa data (Kanwar and Baker 1993, Kanwar *et al.* 1993a) indicate that subsurface drainage systems also reduce the groundwater contamination problems (as tile water is discharged to streams) as improved infiltration provides larger soil depth to filter the chemicals before they reach the water table. Kalita *et al.* (1994), and Kalita and Kanwar (1993) have found that better water table management practices could be used to reduce the risk of groundwater contamination.

7. Summary and Conclusions

Use of agricultural chemicals to increase agricultural production has become a source of concern for environmental pollution. This paper has resulted in the following specific conclusions.

1. Global popluation will double by the year 2050 resulting in severe impact on the environement.
2. Recent studies indicate that nitrate and pesticides are routinely found in drinking water supplies raising questions about the heavy use of agricultural chemicals in agriculture.
3. Studies also indicate that better water and chemical management systems can reduce the risk of contamination of drinking water sources due to the continued use of agrochemicals.
4. More research is needed to better understand the fate of agrochemicals in the environment for developing technologies to reduce the risk of water contamination.

8. Recommendations for Future Research

To develop appropriate technologies for minimizing the impact of agrochemicals on surface and groundwater quality it is necessary to consider the properties of the chemical, and local agronomic and environmental conditions. These technologies may or may not be applicable to other circumstances. What we know, and what we do not know, about agriculture's role in the water quality problems must be continually reassessed as new research findings are released. Following opportunities for research could contribute in bringing the contamination of water resources under control.

a. Research is needed to understand better about the sources of pesticide contamination of groundwater. It is very important to know if the contamination resulted from point sources (like careless disposal or spill) or nonpoint sources (such as the leaching process).
b. We have not yet fully understood the physical processes dictating the fate of chemicals and transport in soil and water system. More research is needed on the effects of microbial activity, pH, organic matter, and temperature on pesticide persistence.
c. What happens once chemicals have leached into a groundwater system? We do not know the ability of ecosystems to cleanse themselves or how long such processes might take place. The existing pesticides and nitrate in the soil and water system

may leach into groundwater for long periods of time even if chemical applications are completely stopped to croplands.

d. More research is needed on risks posed to humans from exposures to agrochemicals at levels commonly found in groundwater.
e. New pesticide products that are effective against pests and have a low probability of leaching are needed. These new chemicals should be tailored to hydrogeologic conditions of high risk areas so that their long-term use will not be a threat to groundwater.
f. Current ongoing research on the development of better agricultural and irrigation management practices should continue under a different set of environmental conditions in different parts of the world.
g. More research is also needed on developing and implementing cost-effective diagnostic and monitoring methods to refine the management of soils, nutrients, pesticides, and irrigation and drainage water.
h. Research on government policies and regulations aimed at controlling groundwater pollution from agricultural sources is needed. The biggest knowledge gap is the lack of adequate computer models in predicting the behavior of irrigation practices and chemical use on the environment before policies can be developed on socioeconomic impacts.

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WATER AND NITRATE BALANCE IN IRRIGATED SOILS

G. VACHAUD, L. KENGNI, B. NORMAND, J.L. THONY,
Laboratoire d'Etude des Transferts en Hydrologie et Environnement,
(CNRS URA 1512, INPG, UJF),
BP. 53 38041 Grenoble Cedex 9 - France

1. Introduction

Non-point source agricultural pollution of ground water has become a real threat to the environment over the last 30 years. In particular, although subject to controversy, the relation between nitrate pollution and agricultural practices remains uncontested (Sébillotte 1987). In Europe, studies have shown that only 50 to 70 % of the fertilizer is generally used by crops, the rest being volatilized, denitrified or leached (Guiraud 1984). Leaching of nitrate is responsible for the ground water pollution. There is a need to determine optimal fertilization rate in such a way that the amount of N remaining in the soil after harvest, and potentially leachable during winter, will be minimized, without negative economic implications concerning the level of crop production. In the same way, irrigation should be optimized to provide the crop with the proper amount of water without induced drainage.

Therefore both the fluxes of water and dissolved chemicals, as well as their spatio-temporal changes, must be determined in-situ in order to assess the importance of possible pollution episodes and to validate numerical models which can then be used to predict the evolution of water quality for different scenarios of agricultural practises.This should be done on the basis of physical models characterizing the transport processes in the soil.

A quick presentation of methods and measurement techniques will first be done in this paper . Some results related with intensively cultivated maïze will then be discussed. They were obtained within the framework of a research programme initiated by the Commission of European Communities (DGXII-STEP)(1) over a multiyear experiment during the period 1991-1994, and under our coordination. Our measurement site was selected for the severe degree of nitrate pollution founded in an underground aquifer used at the same time for the water supply of the surrounding urban communities and for irrigation. A question was to determine which one of irrigation or fertilizer

(1) WASTES, for "Water and Solutes Transport in European Soils", with the participation of : Agricultural University of Wageningen; Catholic University of Leuven; Agricultural University of Athens; Spanish Science Research Council-Institute of Natural Resources and Agrobiology, Sevilla; and the expertise of Cornell University and DSIR-New Zealand.

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 395–406.

application was responsible for the degradation of water quality. Another related point was to determine the proportion of the fertilizer N that leaves the system through the drainage water during and after the crop growing season for different strategies of Nitrogen fertilization, and the effect of N application on crop production, in order to optimize fertilization techniques with respect to sustainability of agriculture and to protection of environmental resources.

2. Methods and Measurement Techniques

This point being discussed in detail in the paper by Van Damm and Feddes in this book, we will limit ourselves here to a brief survey.

2.1. TRANSPORT OF WATER

In terms of water transport, two state variables must be considered and measured:

- the *volumetric water content,* θ (m^3 of water per m^3 of soil) measured classically under field conditions with a neutron moisture meter. Its distribution with depth, at a given time, permits to quantify the volume of water S present in the soil from the surface to a given level (water storage). Its variations with time (ΔS) are induced by mass transfer such as infiltration through the soil surface, root extraction, percolation beyond a given depth, etc...
- the *pressure of water* h (expressed in equivalent height of a water column, m) easured in the field with tensiometers, or its associated variable: the *hydraulic head* H (equivalent m. of water), defined as:

$$H = h - z \qquad [1]$$

where z is the depth oriented downwards from the soil surface.

The gradient of H gives the direction of the flow and determines the importance of the flux.

The kinetics of mass transport is essentially controled by the relationship between the *hydraulic conductivity* K (usually expressed in 10^{-3}meter per day) and the water content: $K(\theta)$. This relationship is strongly nonlinear, K decreasing many times faster than θ, and varies considerably from one soil to another, since it depends essentially on the distribution of solid soil particles and on the tòpology of the pore space .

Finally, the flow of water, is described by a combination of the transport equation, namely Darcy's law generalized to an unsaturated system:

$$q = - K(\theta) \text{ grad } H \qquad [2]$$

together with the equation of conservation of mass:

$$dq/dt = -\text{div } q \qquad [3]$$

where q is the *flux density of water*, generally in 10^{-3}meter per day. Eq. [3] expresses in particular the fact that, except for a steady state system, any mass flux of water in the soil is associated with a change of water content with time.

It is clear from equation [2] that the mass flux of water at a given time t and a given depth z can be determined directly from the measurement of θ and gradH if $k(\theta)$ is known.

2.2. WATER BALANCE

The water balance, determined between the soil surface and a depth z_r just below the root zone, is calculated from the mass conservation equation writen as:

$$\Delta S = R - D - AET \qquad [4]$$

assuming runoff to be negligeable. In Eq. [4] ΔS is the change in water storage in the root zone (0- z_r), R the rainfall and irrigation amount, D the natural drainage at z_r, and AET the actual evapotranspiration, all values being related to a period of time Δt. Rainfall or irrigation can be measured with raingages. ΔS is obtained by the difference of water storage in the root zone as measured by the neutron probe between two consecutive dates. The remaining unknown terms are then D and AET. The drainage component D can be calculated from Darcy's law :

$$D = q\, \Delta t = - K(\theta)\ \text{gradH}\ \Delta t \qquad [5]$$

where q, $K(\theta)$, and gradH are measured at the same time at z_r. AET can be then derived directly from eq[4]. An important point in the application of eq.[5] is to select the proper time interval Δt between measurements, since obviously changes of θ at z_r must be small during Δt. For practical problems, it is often necessary to consider time steps of measurements close from one day.

This method requests that $K(\theta)$ be known. This relationship can be obtained directly in the field through the use of the "**zero flux plane**" method, described in detail by Vachaud et al.(1978).. Because of the high sensitivity of K with θ, $K(\theta)$ must be determined for every measurement site .

2.3. SOLUTE TRANSPORT

At the level of formal description, the convective transport of solute by water represents by far the most important phenomenon. The transport equation (Nielsen et al. 1986) is similar to Darcy's law :

$$J_s = - q\, D_s\, dC/dz + q\, C \qquad [6]$$

where J_s is the mass flux density of solutes, and where the two terms on the righ-hand side represent, respectively, the transport by dispersion, with D_s being the coefficient of dispersity which is strongly dependent on q, and the transport by convection. C is the mass concentration of solute in the flowing liquid. It can be measured quite easily with the use of suction cups, assuming that enough care is taken to avoid microbiological and physico-chemical transformations in the solution from its extraction to its analysis.

In general the second term is an order of magnitude larger than the first one. Therefore it can be often neglected, for practical questions, in the estimation of the mass flux, and the leaching of solute L induced by the drainage D of water (eq.(5)) can be simply approximated by:

$$L = D\,C \qquad [7]$$

It is clear from this equation that the flux of water and the concentration of the soil solution must be measured simultaneously to determine the leaching of solute. Any determination of concentration without knowledge of water flux is **useless**.

2.4. NITROGEN MOVEMENT AND BALANCE

If, as it is often the case, Nitrogen in the soil solution is essentially in N-Nitrate form, the amount of N-Nitrate in a soil layer can be calculated from the formula :

$$N = \frac{\left[NO_3^-\right] \theta_{\Delta z}\, \Delta z}{4.42} \qquad [8]$$

where $\left[NO_3^-\right]$ is the nitrate content in the soil solution, $\theta_{\Delta z}$ the mean water content of a layer Δz, N the nitrogen amount expressed in kgN/ha, and 4.42 the molar ratio between NO_3^- and N. The amount of N-Nitrate leaching below the root zone is given from eq. [7]:

$$L_N = D\,Cz_r \qquad [9]$$

It was shown by Kengni (1993) that, for the example used later on, the dispersive term of the full transport equation represents no more than 6 % of the value of the convective term.

Finally it is possible for Nitrogen to determine the partitioning between N derived from fertilizer and the total amount of mineral N with the use of ^{15}N tagged fertilizer. This was in particular done in our experiment, based on the per cent enrichement obtained for every soil layer :

$$N_E = \frac{N_T\, E}{E_0} \qquad [10]$$

where N_E is the mineral N from the fertilizer, N_T the total mineral N in the layer (Eq.(8)), E the ^{15}N enrichment in the same layer and E_0 the ^{15}N enrichment of the fertilizer (Mariotti, 1982; Olsen,1980). Then, the amount derived from the soil mineralization, N_S, can be obtained through the difference $N_S = N_T - N_E$.

In the same way

$$L_E = \frac{L_N E}{E_0} \qquad [11]$$

where L_E is the amount of fertilizer leached.

3. Illustration on a Field Study

The study was conducted in the Experimental Farm of La Côte Saint-André, located 40 km North-West of Grenoble, France in the heart of an area of very intensive cultivation of irrigated maïze (plaine de la Bièvre). The site is a typical glacial terrace, with approximately 1 m thick soil resting on a layer 10-20 m thick of gravels and pebbles of high permeability. The upper layer (0-0.3 m), is a loamy sand, rich in organic matter (2 to 3 %). An important point is the increase, in percentage and size, of gravels and stones with increasing depth. As a result, the root zone is practically not deeper than 0.8 m, and augering is scarcely possible past 1 m. A very powerful underlying water-table aquifer, undergoing large fluctuations with a depth varying between 6 and 15 m from the soil surface, is intensively used for irrigation and urban water supply. It has a high sensitivity to nitrate pollution. The European limit of 50 mg L^{-1} for nitrate concentration is reached or overpassed in a large number of wells, constituting an important source of conflicts between human health protection and agriculture needs.

Details concerning the experimental settings, the methodology and the results have already been published, in particular by Kengni (1993) and Kengni *et al.* (1994). We will therefore limit ourselves here to the most important findings.

3.1. THE TREATMENTS

In order to determine the amount of leaching (both water and nitrate) below the root zone and to obtain informations on the response of crop to fertilization, different treatments were applied on a plot of 2 ha. . Two of them were instrumented for intensive measurements (Kengni et al. 1994): **fertilization with ammonium-nitrate** applied at sowing (first, in 1991, the traditional rate used by farmers in the area: 260 kgN/ha; then, in view of the results obtained in 1991, 160kgN/ha in 1992, and 180 kgN/ha in 1993); or **no fertilization** (in 1991,1992 only). In the fertilized treatment, tagged ^{15}N fertilizer was also applied on replicate microplots, one of those fully instrumented, as described later. Finally, in parallel with measurements in the cropped plots, two subplots were also instrumented on **bare soil**, one fertilized, one without fertilization. The same irrigation schedule was applied on every plot, with the use of a gun sprinkler.

3.2. MEASUREMENTS

A series of measurement sites were installed on every treatment, each one with the following equipment (Fig.1) :

- one neutron access tube to allow soil water monitoring every 0.1 m down to 1 m,
- five mercury tensiometers installed vertically at 0.15, 0.3, 0.5, 0.7, 0.9 m,
- six suction probes at 0.3, 0.5 and 0.8 m depth, replicated in two series (northern and southern), in order to account for the variability of N-Nitrate concentration and of the ^{15}N enrichment in the soil solution, even at a short distance,
- one rainfall recorder, at the level of the canopy.

Altogether, eight measurement sites were available: 2 on bare soil (T1, fertilized, T8, unfertilized), 4 on fertilized maïze, (T2, T3, T4, T6 one of those for ^{15}N application), and 2 on unfertilized maïze (T5,T7).

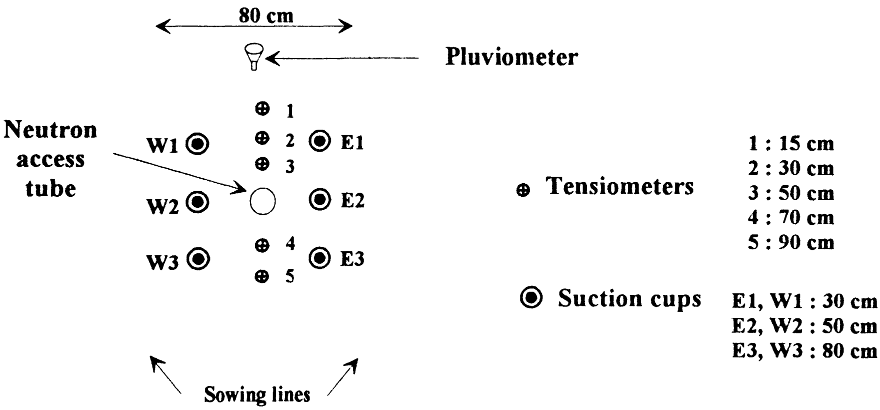

Figure 1. Detail of a monitoring site

Measurements of soil moisture were taken, during the three continuous years, twice weekly from June to October, with exception of intensive periods (irrigation) were this was done on a daily basis, and then every two weeks until mid-February. Tensiometer readings were recorded daily from June until the onset of frost. Rainfall/irrigation and micrometeorological data were obtained every 30 min with the use of a data acquisition system connected by Modem to the laboratory.

The soil solution was extracted from ceramic porous cups once a week. It was immediately sterilized in-situ with the use of a 0.4 mm Millipore filter (MILLEX

SLHV 025LS) and then deep-frozen. The samples were first analyzed by liquid chromatography, to obtain the nitrate concentration, then, for the ^{15}N subplot, reduced by dehydration, and the isotope ratio was determined by mass spectroscopy.

The mass flow of water and solute was determined on every site at the depth z_r = 0.8m with the use of eq.[5] and [8]. This choice resulted from root profiles obtained in the past on the same location. Therefore the hydraulic conductivity - water content relationship was characterized on every measurement site, with the use of the "zero flux method" (Kengni 1993). A typical example is given on Figure 2.

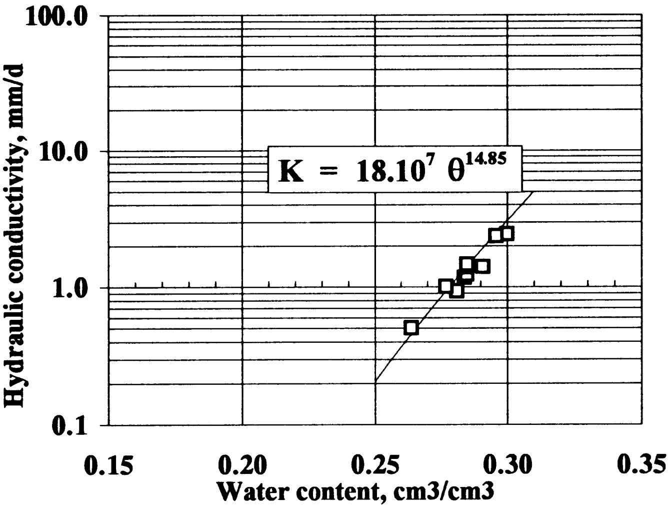

Figure 2. Relation between the hydraulic conductivity and the water content obtained in-situ

3.3. WATER BALANCE, 1991

The climatic conditions were very different during the 3 years of experimentation: for the period going from April 1 to Dec 31, the total rainfall was of 601mm in 1991, 810mm in 1992 and 1096mm in 1993. Cumulative values of the different terms of the water balance during the crop cycle are given on Table 1. Details concerning their determination have been published by Kengni et al. (1994) .It is noticeable that the first year (1991) was atypic in terms of climate, with a fairly dry spring, and moderate rains (321 mm) during fall and winter. On the contrary, in 1992, important rainfall occured during the spring, resulting in fairly large drainage, and low mineralization rate in May-June, whereas the following year an unsual amount of rainfall was obtained in September-October, with a total of 530mm during those 2 months. As a result, the annual repartition, and the total amount of cumulative drainage was quite different from a year to the other, as shown in Figure 3. However a common important point is noteworthy: during the period of irrigation (July-August) there was systematically **no drainage**, a proof that irrigation, as it was done, was very efficient and not responsible for nitrate leaching. It is also clear that rainfall occuring at the end of the crop cycle or after harvest, at a period when evapotranspiration is very small or null, does represent a real threat for groundwater pollution in case of any residual quantity of nitrogen in the root zone at that period.

TABLE 1. Terms of the water balance (in mm) during the cultivation cycle of maize, 1991, 1992, 1993 (average from 6 sites)

April-October	1991	1992	1993
Rainfall	323	504	886
Irrigation	227±12	120±23	121±11
Drainage	82±13	157±11	482±25
AET	460±20	460±21	531±15
PET	250	276	215

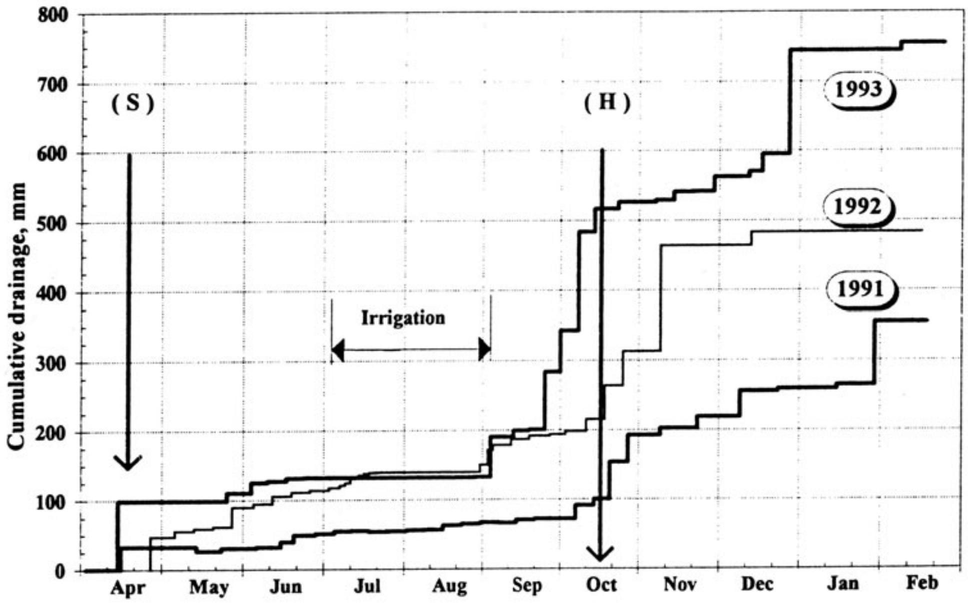

Figure 3. Intercomparison between values of cumulative drainage under the cultivated sites obtained in 1991, 1992 and 1993 (S : sowing ; H : harvesting)

3.4. FERTILIZER RECOVERY AND PLANT RESPONSE

Different experimental conditions were also applied in terms of fertilization:

- in 1991, it was clearly shown (Kengni et al. 1994), that the application rate of ammonium-nitrate used by the farmers (260 KgN/ha) was by far to high. A clear evidence was given by measurements related to the plant uptake (290 KgN/ha) and to the production of N-nitrate by mineralization of the soil organic matter (150 KgN/ha), an information obtained from measurements made on the bare soil sites. As a result, a residue of approximately 150 KgN/ha of N-nitrate was found in the root zone after harvest, 36% being originated from the fertilizer. This amount, plus an excess of approximately 40 KgN/ha produced by a second mineralization flush in october, was totally leached by the rain occuring during fall and winter, as clearly shown in Figure 4. In order to prevent this leaching it was decided to apply reduced rates in 1992 and 1993;

- in 1992, the partition between fertilized and unfertilized subplots was maintained, but with a different application rate of fertilizer: a total of **160 KgN/ha**, splitted in 50 at sowing and 110 at 6 leaves stage;
- in 1993, due to a very strong decrease of yield on the unfertilized subplot for 2 continuous years (Table 2), and in view of results obtained in parallel on classical agronomic tests for crop response to fertilization, it was decided to apply on the whole plot a unique treatment with an input of **180 KgN/ha** splitted in 40 at sowing and 140 at 6 leaves stage.

Both years, one site was again fertilized with ^{15}N tagged ammo-nitrate.

Two important results merit to be commented. First, the amount of N derived from fertilizer and detectable in the root zone was **null**, in both cases, during the period September-December. Then, values of cumulated losses of N-Nitrate by leaching given in Figure 4 show that in 1992 no differences could be found between the fertilized and the unfertilized treatment, a proof that the efficiency of the fertilizer was very good. Approximately 1/3 of the leaching was related to rainfall in May-June. In 1993 only one treatment was applied on all sites. The total leaching was higher than the previous year, as a result of higher input and of probably more important uncertainty on the estimation of drainage due to unusual rainfall during September-October.

3.5. EFFECT ON CROP PRODUCTION

Finally, in terms of plant production and plant uptake, the most important results are given in Table 2.

Two main conclusions can be drawn:

1. The yield is quite unsensitive to the level of fertilization. Clearly the traditional rate of 260 KgN/ha was too high, by respect to plant uptake, as discussed previously since it does not take into account the production of N-Nitrate by mineralization of the organic matter of the soil. A reduction of 80-100 KgN/ha does not affect the production but decreases drastically the amount of nitrate residual in the root zone at harvest, thus the risk of nitrate leaching. This point has been very clearly and quickly understood by the farmer communauty. The corresponding changes have been widely applied with success since 1992.

2. The soil is very fertile, but cannot be cropped with success without a convenient fertilization scheme. After 2 years without fertilization the decrease of yield is drastic and beyond economic sustainable levels. On the contrary, it is remarkable that one year of fertilization suffices to restore the yield at the same level as for a plot continuously fertilized.

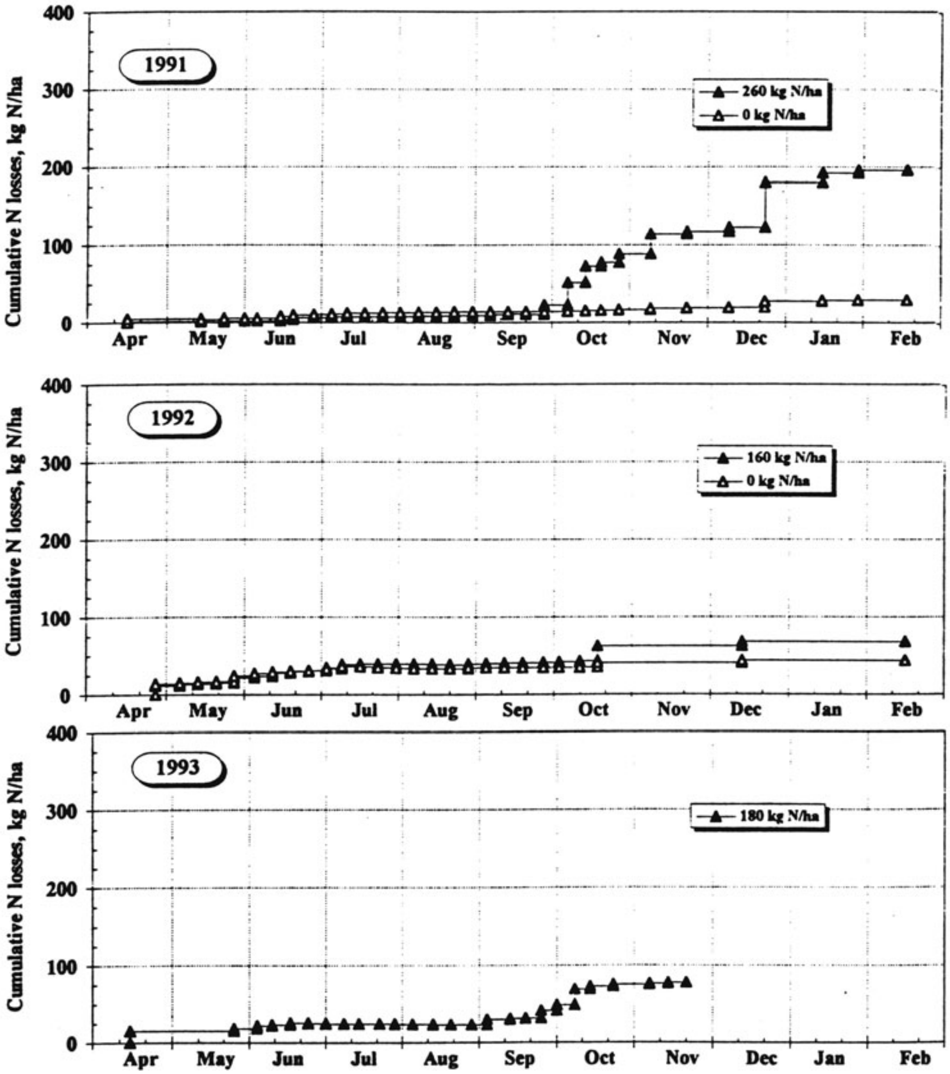

Figure 4. Cumulative losses of nitrates under the cultivated sites in 1991, 1992 and 1993 (average values per treatment)

TABLE 2. Fertilization, and plant production

1991		
Fertilizer input (kgN/ha)	**260**	**0**
Residue at harvest (kgN/ha)	182±50; **(50)***	2±1
Plant uptake (kgN/ha)	284±30	176±4
Yield grains (kg/ha)	**13100**	**10600**
1992		
Fertilizer input (kgN/ha)	**50+110**	**0**
Residue at harvest (kgN/ha)	20±11; **(2)***	4±2
Plant uptake (kgN/ha)	213±17	85±3
Yield grains (kg/ha)	**11600**	**5900**
1993		
Fertilizer input (kgN/ha)	**40+140**	
Residue at harvest (kgN/ha)	24±12; **(0.5)***	
Plant uptake (kgN/ha)	225±23	
Yield grains (kg/ha)	**12200**	

[(xx) corresponds to residual N from fertilizer in the root zone at harvest]*

4. Conclusions

Methods and measurements tools are now available to measure in situ the different terms of the water balance and the leaching of fertilizers beyond the root zone of a crop. It is also possible to determine accurately with the same materials, and with the use of tagged fertilizer, the rate of production of N-nitrate by mineralization of the organic matter of the soil, and to follow kinematically the amount of N-nitrate derived from fertilizer in the leaching water.

Very interesting results were recently obtained in term of numerical simulation of coupled transport of water and nitrogen in the soil- plant- atmosphere continuum, in particular those published by van Clooster et al, (1994). It is now expected that the coupling between this modelling approach and field measurements, such as those described here, will be fruitful in terms of development of optimized cultivation schemes in the context of sustainable agriculture and environmental protection.

5. Acknowlegments

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NITRATE LEACHING UNDER IRRIGATED AGRICULTURE

F. MORENO, F. CABRERA, J.M. MURILLO,
J.E. FERNANDEZ, E. FERNANDEZ-BOY AND J.A. CAYUELA
Instituto de Recursos Naturales y Agrobiología de Sevilla (CSIC),
P.O. Box 1052
41080 Sevilla, Spain

1. Introduction

In the last two or three decades nitrogen (N) fertilizers have been applied to agricultural soils at high rates to obtain higher crop yields. The increase in the nitrate concentration in both groundwater and surface water is related to agricultural practices. The use of nitrogen fertilizers at rates higher than the rate of uptake by the plant increases the potential for increased nitrate leaching, as has been shown by Roth and Fox (1990) for nitrogen-fertilized corn.

Farmers, in many countries, often use amounts of N-fertilization that exceed the N requirements of crops, and they, thereby increase the amounts of potentially leachable nitrate in the soil. Under irrigated agriculture, drainage below the root zone is required to maintain the salt balance. The water flow below the root zone can produce nitrate losses. Water and nitrate flow depends on the soil characteristics, amount of water applied by irrigation or natural precipitation and the amount, timing and species of nitrogen applied. Shepherd (1992), has posed the question "are the effects of irrigation on nitrate leaching loss good or bad ?", and points out that "both opinions have recently been expressed". This paper presents the results of two field studies conducted on nitrate leaching under irrigated crops as well as some of the main characteristics of nitrate leaching under agricultural practices found in the literature.

2. Review

One of the first discussions about the movement of nitrate in soils was presented by Boussingault (1856). Several papers dealing with the nitrate leaching have been published since the beginning of this century and many of these were cited in the interesting review published by Gardner (1965). Recently, Addiscott *et al.* (1991) have published a book on the relationship between farming, fertilizers and the nitrate problem. Because of the limited space, in the present paper we will only review some of the main works related to nitrate leaching in agricultural soils.

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2.1. GENERAL CHARACTERISTICS OF NITRATE LEACHING UNDER AGRICULTURAL PRACTICES

Nitrogen losses by leaching occur mainly in the nitrate form. Some leaching of ammonium may occur in sandy soils, but its leaching is limited by adsorption to the soil's exchange complex. The leaching of soluble soil organic nitrogen seems to be of little importance (Smith, 1987). Nitrogen losses can occur in the water runoff, mainly after application of nitrogen fertilizers (Smith *et al.* 1990). Particulate N losses in runoff occur primarily in the form of soil organic matter components associated with the suspended sediment.

Issermann (1987), studied the vertical distribution of nitrate to a depth of 10 m in soils under intensive agricultural practices. His results showed significantly higher quantity of nitrate in the profile of these soils than in soils under forest.

Tillage is one of the factors that affects the potential leaching of nitrate. Goss (1990) found that the nitrate leaching losses during winter in Scotland were 25 % higher in plots with a tillage depth >15 cm, than in plots with a tillage depth of 7.5 cm or in direct drilled plots. In contrast, after sowing the losses of nitrate were 18 % higher in the direct drilling plots than in the tilled plots. Results obtained by Angle *et al.* (1989) show that nitrate concentrations in non-tilled soil under corn were lower than those under conventionally tilled soil.

Surface mulch can increase the infiltration rate, hence the potential leaching of nitrate can be increased. Thomas *et al.* (1973) showed that the use of a killed sod mulch increased the nitrate leaching from the top 90 cm of the profile. In contrast no leaching was observed in plots under conventional tillage.

2.2. IRRIGATION AND NITRATE LEACHING

In many parts of the world, the number of irrigated areas have increased very rapidly in the last two decades. At the same time, nitrogen fertilizer application rates have also increased. Both water management and nitrogen management are important in controlling nitrate leaching. Cassel *et al.* (1978) have shown that nitrate moves below the root zone because of heavy fertilizer nitrate applications as well as high irrigation rates that exceed the evapotranspiration requirements.

Ritter (1989) in a review on nitrate leaching under irrigation in the United States, described some of the major findings which are listed below:

- Water management practices that control both the amount and the timing of the water applied, reduce nitrate leaching ;
- Applying only enough nitrogen to meet realistic yield goals, will reduce nitrate leaching ;
- It is impossible to reduce nitrate leaching to zero in all regions on coarse-textured soils while maintaining adequate crop yields ;

- Nitrogen simulation models cannot be widely used to evaluate nitrogen management and water management practices, because of the lack of required field data to validate the models.

Letey *et al.* (1977) reported high nitrate losses in the drainage water in the Salinas Valley (California) due to the high application rates of nitrogen and water (nitrate losses of 336 Kg/ha yr under irrigated corn fertilized with 717 Kg N/ha). Ritter *et al.* (1991) showed that the largest part of the nitrate was leached during the fall and winter months in the irrigated area of the Coastal Plain region (USA). In contrast, very little nitrate was leached during the growing season, except for one year when 300 mm of rainfall occurred during August.

Andreu *et al.* (1991) have shown the importance of preferential paths in nitrate leaching during the growing period of cotton crop in the reclaimed and irrigated marsh soils in SW Spain. The total amount of nitrate in the drainage water represented 12 % of the applied nitrogen.

In the irrigated coastal area of the Valencia region (Spain), Ramos and Varela (1990) have reported an important reduction of nitrate leaching by reducing the N application rates by 50 % of the rates traditionally used by farmers and by using different times of application. In this experiment the water applied by irrigation was the same in plots with conventional N fertilization and in those receiving reduced amounts of N fertilizers.

Differences in nitrate leaching are strongly influenced by nonuniformity in the water applied by irrigation. Artiola (1991) has shown that variations in water application in a furrow-irrigated field were more important in determining the status of nitrate in the root zone than the N treatment.

Improving the irrigation scheduling can reduce nitrate leaching below the root zone. By irrigating on the basis of potential evapotranspiration Wendt *et al.* (1976) were able to maintain the nitrogen in the root zone for furrow, sprinkler and subirrigation systems. In contrast, when the water application on a fine loamy soil was greater than 2-2.5 times the potential evapotranspirations nitrate leaching increased. Results on water and nitrogen management in the Central Platte Valley of Nebraska reported by Ferguson *et al.* (1990) have demonstrated that irrigation scheduling and nitrogen accounting procedures can, in many cases, reduce both irrigation water and nitrogen fertilizer requirements. This practices can maintain crop yield while reducing the rate of groundwater contamination.

The most efficient method of applying water and nutrient seems to be by drip irrigation. Even in this case, irrigation management must be considered in order to reduce nitrate leaching. As shown by Troncoso *et al.* (1987) in the soil of an olive orchard under drip irrigation a significant concentration of NO_3-N was observed at a depth of 90 cm in the wetted zone. Similar results were found by Klein and Spieler (1987) under drip-irrigated apple trees.

The use of nitrogen simulation models seems to be an important tool to simulate nitrogen losses. Of the twenty models reviewed by Tanji (1982), several of them deal with irrigated agriculture. The scope of these models varies widely. A significant number of these models have been developed to simulate water and nitrogen fluxes in lysimeters or in field plots. One of the first models that incorporated N transport was ACTMO (Frere *et al.* 1975). Since then, several models have been developed. The GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model was developed by Leonard *et al.* (1987) for field-size areas to evaluate the effects of agricultural management systems on the movement of agricultural chemicals within and through the root zone, which model is also useful for simulating potential nitrate movement and leaching. The LEACHMN model (Leaching Estimates And Chemistry Model Nitrogen) is a process-based model of water and N-movement, transformations, plant uptake and N-reactions in the unsaturated zone (Wagenet and Hutson 1987). The NITWAT (Nitrogen and Water management) model (McIsaac *et al.* 1985, Watts and Hanks 1978) was developed for irrigated corn on sandy soils. The SWANIT model (Vereecken *et al.* 1990) is a mechanistic one-dimensional nitrogen leaching model. In this model the two component model equation was included for predicting nitrogen leaching out of the root zone of arable land (Vanclooster *et al.* 1992), that offers a flexible framework for describing the solute transport on a field scale.

Many of these models need to be validated by a significant amount of field data. The field data are not always available and for this reason the use of the models is severely limited.

2.3. RESULTS OF FIELD EXPERIMENTS ON NITRATE LEACHING

In this section details and results of two field studies are presented.

The first experiment deals with the losses of nitrate during the growing period of a cotton crop in the drained and irrigated marsh soils (marshes of the Guadalquivir river) in SW Spain (Andreu *et al.* 1991). Experiments were carried out on a 1 ha plot (40 x 250 m) situated in the area. The soil is of clayey texture (70 % clay). Swelling and shrinking processes occuring in these soils create a large system of interconnected vertical and horizontal cracks. The experimental plot is situated within an area of 12.5 ha, in which a drainage system has been installed, consisting of ceramic pieces (30 cm long) forming a pipe of 250 m long buried at 1 m depth and 10 m intervals, discharging into a collecting channel perpendicular to the drains. This drainage system controls the water table level.

During the growing period of cotton nitrogen fertilizer was applied on May 25, 1990 (200 Kg urea/ha, 46 % N) with the next irrigation being applied on June 17, 1990 (56 mm by furrow irrigation). The drainage outflow was continuously recorded, while at different time intervals samples of drainage water were taken to determine the nitrate concentration. Fig. 1 shows the drainage outflow rates. The drain discharge started half an hour after the beginning of irrigation. The maximum drainage outflow rate

(0.7 l/s) was reached when irrigation had stopped. Results of NO_3-concentration in the drainage water are also shown in Fig. 1. The highest NO_3 concentration in the drainage water was observed for the maximum flow rate. Due to the time interval between the fertilizer application and the irrigation a considerable amount of NO_3 was present in the top soil layer as a consequence of the urea transformation. Under such conditions irrigation water produced significant nitrate leaching and this nitrate reached the drain very rapidly through the preferential paths created by the crack network. The total nitrogen leached with the drainage water during this irrigation represented 12 % of the fertilizer applied.

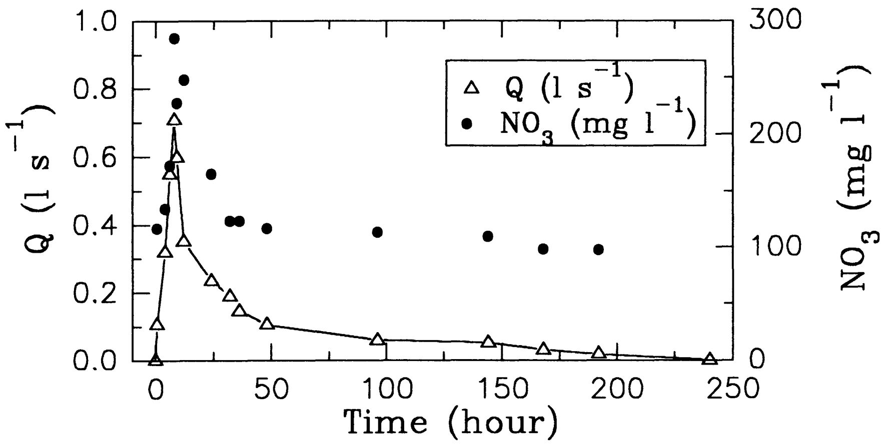

Figure 1. Drainage outflow rate and NO_3 concentration in drainage water after 56 mm of irrigation

The second experiment deals with nitrate leaching under an irrigated maize crop. The experiment was carried out on a sandy loam soil in the province of Seville (SW Spain). Two experimental plots (each 450 m^2) were used with a maize crop (plant density: 75,000 plants/ha) which was furrow irrigated. One of the plots (A) was fertilized with 510 Kg N/ha, which is one of the rates traditionally used by farmers in this area. The other plot (B) was fertilized at one third of this rate (170 Kg N/ha). Both fertilization rates were distributed in three applications (one deep fertilization applied before sowing, and two top dressing). The irrigation (amount and timing) was the same in both plots. Measurements of water flow and nitrate leaching below the root zone (100 cm depth) were carried out at several sites in each plot equipped with access tubes for the neutron probe, tensiometers at different depths and suction cups (at 30, 60 and 90 cm depth) for soil solution sampling. The estimation of water flow was carried out using Darcy's law and hydraulic conductivity-soil water content relationships determined in situ.

Nitrate leaching below a depth of 100 cm, over the period between two sampling dates was calculated by multiplying the NO_3 concentration in the soil solution by the amount of drainage during the period.

Results shown in Fig. 2 correspond to the period June 3, 1991 to August 25, 1992 (two crop seasons and the fall and winter in between). The most important finding is the considerable reduction of the nitrate leaching resulting from the use of a much lower rate of N-fertilization than that used by farmers. Nitrate leaching during the fall and winter periods was also greater in the plot with the highest N-fertilization rate (between days 200 and 350, Fig. 1) but these nitrate losses were smaller than expected because of rainfall during this period lower than average. In contrast, significant nitrate leaching was observed during the early growth period in the second crop season, due to rainfall (90 mm) when the soil still was wet from the previous irrigation. In general, during the crop season the nitrate leaching was low due to good irrigation management that reduced the water flow below the root zone. In both years, no significant differences in crop yield were observed between plots receiving the two fertilization rates.

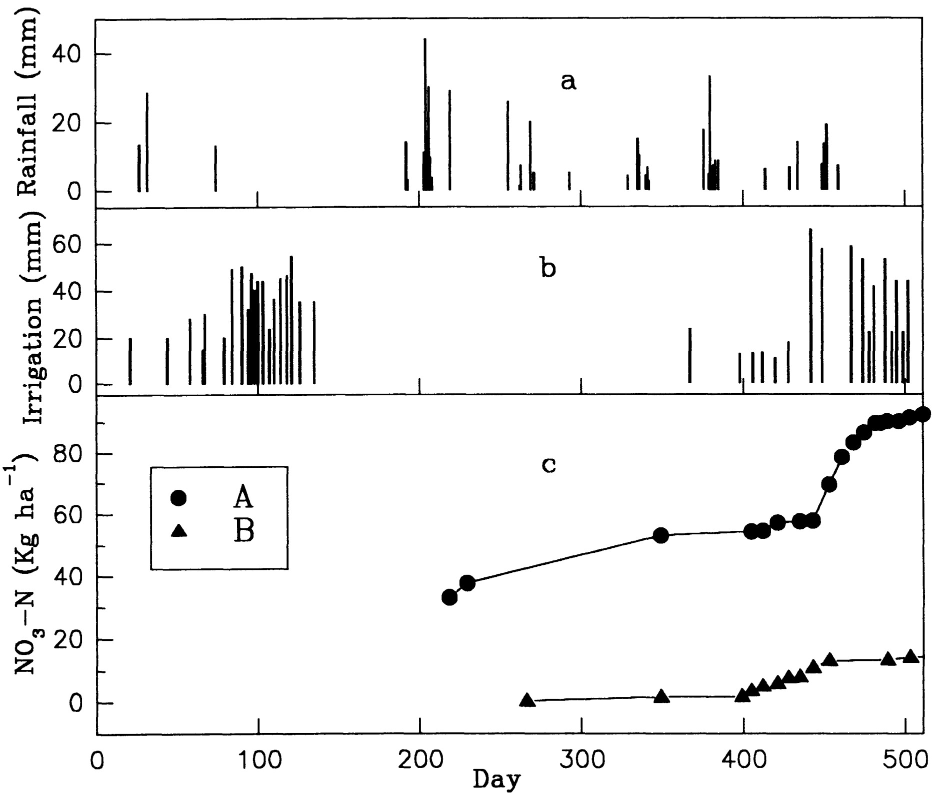

Figure 2. Rainfall (a), irrigation (b) and nitrate leaching (c) below the root zone in plots A and B (Day 0:20.3.91)

2.4. IDENTIFICATION OF GAPS IN KNOWLEDGE AND RESEARCH NEEDS

From the literature it can be seen that a considerable amount of papers dealing with nitrate movement in soils have been published. Most of the resarch was carried out considering soil sampling only. Very little research has been done to quantify nitrate leaching losses by measuring them. Only few studies reporting on measurements of the actual water flow in the soil and the concentration of the soil solution on a field scale, can be found in the literature, although this is the most appropriate way to quantify nitrate leaching losses below the root zone.

To reduce the risk of nitrate contamination a better knowledge of the integrated water and nitrogen fertilization management is needed. There are few papers dealing with integrated studies of the different form of nitrogen losses under agricultural practices on a field scale. In general, not more than two or three of the possible ways in which N may be lost (nitrate leaching, volatilization, etc.) are considered simultaneously. The lack of this integrated knowledge makes it difficult to adopt a strategy for the management of nitrogen fertilizers in order to improve its efficiency and to reduce the possible contamination by nitrate leaching.

As mentioned before, the nitrogen simulation models need to be validated by a significant amount of field data. The lack of part of this data is a common problem in many areas, and this is the factor which limits the use of the models.

Taking into account the aspects considered in the previous sections, to improve the sustainabilty of irrigated agriculture attention should be paid to the following research need.

Experimental work on integrated water and nitrate flow for different soils and different climatological conditions, should be conducted to establish a better combined management of irrigation and nitrogen fertilization practices.

2.5. CONTROL OF THE NITRATE CONTAMINATION

- To control and reduce the nitrate contamination of surface and groundwater sources more investigation is needed on integrated water use, nitrogen uptake by plant, nitrogen transformation in the soil and nitrogen losses by volatilization (directly from the soil and through the plant). These studies need the participation of experts from different disciplines.
- Continuous studies are required on irrigation techniques to improve the uniformity of water applied.
- There is a need to study new forms of applying nitrogen fertilizers (sources and timing) taking into account irrigation practices, in order to improve its homogeneous distribution into the soil and its availability for the plant.
- Studies of winter cover crops should be conducted to reduce nitrate leaching during the non-growing season.

- Detailed experiments on water and nitrogen applications on irrigated crops are necessary to generate field data for the validation of water and nitrogen simulation models.

3. Conclusions

The results found in the literature and our experimental results presented in this paper show that nitrate leaching is dependent on many factors, such as soil characteristics, climatic conditions, and water and nitrogen fertilization management. More experimental research is needed to improve water and nitrogen fertilization management, in order to reduce and control nitrate leaching losses under irrigated agriculture while maintaining acceptable crop yields. Field data are needed to validate water and nitrogen simulation models for application in different areas.

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WASTE - WATER REUSE

SPYROS KYRITSIS
Professor, Agricultural Engineering Department.
Agricultural University of Athens
Iera odos str. 75, Athens, Greece

1. Introduction

In the last decade humanity has been facing two crucial problems concerning fresh water. The first is the lack of water because of the always growing water demand, which has tripled around the world over the last 40 years, the trend expected to be higher in the near future. The second is the environmental concern to stop waste water discharge into surface water prior to the removal of major pollutants.

Water demand. Water as a natural resource is not equally distributed neither on time nor among the different regions of the earth. Thus, certain areas or regions face severe water supply problems. Inadequate water collection and distribution systems are another parameter of water shortage in several places.

The new trends in those well known water problems are :

1. the quality degradation of the natural renewable water sources (underground water, surface water and in some cases rains) because of the intensification of the production systems, especially in developed countries ;
2. the large concentration of population in large cities and their dependency for higher water consumption ;
3. the growth of world population and the need for more food.

According to the U.S. Water Conservation Laboratory, not long ago, 90% of all the water consumed in the world was used for irrigation, by 1960 it was about 80%, currently it is about 70%, irrigating approximately 17% of the world's total arable land, and in the year 2000 it is expected to be about 60%. The conclusion is that more food will have to be produced with less water and that water in the near future will become more precious and vital for the world population.

Water Pollution. If one follows the evolution of waste water disposal practices over the last 40 years in developed countries, it may be realised that the major concern was to remove pathogens from surface water used for drinking. Consequently, simple methods of treatment like lagoons and land disposal systems were developed. Then, the

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sewage treatment came, followed by discharge into rivers, lakes and the sea, practices that still are applied in the majority of the countries.

At the present, environmental concerns in several developed countries impose the removal of nitrogen, phosphorus, heavy metals and toxic organic compounds before discharging waste water into surface water. This is achieved by means of expensive treatment procedures.

It is obvious that integrated management of wastewater towards zero discharge, including reuse, can give solution to short-term needs as well as increase long-term water supply reliability by simultaneously reducing fresh water use.

Reuse and recycling are the ultimate forms of resource management and water is no exception.

Judging from the progress so far, during the relatively long time applications of the reuse technology (California, Israel and elsewhere), it may be claimed that we are at the beginning of a technology that is expected to be generalized all around the world in the near future as the unique, obvious solution to the above mentioned growing water problems in the world.

2. Technology

As it is expected the use of wastewater will be generalized in the near future. However, the risk of an uncontrolled reuse for the public health is very high.

The majority of wastewaters are municipal effluents which are normally loaded with: a) pathogens that can spread acute infection deseases b) nutrients that can eutrophy surface water, c) toxic chemicals and with heavy metals that can have severe effects on health.

Municipal wastewaters are normally collected and treated near the cities and, for economic reasons, the first uses are in the cities and around them. So, irrigation of parks and vegetation in the borders of streets, playgrounds, sport fields constitute the first priority.

Agricultural irrigation in fields around the cities, normally for vegetables, is the largest demand of that kind of water, especially because other cleaner sources of fresh water have been captured for other priority uses consisting mainly of domestic purposes (drinking water).

Other wastewater uses besides irrigation are aquaculture, street washing, industrial (like cooling of power plants, washing in the textile industry) and many others.

2.1. EFFLUENT QUALITY

The quality of effluents is related with two targets, namely human health protection and optimum crop production.

2.1.1. *Health Risks*

Untreated wastewater contains pathogenic organisms (Table 1) through which infections can be transmitted to plants, animals and humans through land application. However, up to now only few epidemiological impacts have been reported from food grown in places irrigated with municipal wastewater (Pescod 1993). Specialists have found out that favorable conditions for survival of some enteric pathogens on crops and in the soil may prevail (Feachem *et al.* 1983).

TABLE 1. Possible levels of pathogens in wastewater, source : Feachem *et al.* (1983)

TYPE OF PATHOGEN		Possible concentration per litre in municipal wastewater [1]
Viruses	Enteroviruses[2]	5000
Bacteria	Pathogenic E. coli[3]	?
	Salmonella spp	7000
	Shigella spp	7000
	Vibrio cholerae	1000
Protozoa	Entamoeba histolytica	4500
Helminths	Ascaris Lumbricoides	600
	Hookworms[4]	32
	Schistosoma mansoni	1
	Taenia saginata	10
	Trichuris troihiura	120

? Uncertain
1 Based on 100 lpcd of municipal sewage and 90% inactivation of excreted pathogens
2 Includes polio-, echo- and coxsachieviruses
3 Includes enterotoxigenic, enteroinvasive and enteropathogenic E. coli
4 Anglostoma duodenale and Necator americanus

Other reports from specialists around the world, reviewed by Pescod (1993), claim that helminthic and cholera infections can occur from untreated wastewater irrigation of vegetables eaten raw. Infections (Taenia Saginata) can also be transmitted to animals and to people consuming the meat of cattle grazing on fields irrigated by wastewater or the crops grown in them.

Direct contact of non treated wastewater with hands has always been a potential risk of infections, eventhough no concrete confirmation up to now has been reported. Since there is always a risk for the consumer or for the farmer or other people in contact with wastewater (sport places, etc), considerable efforts have been made to establish conditions and regulations that would allow safety use of effluents.

The survival of all types of pathogens is a matter of the technology used for treatment, but also a matter of exposed time to wastewater in different conditions (see Table 2).

TABLE 2. Survival of excreted pathogens (at 20-30°C), source : Feachem *et al.* (1983)

TYPE OF PATHOGEN	Survival times in days			
	In faces nightsoil and sludge	In fresh water and sewage	In the soil	On crops
Viruses				
Enteroviruses	<100 (<20)	<120 (<50)	<100 (<20)	<60 (<15)*
Bacteria				
Faecal Coliforms	<90 (<50)	<60 (<30)	<70 (<20)	<30 (<15)
Salmonella spp.	<60 (<30)	<60 (<30)	<70 (<20)	<30 (<15)
Shigella spp	<30 (<10)	<30 (<10)	-	<10 (<5)
Vibrio cholerae	<30 (<5)	<30 (<10)	<20 (<10)	<5 (<2)
Protozoa	<30 (<15)	<30 (<15)	<20 (<10)	<10 (<2)
entamoeba				
histolytica cysts	<30 (<15)	<30 (<15)	<20 (<10)	<10 (<2)
Helminths	Many	Many	Many	<60 (<30)
Ascaris				
Lunbricoides eggs	Months	Months	Months	

* Figures in brackets show the usual survival time

For the time being, there is no uniform set of standards existing, but several international, national and state wastewater regulations have been available (State of California, 1978; World Health Organisation, 1989 ; U.S. EPA, 1992). These regulations have succeeded to be considered as regulations in the planning and implementation as wastewater reclamation and reuse projects in many places in the world (Asano *et al.* 1992).

Especially for the wastewater use in agriculture, a WHO Scientific Group on Health Aspects of Use of Treated Wastewater for Agriculture and Aquaculture recommended microbiological quality guidelines shown in Table 3. These guidelines are intended as design goals for wastewater treatment systems, rather than standards requiring routine testing of effluents (Pescod, 1992). A summary of the California Wastewater Reclamation Criteria are given in Table 4. Concerning the trace elements contained in effluents, Pescod (1992) gives the tolerated levels for crop production in Table 5.

2.1.2. *Water Quality for Crop Production*

Main parameters of water quality for optimum crop production are : the total dissolved solids (T.S.S.), sodium absorption ratio, nitrogen concentration, chloride concentration, other toxic trace elements and heavy metals.

To achieve the best possible crop production there are different quality classes for the irrigation water to be applied according to the potential advantages as well as problems associated with its use. We should have in mind that water quality classifications are only indicative and in application quality depends to the local conditions (climatic, physical and chemical properties of the soil, crop tolerance to the salt and management practices). Ayers and Westcot (1985) gave the guidelines for water quality interpretation for irrigation shown in Table 6.

TABLE 3. Recommended microbiological quality guidelines for wastewater use in agriculture (WHO, 1989)

Category	Re-use condition	Exposed group	Intestinal nematodes[b] (arithmetic mead no eggs/l[c])	Faecal coliforms (geometric mean no /100 ml[c])	Wastewater treatment expected to achieve required biological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[d]	Workers consumers public	≤1	≤1000[d]	Series of stabilization ponds designed to achieve the microbiological quality indicated or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	Workers	≤1	No standard recommended	Retention in stabilization ponds for 8-10 days or equivalent helminth and faecal coliform removal
C	Localized irrigation of crops in Category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pre-treatment as required by the irrigation technology but not less than primary sedimentation

a. In specific cases, local epidemiological socio-cultural and environmental factors have to be taken into account and the guidelines modified accordingly
b. Ascaris and Trichuris species and hookworms
c. During the irrigation period
d. A more stringent guideline (≤200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contract
e. In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Spinkler irrigation should not be used.

TABLE 4. Summary of the California Wastewater Reclamation Criteria (State of California, 1978)

	Description of minimum wastewater characteristics			
Reclaimed wastewater applications	Primary effluent with less than 0.5 mL/L/hr of settleable solids	Secondary and disinfected	Secondary coagulated, filtered and disinfected (1)	Median total coliform /100 mL
Crop Irrigation	X			No Require.
Fodder crops	X			No Require.
Fiber	X			No Require.
Seed crops				
Produce eaten raw, surface irrigated		X		2.2
Produce eaten raw, spray irrigated			X	2.2(2)
Processed produce, spray irrigated		X		23(3)
Landscape Irrigation:				
golf courses, freeways				
parks,			X	23
playgrounds			X	2.2
Recreational Impoundments:				
No public contact			X	23
Boating & fishing only			X	2.2
Body contact (bathing)			X	2.2

(1) Effluent does not exceed an average of 2 turgidity units (NTU) and does not exceed 5 NTU more than 5 percent of the time during any 24-hr period.
(2) The median number of total coliform organisms in the effluent does not exceed 2.2/100 and the number of total coliform organisms does not exceed 23/100 mL in more than one sample within any 30-day period.
(3) The median number of total coliform organisms in the effluent does not exceed 23/100 mL in 7 consecutive days and does not exdeed 240/100 mL in any two consecutive samples.

TABLE 5 .Threshold levels of trace elements for crop production, source : Pescod (1992)

Element		Recommended maximum concentration (mg/l)	Remarks
Al	(aluminium)	5.0	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
As	(arsenic)	0.10	Toxicity to plants varies widely, ranging from 12 mg/l for Sudan grass to less than 0.05 mg/l for rice.
Be	(beryllium)	0.10	Toxicity to plants varies widely, ranging from 5 mg/l for kale to 0.5 mg/l for bush beans.
Cd	(cadmium)	0.01	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/l in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Co	(cobalt)	0.05	Toxic to tomato plants at 0.1 mg/l in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Cr	(chromium)	0.10	Not generally recognized as an essential growth element. Conservative limits recommended due to lack of knowledge on its toxicity to plants.
Cu	(copper)	0.20	Toxic to a number of plants at 0.1 to 1.0 mg/l in nutrient solutions.
F	(fluoride)	1.0	Inactivated by neutral and alkaline soils.
Fe	(iron)	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment and buildings.
Li	(lithium)	2.5	Tolerated by most crops up to 5 mg/l; mobile in soil. Toxic to citrus at low concentrations (<0.075 mg/l). Acts similarly to boron.
Mn	(manganese)	0.20	Toxic to a number of crops at a few-tenths to a few mg/l, but usually only in acid soils.
Mo	(molybdenum)	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Ni	(nickel)	0.20	Toxic to a number of plants at 0.5 mg/l to 1.0 mg/l; reduced toxicity at neutral or alkaline pH.
Pd	(lead)	5.0	Can inhibit plant cell growth at very high concentrations.
Se	(selenium)	0.02	Toxic to plants at concentrations as low as 0.025 mg/l and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. As essential element to animals but in very low concentrations.
Sn Ti W	(tin) (titanium) (tungsten)	-	Effectively excluded by plants; specific tolerance unknown.
C	(vanadium)	0.10	Toxic to many plants at relatively low concentrations.
Zn	(zinc)	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine textured or organic soils.

1 The maximum concentration is based on a water application rate which is consistent with good irrigation practices (10 000 m^3 per hectare per year). If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjustment should be made for application rates less than 10 000 m^3 per hectare per year. The values given are for water used on a continuous basis at one site.

TABLE 6. Guidelines for interpretation of water quality for irrigation, source : Ayers and Westcot (1985)

Potential irrigation problem	Units	Degree of restriction on use		
		None	Slight to moderate	Severe
Salinity				
Ec_w[1]	dS/m	<0.7	0.7 - 3.0	>3.0
or TDS	mg/l	<450	450 - 2000	>2000
Infiltration				
SAR[2]=0-3 and Ec_w		>0.7	0.7-0.2	<0.2
3-6		>1.2	1.2-0.3	<0.3
6-12		>1.9	1.9-0.5	<0.5
12-20		>2.9	2.9-1.3	<1.3
20-40		>5.0	5.0-2.9	<2.9
Specific ion toxicity				
Sodium (Na)				
Surface irrigation	SAR	<3	3-9	>9
Sprinkler irrigation	me/l	<3	>3	
Chloride (Cl)				
Surface irrigation	me/l	<4	4-10	>10
Sprinkler irrigation	m^3/l	<3	>3	
Boron (B)	mg/l	<0.7	0.7-3.0	>3.0
Miscellaneous effects				
Nitrogen (NO_3-N)[3]	mg/l	<5	5-30	>30
Bicarbonate (HCO_3)	me/l	<1.5	1.5-8.5	>8.5
pH			Normal range 6.5-8.4	

1. EC_W means electrical conductivity in deciSiemens per metre at 25°C
2. SAR means sodium adsorption ratio
3. NO_3-N means nitrate nitrogen reported in terms of elemental nitrogen

2.2. WASTEWATER TREATMENT

In principle, all kinds of wastewater can be treated with the technology available today in order to meet the quality requirements for any purpose. Due, however, to treatment costs, wastewater is most commonly used for non-drinking purposes, such as : irrigation, industrial uses, urban uses and recreation places.

In any case the principal objective of wastewater treatment is to allow effluents to be disposed without any danger to human health or unacceptable damage to the natural environment. The State of California requires that reclaimed water used for landscape irrigation, of areas with unlimited public access, must be "adequately oxidized, filtered and disinfected prior to use, with medium total coliform count of no more than 2.2/100 mL". One adequate technology to achieve such requirements (Asano, 1993) includes biological secondary treatment and tertiary treatment with filtration followed by disinfection. This regulation requires expensive wastewater treatment but some applications do not require such a high degree of treatment like groundwater recharge, cooling towers in industry and some housing applications (toilet flushing etc).

Concerning irrigation with wastewater, the technology to be used in order to arrive to an acceptable degree of treatment depends on the charge of pollutants present in the raw wastewater.

For raw municipal wastewater, without any contribution of wastewater from industrial activities, the required quality of effluent, so the degree of treatment, will depend on the local conditions, but including some crop restrictions and the selection of the irrigation systems. The degree of wastewater treatment can be reduced and irrigation with wastewater can normaly be considered both a form of disposal and of water utilisation since indeed it is an effective form of wastewater disposal (Pescod 1992).

Most appropriate wastewater treatment should respond to the following conditions :

- The effluents should meet recommended microbiological and chemical quality guidelines ;
- Low cost technology and management ;
- Simplicity in operation and maintenance, especially for developing countries.

Pathogen removal, however, for use of effluents in agriculture, is of primary concern and processes should be selected and designed accordingly (Hillman, 1988).

General terms used to describe different degrees of treatment in order of increasing treatment level are : preliminary, primary, secondary, tertiary or advanced wastewater treatment, disinfection. A generalized wastewater treatment diagram given by Asano *et al.* (1985) is shown in Figure 1.

Preliminary treatment includes course screening and grit removal.

Primary treatment is the removal of settleable organic and inorganic solids by sedimentation, and the removal of materials that will float by skimming. In many developed countries, primary treatment is the minimum level of preapplication treatment required for wastewater irrigation (Pescod 1992) and it may be considered sufficient treatment if the effluents are used to irrigate crops that are not consumed by humans, or to irrigate orchards, vineyards, and some processed food crops.

Secondary treatment is the further treatment of the effluent to remove the residual organics and suspended solids. In most cases, aerobic biological treatment processes are used.

Tertiary or advanced treatment is employed when specific wastewater constituents, which cannot be removed by secondary treatment, must be removed. it can be necessary to remove nitrogen, phosphorus, additional suspended solids, refractory organics, heavy metals and dissolved solids. Advanced treatment is sometimes combined with primary or secondary treatment.

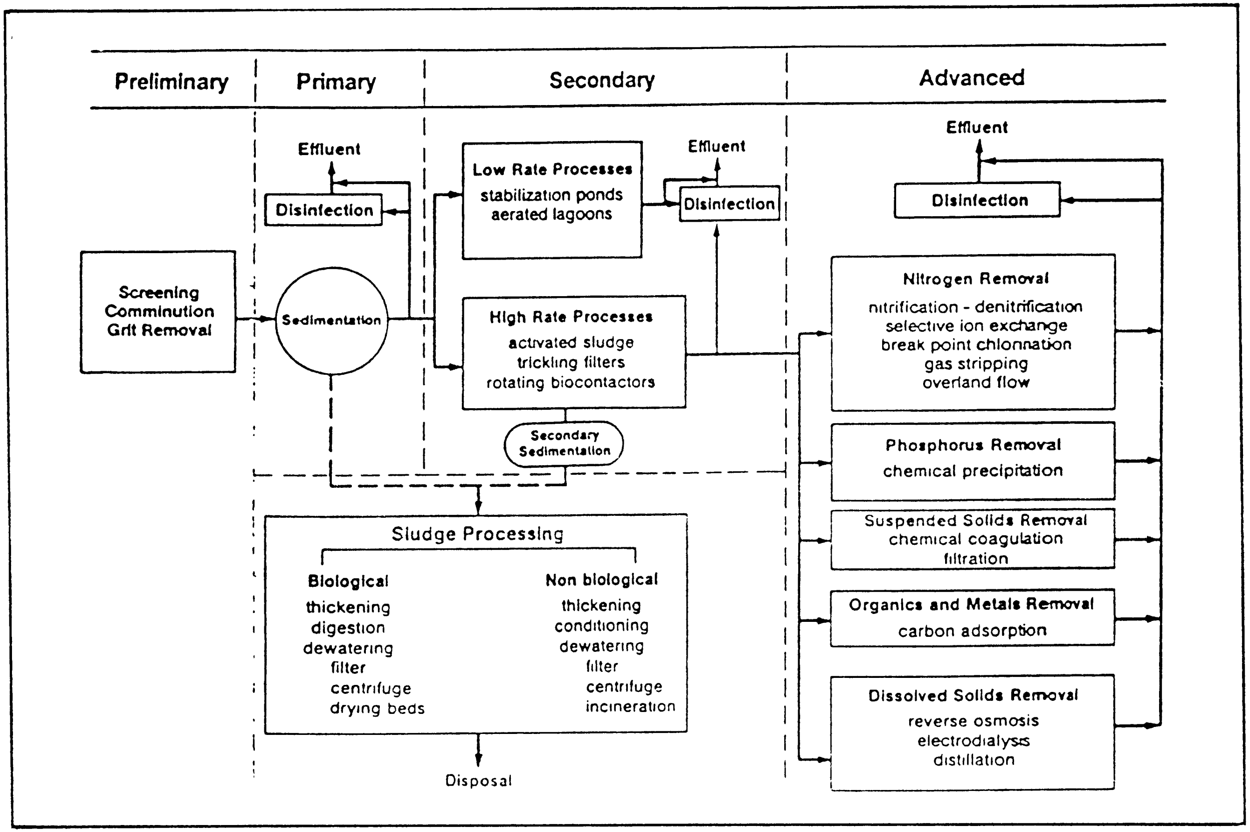

Figure 1. Generalized flow diagram for municipal wastewater treatment (Asano et al., 1985)

2.3. LOW - RATE BIOLOGICAL TREATMENT SYSTEMS

Efficient solutions for the removal of organic and suspended solid loads from wastewater could have a prohibiting cost for the reuse of effluents. The international organization FAO, oriented mostly for the water shortage in developing countries and for countries where there is no experience in operating wastewater treatment plants, tries to give simple and less expensive solutions. Such solutions are given in FAO paper 47 (Pescod 1992). A simple system there is the lagooning for the wastewater stabilization which allows to remove pathogens effectively if it is properly designed and operated. The same system is also recommended in the WHO Technical Report No 778 (1989) for the use of effluents in irrigation. Large application of stabilization ponds can be seen in the Al Samra Pond in Jordan (Al-Salem 1987).

Another low cost treatment system, which is simple in application respecting several conditions and can improve the quality of the sewage effluents for non potable uses, is the Soil-Aquifer Treatment (SAT) or Geopurification system. This system operates with infiltration basins and is reported by many specialists as a simple and low technology one. However it can not be generalized for every effluent use. Toxic trace elements and heavymetals should be eliminated from the industrial effluents. The remaining effluents after primary or secondary treatment can be used for groundwater recharge through infiltration basins. The quality of the water improves significantly moving down through the unsaturated zone to the ground water and then laterally through the aquifer to the collection system (pumping wells or other). Under normal conditions, from a basin of 1000 m^2 it is expected to obtain infiltrations of 50.000-100.000 m^3/day.

3. Environmental Aspects

The spread of untreated wastewater on soils can easily pollute surface and ground water and soils.

Nitrates is the well known problem arising from this application. Other pollutants like phosphorus, potassium, other organic matter, and other toxic trace elements already mentioned, exist in a non treated effluent. The groundwater contamination occurs through the movement of pollutants down to the unsaturated layer of soil. Of course there are conditions where percolation is very reduced, but we should always suspect that there could exist areas with highly porous soil in the unsaturated zone or fissured zones.

Another long-term problem of wastewater use for irrigation is the progressive accumulation on the soil of salts or toxic materials and heavy metals after many years of irrigation. Besides damages to the plantations, the accumulated toxic material could reach such concentration levels that the risk to be leached deeper, into the groundwater, is obvious with the result to make groundwater unusable. But even remaining in the soil, some of these toxic elements can be absorbed by the irrigated crop and thus affect yields.

Salinity can reach high levels in the soil and finally turn the land unusable for agriculture. This is a problem of high importance.

As it was pointed out, properly treated wastewater effluents are a considerable water resource that in some places is the only one available. There are many benefits to the environment from the proper use of this water and among them one can mention the substitution of groundwater for irrigation in several places, where the over-use of groundwater can create salinity in coastal lands (common problem in the greek islands and coastal places) by salt water intrusion.

Proper management of raw or treated wastewater can offer to the irrigated crop the majority of the nutrients N and P needed and so reduce the need for commercial fertilizers. Also, the organic matter added to the soil can form a good conditioner over time, especially in arid places where soils are poor in organic matter.

Irrigation of poor forest in arid regions can create conditions that prevent erosion and forest fires, helps wild life and create a pleasant environment.

4. Research Needed

Because of the environmental concern and because treated wastewater effluents are a precious water resource, mainly for irrigation, the practice of water reuse is expected to become generalized in the near future.

For the irrigation we should adopt safety technologies (applying used water), Sprinkler irrigation may not be a good solution because there is a risk (even very small) associated with pathogens present in the wind-dispersed droplets. New irrigation systems (subsurface trickle systems) must be developed to be capable of delivering low quality wastewater. Restrictions on irrigation techniques should be applied.

Rules should be studied and imposed especially for the irrigation of crops eaten raw and for the commercialization of these products, coming in a market from a variety of long or close distance production places. If this control is easy for pathogens, it is not the same for heavy metals and other toxic.

Grace of the experience gained in several places (California and elsewhere) the way to make effluents less risky or not risky at all, but with a cost that the developing countries can not support, is known to us. So, there is a need for research for less costly alternative treatment methods, more safety and for an efficient control of the products irrigated by the effluents.

More research is also needed in order to avoid the risk of damage underground aquifers by using SAT. Special efforts should be made for efficient control before these low cost alternative could be commonly utilized since the damage resulting from unappropriate use could be non reparable.

Health risk and environmental concerns from the use of wastewater require an integrated approach based not only on a better know how of the appropriate technologies to be applied but also on efficient monitoring and control of application.

5. Conclusions

Water reuse is one solution to the actual pollution and water shortage problems. Several technologies are available but the most efficient of them are too expensive for developing countries. The less expensive alternatives should be further investigated to make them less risky. Facing the urgent need for the wastewater use, a combination of measures should be applied for : the appropriate treatment technology adoption, the irrigation method selection, the crop selection, the imposing of limits and efficient monitoring and control of wastewater use as well as of the products from the irrigated lands.

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PART VI

IRRIGATION SCHEME MANAGEMENT

SUSTAINABILITY CONCERNS IN THE OPERATION AND MAINTENANCE OF IRRIGATION SYSTEMS

J.A. SAGARDOY
Senior Technical Officer (Water Management)
Water Resources, Development and Management Service
FAO (Food and Agriculture Organization of the United Nations)
Viale delle Terme di Caracalla
00100 Rome, Italy

1. Future Food Production and Irrigation Development

At present, some 35% of the total world agricultural production comes from irrigated land. As reported in the FAO Study "Agriculture towards 2010", future growth of population will require that agricultural production continue to grow at the rate of 2% annually. This means that irrigated agriculture must continue to grow at the rate of at least 0.8% per year.

The possibilities of expanding the irrigated area in many countries are finite consequently a substantial part of the arable land is already under irrigation. In several countries the percentage of arable land already under irrigation is about to 60% and in some countries located in arid regions it reaches a maximum of 90%, as in the case of Egypt. Development of new areas has become in many cases too expensive to be acceptable for national or international financing. Although new developments will continue to play an important role, much of the increase required in irrigation will have to come from the increase in productivity from existing irrigated lands. To realize this potential it is essential that future investments go in the direction of overcoming the constraints that threaten the sustainability of existing irrigation systems in many parts of the world.

2. Sustainability and Irrigation Development

The first questions that may be asked are: to what extent is irrigation sustainable and under which conditions?

Irrigation has been under heavy attack by many environmentalists on the basis that it transforms a part of the territory and produces changes that in the long run may not prove sustainable. While there is little doubt that irrigation development involves profound changes in the physical and sociological environment, these changes have

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 431–439.

proved to be sustainable over time. The living testimony of irrigation systems that have been in operation for centuries and continue to operate include those in the Nile Delta of Egypt, the Valencia and Murcia system in Spain, large parts of the Indus Basin, China, North Africa and in many other arid and semi-arid areas in the world, provide enough evidence that irrigation systems *when properly managed* are more sustainable than many of the industrial undertakings from more recent times.

Admittedly there are enough "white elephant" irrigation projects to illustrate that irrigation systems may have considerable sustainability problems if not properly planned or managed. In fact, the problem is not the durability of the system over time but the economic viability. In other words, many of the white elephants continue to exist because governments continue to subsidize a large part of their costs. Their existence will therefore not be threatened as long as governments continue to pump money into them. As soon as those subsidies are eliminated, dramatic changes in sustainability will occur.

In conclusion irrigation when properly managed is a highly sustainable undertaking if certain basic conditions are met. If the reasons and causes of failures of irrigation are analyzed, common denominators can be found in all of them, which can be summarized as follows:

- *Diminishing water resources*: Competition for water has reduced the availability for each individual user who is often forced to reduce consumption. Furthermore, deforestation and soil erosion have greatly reduced the flows of many rivers and aquifers. The competition for water is becoming particularly intense in arid environments and particularly due to demands from non irrigator needs (domestic and industrial) found to be a more profitable undertaking than producing crops under irrigation.
- *Weak financial viability*: An irrigation system where O&M expenditures do not match the fees recovered from farmers, can only subsist as long as somebody, governments in most cases, pays the balance. With a nearly universal outcry for reductions in public expenditures, prospects for survival of many of those systems are grim.
- *Decreasing productive areas*: Some irrigation systems, in particular in arid and semi-arid areas, after initial success see their productive areas decrease due to soil salinization and waterlogging problems. Two main factors contribute to this undesirable situation: the excessive applications of water by farmers and the water losses from unlined canals. It should be stressed that this is a reversible process; installation of a suitable drainage system can fully overcome waterlogging problems but also a more rational water distribution and more efficient water use may reduce the magnitude of this problem. These problems appear mainly under arid conditions and in irrigation systems in flood plains subject to rising groundwater levels.
- *Reduced land productivity*: Several factors can decrease the productivity of irrigated land. They include soil salinization, soil erosion as a result of poorly designed or managed methods of irrigation, and the leaching of nutrients due to

excess irrigation water application. Obviously, low productivity land will reduce the income of farmers and make farm operations less profitable. To recover or improve productivity, expensive investments in land levelling, in fertilization and other agricultural practices are required which may sharply reduce profits.

- Land fragmentation: Many of the irrigation systems, particularly in Asia, are located in heavily populated areas where farm sizes are very small. Population growth associated with an inheritance system, where land is divided among heirs, has led in many cases to uneconomic farm sizes sufficient to produce food for the family. Subsistence irrigation farming does not generate economic welfare and can make irrigation systems financially weak and unsustainable in the long run.
- *Low prices for agricultural products*: Many irrigation systems were planned and constructed on the assumption of higher value agricultural crops, profitable markets and competitive prices for example. The Gezira Irrigation System in Sudan was designed and built in the mid 1920s when high prices were paid for cotton. In the early 1950s and 1960s many schemes were designed for sugar cane when the price of sugar was very high. Presently due to the prevailing low prices for most agricultural commodities and the restructuring of these systems to accommodate more flexible cropping systems are often problematic.

The equilibrium of an irrigation system is delicate. There are many threats that can disturb the balance and affect the viability and sustainability of the system. Adequate financial and technical measures are needed to make irrigation a durable investment.

3. Sustainability Concerns in Operation and Maintenance

The constraints that most frequently affect the sustainability of irrigation systems are those associated with the operation and maintenance activities of the system.

3.1. IMPROVED METHODS FOR WATER DISTRIBUTION

Traditionally, the distribution of irrigation water is arranged according to the *area to be irrigated*. The possibility of regulating the amount of water with the requirement of the *crops irrigated* has only been possible in recent times when systems where designed with sufficient flexibility in the network to suit varying demand from different crops. But as long as water continues to be distributed in traditional systems, by rigid methods of rotation, important water losses will continue to occur at the farm level because of the difficulty in providing irrigation water to meet crop water requirements. The serious consequences of excessive irrigation in waterlogging and land salinization have already been mentioned. Modern techniques supported by computer methods and models offer at present considerable potential for improving water delivery systems.

3.2. IMPROVING THE FINANCIAL VIABILITY OF OPERATION AND MAINTENANCE ACTIVITIES

Table 1 summarizes the results of the actual fees paid for O&M carried out in 13 countries. This survey clearly illustrates that in many public irrigation systems the O&M costs are heavily subsidized. Before discussing the possible effects of eliminating those subsidies, the various interrelationships affecting the economic viability of O&M activities will be looked into.

Many irrigation systems are affected by a kind of vicious circle (Figure 1).

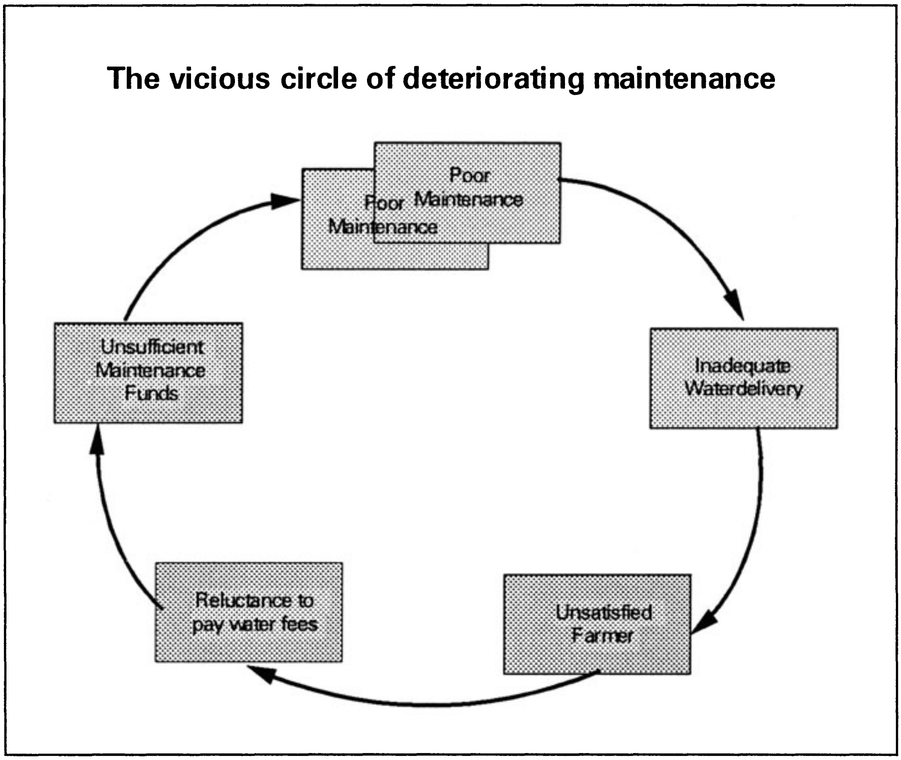

Figure 1. The vicious circle of deteriorating maintenance

In reality, the circle is a spiral where every year the situation deteriorates further until the system totally collapses or a major investment in rehabilitation is required to sustain productivity. It is difficult to identify where the declining situation starts and what measures can be taken to prevent it. A crucial point is the farmer, unsatisfied with the services received, feels a moral justification not to pay the imposed water fees. This feeling of receiving a poor service is not equally perceived by all farmers. Even under situations of water scarcity those located at the heads of canals may still receive enough water to satisfy their needs. Further down the canal, water supply will rapidly decrease resulting in the disappointment of many farmers. In such situations the collection of water fees is made accordingly. The greater the number of farmers who consider their water delivery unsatisfactory, the smaller the total amount of fees collected.

TABLE 1. Recovery of Actual Operation and Maintenance Costs*

COUNTRY		Amount actually collected US$/ha	Average estimated cost for O&M US$/ha	Percent of O&M cost recovery
CYPRUS:	Operational Projects	133	420	32
	Priori projects	399	560	71
	South Conveyor Project	n.a	840	n.a
JAMAICA:	High fees	56	333	17
	Low fees	13	49	26
MEXICO:	High fees	55	70	78
	Low fees	30	40	75
NIGERIA:	Surface Systems	3.6	49.0	22
	Pump Irrig. Systems	24	137.5	18
CHINA:	Cereal Crops			
	High fees	105	105	100
	Low fees	15	15	100
	Cash Crops			
	High fees	90	90	100
	Low fees	45	45	100
PHILIPPINES:	National systems	13	15	87
	Communal systems	3	3	100
	Pump systems	52	60	87
PAKISTAN:	Surface Systems			
	Punjab Province	5.1	7.6	67
	Sind Province	4.8	12.6	38
	Pump Irrig. Systems			
	Punjab Province	10.2	33.6	30
	Sind Province	8.5	38.7	22
TUNISIA:	Public Oasis	105	210	50
JORDAN:	Jordan Valley Auth.	6.3	63	10
KOREA:	High fees	196	196	100
	Low fees	130	130	100
NEPAL:	Sunsari Project	9.17	27.52	33
	Kamala Project	4.81	9.17	52
	Kankay Project	9.17	13.76	67
	Narayani Project	9.99	11.67	86
THAILAND:	High fees	15	15	100
	Low fees	8	8	100
ZIMBABWE:	Assured water supply	85.5	95.0	95
	Uncertain water supply	42.5	42.5	100

* Data collected from several reports (period 1988-1990)

People unfamiliar with the farming reality in the developing world often wonder why it is not possible to oblige all farmers to pay their dues enforcing the principle that those who do not pay fees will not receive water. There are many reasons why a rigid application of this rule in the field is often not possible and every case has to be analyzed on their own merits. Perhaps the most important reason is that the persons responsible for enforcing such rules are individuals whose motivation and salaries are too small to risk their physical integrity and in certain cases their lives. Furthermore, with the small salaries that they receive, it may be difficult to resist bribes from wealthy farmers.

The farmers dissatisfaction may not only be caused by the fact that they receive insufficient water but also because they consider that irrigation fees are disproportionably high for the services rendered. The problem has two different sides: one is the fact that although fees may reflect real costs, it may be possible to obtain similar levels of maintenance with cheaper methods. For instance, with a greater participation of the beneficiaries in the activities. However, even if the fees imposed are fully justified, public administrations often fail to establish the necessary communication channels with the farmers to explain convincingly how money was spent.

In many cases, though, the services provided are inefficient and the imposed fees are difficult to justify. Here farmers have a strong point for not paying.

In some countries the situation is even more complex as the fees paid by the farmers go directly to the National Treasury Office. The directors of the irrigation systems receive in turn their budget allocation from the National Treasury, through the corresponding ministry, and often there is no relation between the budget received and the funds collected. The situation is aggravated through bureaucratic procedures and other reasons. Budget allocations often arrive late and must be spent in a short time.

A distinct separation should be made between those who can pay and do not pay the fees, and those that genuinely cannot pay. There may be a considerable number of farmers who are unable to pay. This may due to the small size of their farms, loss of productivity (by salinization or other causes), credit difficulties, falling market prices, and other reasons. They are in such financial difficulties that payment of water dues has to be exempted, reduced or postponed. When examining the financial viability of imposing a certain O&M rate the number of cases affected by those situations mentioned should be properly accounted for.

4. Government Options

Given the fact that many irrigation systems are affected by the vicious circle of poor maintenance, the question is what can be done to give sustainability to a situation that is essentially unsustainable in the long run. Four approaches can be listed, which are available to governments to address the situation, of which only one is really sustainable. The other options are medium-term solutions bound to fail in the long run.

4.1. SUBSIDY APPROACH

Radical changes are always difficult to implement. For many governments it is therefore easier to continue the *status quo* and continue to subsidize part (or the total) of the O&M costs. By doing so, thousands of farmers may be kept quiet and even happy to a certain degree as long as someone else is subsidising their undertakings.

To illustrate the financial implications of such an approach, a hypothetical country with 2.0 million hectares of irrigated lands mostly under public management may be considered. Assuming that the actual O&M costs are in the order of US$ 30 per hectare (which would be a realistic figure for many Asian systems but too low for many arid countries) only US$ 10 per hectare are collected from farmers, forcing the government to cover a deficit of US$ 40 million per year. The figure is substantial and its significance can be realized when considering that with a similar amount 10-20.000 ha can be developed.

4.2. REHABILITATION APPROACH

This approach consists basically of allowing the irrigation facilities to deteriorate to the point that rehabilitation of the system is needed and for which international financing may be available at relatively easy terms. This approach appears in combination with the former one. Rather than subsidizing the O&M costs, governments tend to finance only some major repairs that may be indispensable for keeping the system functioning until further financing can be secured for rehabilitation of works.

In principle international loan institutions try to avoid the repetition of these situations but reality shows that this is difficult. Examples of "third and fourth generation rehabilitation projects" can be found without much difficulty.

4.3. TOTAL COLLAPSE APPROACH

An ultimate strategy is not to wait until the irrigation system deteriorates and ceases to function. Although such a negative approach is difficult to realize in an open canal system where some water is always likely to run, it can easily happen in irrigation systems that depend on pumping stations and where lack of maintenance may lead to a total breakdown of the facility. Although such a possibility exists, very rarely do such cases really happen and no actual examples can be quoted. This probably indicates that irrigation is far too important to allow a complete collapse. Solutions are always found to critical situations preventing a complete breakdown either through farmers' self-help actions or government interventions.

4.4. TRANSFER OF MANAGEMENT RESPONSABILITIES TO FARMERS

In the 1980s efforts have been initiated in many countries to transfer the management of irrigation systems from the public administration to water users' associations of various forms. Although not all experiences have been positive, the approach has shown a great deal of success and is likely to be pursued with greater strength in the near future.

The attraction of this approach is the responsibility for management is directly placed in the hands of the beneficiaries of the irrigation system. If farmers are not satisfied with the management of the system, they have the capacity to change it; if they consider the fees too high, they can veto them and request their elected managers to lower them. In public-run irrigation systems each side, farmers and public servants, blames each other for anything that goes wrong. In farmer-run systems, farmers can only blame their own elected managers and directly propose and implement improvements.

For all these reasons this approach is seen as a solution to overcome many of the sustainability constraints that affect the O&M of irrigation systems.

5. Research Needs

5.1. IMPROVED METHOD FOR WATER DISTRIBUTION

It has been pointed out that there is a strong need to improve traditional methods of distributing water for irrigation. A closer relationship must be established between the water distributed and the crops planted rather than a distribution according to the size of irrigation areas only.

Considerable research is needed to develop suitable automation procedures and models to deliver water effectively at the right place, at the right time and in the right quantity. Adaptation of traditional irrigation canal networks to respond to the variable demands of farmers needs considerable study. Automatic response of the canal systems to the demand may be an approach but also simulation models can be effective in predicting the behaviour of the canal network under variable demand. Such technical research must be accompanied by the necessary field verifications including the acceptance by farmers through special extension programmes.

5.2. MAINTENANCE METHODS

Maintenance of irrigation systems is done according to local traditions and use of equipment available on site. Very little effort is dedicated so far in research to examine and to find economically viable solutions for such activities. Little exchange of information exists on methods practised in different parts of the world that have proven to be efficient and practical.

5.3. TRANSFER OF MANAGEMENT RESPONSIBILITIES

This approach has proven to be very successful in some countries and regions. However, in other places it has not been possible to bring it to a successful end. A close analysis of the factors that determine the success or failure of this approach is required.

5.4. TRADE-OFFS BETWEEN MAINTENANCE AND REHABILITATION

There is no doubt that maintenance and rehabilitation are intimately related activities. This close interrelationship has not been analyzed in detail. The effects of rehabilitation programmes to reduce maintenance or the capacity of regular maintenance to defer rehabilitation have not received the attention that they deserve. If evidence can be given on the importance of regular maintenance, many rehabilitation projects would not have been necessary.

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PERFORMANCE PARAMETERS FOR A DECENTRALIZED AND PARTICIPATORY WATER ADMINISTRATION

J. CHAMBOULEYRON
Agricultural Engineer
Head of the Department of Irrigation and Drainage Engineering
INCYTH - Andean Regional Centre
P.O. Box 6, 5500 Mendoza
Argentina

1. Introduction

In recent years different international aid and lending agencies have laid emphasis on the promotion of decentralized and participatory irrigation water management systems. Likewise, experts participating in international meetings have been discussing ways to involve the users in water management activities as the conclusion had been reached that water management is more efficient when the administration is decentralized and participatory.

The concept has attained widespread dissemination and international lending agencies as well as agricultural aid institutions like FAO (1982, 1894) and IIMI (Manor and Chambouleyron 1992) have already taken the lead in its development.

Perhaps the most telling example of the changes that are taking place are the projects being implemented by Mexico. Mexico, until recently the Latin American leader in centralized water management, is now undergoing a most important change in its history towards a decentralized and participatory water management. The same can be said of other Latin American countries such as Colombia, Costa Rica and Ecuador (Chambouleyron, 1993b), where other less dramatic water management changes have been proposed.

There are two main reasons for these changes: on the one hand, the increase in water consumption in developing countries because of the expansion of agricultural activities to feed a growing population and the consequent need for water supply; on the other hand, the worldwide concern for both the environmental deterioration resulting from an inadequate water management and the development of a sustainable irrigated agriculture.

So far it has not been possible to design a decentralized and participatory management model that reconciles the interests of agency and water users alike. Of all models applicable in developing countries the most adequate seem to be those based on the

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Spanish participatory model. It is simple, it can be readily applied in countries with little tradition in water management, and it generates an acceptable irrigation efficiency level.

At the same time, great technological efforts have been made to improve water utilization. Sophisticated models inundate the most important libraries and keep thesis-writers busy. New water application techniques generating great efficiencies have been developed but the existence of obsolete administrations prevent their massive use in agriculture.

This paper deals primarily with performance parameters and their application to irrigation water use. To illustrate it, reference is made to the decentralized and participatory water management model implemented in Mendoza, Argentina. It describes how management responsibilities are allocated to the Agency and the users, how water management policies are discussed at a horizontal level, i.e., by all parties involved, and how both users and Agency assess their respective performance by means of the simple performance parameters described below.

Sustainability means profitability. In arid zones irrigation water management is associated to the economic success of agriculture. In other words, an efficient water administration is the basis of sustainable agriculture.

2. Background Information

The Province of Mendoza is situated in the arid western region of Argentina and borders on the Republic of Chile. It has 360,000 hectares under irrigation planted with different crops, similar to the cropping pattern prevailing in the Mediterranean Basin (vineyards, stone-fruits, olive trees, vegetables and forage crops). The irrigated areas are located in five large oases. The province's water supply is 5,300 hm^3/year and it has a population of 1,500,000 for a total area of 150,000 km^2.

As it is a desertic area, the population has settled in the cultivated oases, that is in 3,600 km^2, which yields a population density of 416 inhabitants per km^2 within the oases and no inhabitants in the rest of the province. This is the reason why all the water is used and devoted to different uses --agricultural, urban, industrial, public and recreational-- in a small area.

Due to the limited availability of water (3,500 m^3/inhab./year) and the expected shortages for the future, water administration in Mendoza has been given a decentralized and participatory organization. Over 100 years old, its General Irrigation Department (DGI) is responsible for the administration of water resources.

Since Mendoza's was an agricultural society, the DGI was originally designed to manage water for agricultural purposes, but as it has evolved into an urban-agricultural-industrial society water now must be allocated to different uses, which has complicated its operation (Chambouleyron, 1992a). Therefore, it is most important to exercise a greater control over water use in order to prevent water pollution and to promote a sustainable agriculture that will help to avoid use conflicts among the different sectors.

The utilization and importance of performance parameters in irrigation water administration will be explained by means of examples taken from water administration in Mendoza.

2.1. THE AGENCY

The Provincial Constitution sets forth that water resources are to be administered by the General Irrigation Department (DGI) (Cano, 1967). It is an autarchic and autonomous agency because it prepares its own budget and dictates its own regulations within the framework provided by the provincial Water Law. The DGI is headed by a Superintendent, who is appointed by the provincial senate for a period of 5 years. He is the highest-ranking executive and technical authority at the DGI, being responsible for the administration and enforcement of the Water Law. He performs the functions of a Water Judge and submits applications for public water concessions to the approval of the provincial legislature. He also administers the DGI funds and calculates the irrigation water rate every year.

To assist the Superintendent there is an Administrative Tribunal, made up of five users representing each of the five irrigated oases in the province. The Administrative Tribunal appoints DGI personnel, prepares the annual budget, supervises the elections carried out by the users' associations, and grants permits for public surface and underground water use.

There is also an Appeals Council made up of a councillor for each of the main rivers, which is the highest tribunal of administrative instance for all water use conflicts.

Each provincial river is administered by a Superintendent's representative (a Subdelegate). The subdelegate is responsible for managing the dams, rivers and primary canals as well as for delivering irrigation water to the users' associations at secondary canal level.

Users participate in the administration of the Subdelegation through Honorary Users' Boards, which are made up of users from the upper, middle and lower irrigated areas along the network.

Water management in Mendoza is an example of authentic administrative decentralization since the DGI does not depend on the provincial government nor does it manage the irrigation network as this part of the system is managed by the farmers themselves through their Users' Associations.

2.2. WATER USER'S ASSOCIATIONS

Due to the administrative decentralization, Mendoza's canal network is administered by the users. Water Users' Associations (WUAs) manage secondary, tertiary and quaternary canals. It is their responsibility not only to convey water but also to operate the drainage network. The main drainage collectors are maintained by the DGI.

According to Zuleta *et al.* (1992), in Mendoza there are 366 WUAs using surface water and 10 WUAs using pumped groundwater exclusively. Within the first group there are some associations which make use of both surface water and groundwater extracted from artesian wells.

WUAs are classified into large (more than 10,000 ha), medium (between 1,000 and 10,000 ha) and small (less than 1,000 ha). They are headed by an Inspector (Administrator), who is also a Water Judge of first instance. The Inspector is assisted by three elected delegates and he can appoint employees --gatekeepers-- to manage the irrigation network. Except the gatekeepers', all other posts are honorary, although in certain cases per diem expenses are paid to the Inspector.

Every year, the WUAs prepare the respective associations' budgets --which include salaries and per diem expenses, operation and maintenance costs, works to be done in the canals-- and submit them to the DGI. The water rates collected by the DGI are calculated on the basis of both the WUAs' budgets and the DGI's budget. It should be pointed out that the DGI acts as a revenue collection and distribution agency for it collects the irrigation water rates and monthly deposits the corresponding sum in the bank account each association has.

At present, all water requirements of Mendoza's 360,000 irrigated hectares --not only those exclusively agricultural-- are managed by the 376 WUAs and by the DGI's 550 employees. This corresponds to about 1000 ha/WUA and 650 ha/DGI employee.

2.3. PERFORMANCE PARAMETERS

As described above, water is managed by the DGI and the WUAs, which means that responsibility for the operation of the system is shared between the two. Whenever a decision has to be made on regional water policy, construction of infrastructure works, cleaning of drainage collectors, etc. both parties meet and discuss the actions to be taken and an agreement is reached. This is an example of the so-called horizontal administration as one sector supports the other.

When budgets are discussed to calculate the water rates, the horizontal administration becomes evident because each sector is of the opinion that it is the other that must economize. It is at those moments that parameters should be used to assess the performance of the parties.

Performance parameters have lately acquired great importance in evaluating decentralized and participatory administrations as they render it easier to assess the way activities are carried out and the results to be expected.

Rusche (1985) states that performance parameters are ratios that make it possible to readily assess the most relevant elements in a management system. They contribute to the decision-making process and, if accompanied with a brief analytical report, to the precise definition of management actions. The number and type of parameters are defined on the basis of the enterprise's characteristics and the available information.

The basic requirement to calculate performance parameters is the temporal consistency of the data to be processed: data from different periods cannot be compared. Furthermore, the information must be available upon request.

Performance parameters should not be determined in isolation but through comparison in order to obtain a consistent and effective analysis for a given period. It is convenient to analyze, at least, five consecutive periods so as to establish adequate values for parameters and determine tendencies in management development.

There are different performance parameters:

- Productivity parameters provide information on the yield obtained per unit of resource applied.
- Efficiency parameters are used to measure the physical results obtained in relation to the inputs.
- Technical parameters are used to assess technical evolution in the Agency's activities.
- Administrative parameters contribute to the analytical follow-up of administrative processes.
- Financial parameters are used to analyze and measure the Agency's financial system and performance.
- Social parameters are used in the analysis of the users' capacity to pay, which may or may not exert economic impacts on the productive sector.

The grouping of indicators must be done to suit the Agency's or WUAs's needs. It is advisable to select them according to the enterprise's different activities to be able to make an analytical assessment of all processes involved in a given activity and then anticipate the necessary planning.

According to Bos *et al.* (1994) it is possible to consider the following main groups of parameters in water administration:

a. *Water supply performance. This deals with the primary task of irrigation managers in the capture, allocation and conveyance of water from source to field by management of irrigation facilities. Indicators address several aspects of this task: efficiency in conveying water from one location to another, the extent to which agencies maintain irrigation infrastructure to keep the system running efficiently, and the service aspects of water delivery which include such concepts as predictability and equity.*
b. *Agricultural performance. This group addresses the direct impact of operational inputs in terms of such aspects as actually irrigated area and crop production, over which an irrigation manager may have some but not full responsibility. Agricultural performance is a 'direct outcome' of water delivery performance in Small and Svendsen's terms.*
c. *Economic, social and environmental performance. This group comprises*

parameters dealing with the impact of both operational and agricultural inputs on the viability and sustainability of irrigated agriculture; these impacts include both the physical and socio-economic sustainability of irrigated agriculture. This type of 'impact' performance is considered and 'effect' in Small and Svendsen's terms because it is further removed from water delivery performance causally as well as in time and space.

3. Performance Parameters in a Decentralized and Participatory Administration

3.1. PARAMETERS TO CONTROL THE AGENCY'S PERFORMANCE

Chambouleyron (1992b) states that, in assessing a decentralized and participatory agency, WUAs should control its administrative, financial, employment, physical and socio-economic parameters.

3.1.1. *Administrative Performance Parameter*
It is the ratio between the actually spent revenue and the total budget. This ratio should be **1** as it is not advisable to spend more than has been budgeted (Table 1). This is one of the most important indicators with which to measure an agency's administrative performance as regards its revenue policy.

$$\textit{Administrative performance} = \frac{\textit{Actually Spent Revenue}}{\textit{Agency Budget}}$$

3.1.2. *Financial Performance Parameter*
It is the revenue collection percentage. The higher the percentage the more money available for a more efficient administration. For the DGI an ideal collection level should represent 70 percent of the total billed as water rates for all registered irrigation water rights. This percentage is made up as follows: 40 percent from the current year's billing and 30 percent from fees due (Table 1).

$$\textit{Financial Performance Parameter} = $$

$$\frac{\textit{Waters Rights Paid Current Year} + \textit{Water Rights Paid Previus Years}}{\textit{Total Water Rights Due for Current Year}}$$

3.1.3. *Personnel Employment Ratio*
It is the relationship between the Agency personnel assigned to administrative and technical activities and the irrigated area it serves. Local and Spanish experience indicates that only one employee per 1,000 irrigated hectares is a good ratio (Table 1).

$$\textit{Personal employment ratio} = \frac{\textit{Agency Employees}}{\textit{Total Irrigated Area}}$$

3.1.4. *Overall Project Efficiency*

This indicator helps to define project efficiency in the oasis and provides information on the volume of water available for the different uses required by the area served. It also shows the level of investments made in physical infrastructure to manage the resource. It is generally agreed that with adequate management and operation practices a 50 percent efficiency can be attained (Table 1).

$$\textit{Overall projet efficiency} = \frac{\textit{Crop Water Requirement-Efective Rainfall}}{\textit{Total Inflow into Canal System}}$$

3.1.5. *Relative Water Cost*

It is a socio-economic parameter that shows the impact of the water rate on production. Locally, it is considered to be the ratio between the value of the water rate and the production cost of the region's most important irrigated crop. Roig (1984) suggests that the water rate in the Mendoza region should represent no more than 3 to 5 percent of the production costs. This is so depending on whether minimum or maximum production levels are taken into account (Table 1).

$$\textit{Relative Water Cost} = \frac{\textit{Total Cost of Irrigation Water}}{\textit{Total Production Cost of Major Crop}}$$

Table 1 shows the variations in performance parameters for the DGI during the 1981-1989 period. A thorough analysis of the different parameters reveals the way the Agency was managed and their assessment provides basic guidelines to improve its administration.

TABLE 1. Parameters to control the DGI's performance in Mendoza, Argentina, for the 1981-1989 period

Parameter	Ref. Value	YEAR									Mean
		81	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	
Administrative	1	0.9	0.9	0.5	0.6	0.7	0.7	0.7	0.8	0.9	0.77
Financial	70 %	64	86	53	53	55	54	41	57	70	59
Personnel Employment	1/1000ha	1.7	1.8	1.9	1.9	1.9	1.7	1.7	1.7	1.7	1.9
Projet Efficiency	50%	37	50	24	33	35	45	31	26	44	38
Relative Water Cost	3%	4	27	3	4.6	3	2.5	2.9	2.5	2.2	3

As shown in Table 1, only in 1981 and 1989 did the fee collection parameter approach the reference value.

For the administrative performance parameter, the results for period under analysis, with the exception of 1982 and 1989, are far from the reference value: in other words, the collection policy did not meet expectations.

As regards the DGI's personnel, although efforts and investments in computers and automating operations have been made, the reduction in the number of employees has not been fully effected and the values obtained practically double the reference value.

Overall project efficiency shows that, given the present water distribution conditions, it is difficult to improve irrigation efficiency above 40% . Regional efficiency reaches the reference value when, under drought conditions, water supply diminishes.

The relative water cost parameter shows that there have been periods during which the Agency has failed to take advantage of an accepted water fee representing up to 3% of the total production cost, and has let the value of the service drop unnecessarily.

3.2. PERFORMANCE PARAMETERS FOR THE USERS' ASSOCIATIONS

As mentioned above, there are different parameters the Agency can use to control users' performance in irrigation water management. The most important ones are those related to network operation and maintenance, administrative aspects (which help draw up the budget), and general expenditures. There are also physical and production parameters, the latter referring to those activities that contribute to the payment of the operation costs. In this case, two indexes are used: timber production and power generation.

3.2.1. *Operation and Maintenance Ratio*

It is the length of secondary and tertiary irrigation and drainage canals divided by the total irrigated area served by the WUA in hectares.

$$\textit{Operation Mantenance Ratio} = \frac{\textit{Length of canals, drains}}{\textit{WUA's Irrigated Area}}$$

To further establish the cost of canal cleaning information should be available on:

- length of irrigation (and drainage) canals per unit irrigated area (e.g. in m/ha), and on
- maintenance cost per unit length of canal, thus per hectare (Bos *et al.*, 1994).

In view of this ratio, the values indicated in Table 2 have been derived.

Locally, a normal value for the annual maintenance of the canal system is considered to be between 25 and 30 metres per hectare. This parameter is equivalent to 1 daily wage/ha.

The above parameters are used to indicate the length of the irrigation network corresponding to the canals in a given irrigated area. The wages paid for weeding and desilting a system of earthen canals and open drains are included. The farm irrigation and drainage system is maintained and cleaned by hand by hired workers. When preparing the budget, the money required to pay the wages for the annual or biannual cleaning of the network can be calculated on the basis of the length of the canals controlled by the WUA. Likewise, the values given are useful in establishing whether the estimates for system maintenance are correct or excessive.

TABLE 2. Length and daily wages corresponding to the maintenance of the irrigation and drainage system

Type of canal	m/ha	Daily wage/ha	
		Weeding	Desilting
Tertiary canals	15	0.14	0.29
Secondary canals	5	0.06	0.25
Farm drains	5	0.09	0.19
Total	25	0.29	0.73[1]
Drainage collectors[2]	6		

[1] 0,299 + 0.73 = 1.02 daily wage/ha/year.
[2] Machine-cleaned once every 5 years. US$ 3/ha/year. A daily wage in Mendoza is US$ 13/day. System maintenance is not included in the WUA's budget, being usually done by the users themselves.

3.2.2. *Financial Self-Sufficiency*

Financial self-sufficiency comprises several parameters that are associated to the WUA's budget including the amounts required to defray the Inspector's per diem expenses, payments to contractors, wages and fuel expenses. The optimal reference value of 1 becomes in practice 0.7 approximately.

$$\textit{Financial Self-Sufficiency} = \frac{\textit{Actual Income}}{\textit{Total MOM Requirements}}$$

There are different budget items in Mendoza's WUAs. In the example, US$ 8.98/ha (practically US$ 9) is the expenditure per area unit in a WUA's budget. To calculate the water rate the DGI's budget --also expressed in US$/ha-- should be added to it. Thus, the budget for a 5,000 ha WUA results from multiplying the registered area by US$ 9/ha. This index helps not only to structure budgets but also to assess WUAs's performance. It is worth noting that the average water rate in Mendoza (1993) is US$ 35/ha, which means that a WUA's budget represents only 25% of the water rate. This parameter is also much used in the drawing up of the DGI's general budget.

TABLE 3. The structure of a WUA's budget

Budget Item	Percentage	Value inUS$/ha
Personnel (Gatemen) WUA Inspector's		3.5
per diem expenses	39	1.7
Accountant's fees	19	0.36
Operation and Maintenance[1]	4	2.7
Gate repairs	30	0.45
Fuel and other	5	0.27
	3	8.98
Total	100	

[1] Maintenance here refers **only** to the money returned by the WUAs to the DGI for the loan received to construct minor works. It does **not** include the weeding and desilting of the irrigation network as this is done by the farmers themselves.

3.2.3. *Farm Irrigation Efficiency*
This parameter is especially useful in the case of WUAs using pumped water on account of the impact of energy costs on water extraction. Here, the index is the ratio between crop water requirements and the water actually supplied by the canal system. It comprises field application efficiency and conveyance efficiency of the field canals. The generally accepted target value for this efficiency is 60 percent.

$$\textit{Farm Irrigation efficiency} = \frac{\textit{Crop Irrigation Water Requirements at Farm}}{\textit{Actually Delivered Volume of Water at Farm Gate}}$$

3.2.4. *Production Parameters*
There are two parameters referred to WUAs's activities in Mendoza which reduce administration costs: timber production and power generation. As regards the first one, it has long been a common practice in Mendoza to plant poplars along canal borders to take advantage of water percolating from the unlined earthen canals. In this way, the system losses are used to grow timber and prevent both the erosion of canal slopes and water table rises. As for the second activity, turbines are installed in canals with important flows and steep slopes; the hydraulic power generated is sold in the local market. It must be explained that depending on where the turbine is installed - i.e., at which geographical point in the irrigation system - the power generated is controlled by the DGI (main canal) or by the corresponding WUA (secondary or tertiary canal). In the first case, the sale of the power generated by a turbine installed in a main canal helps reduce the DGI's budget and, hence, the <u>water rate</u>. In the second case, the sale of the power generated by a turbine installed in a secondary or tertiary canal contributes to a reduction in the <u>WUA's budget</u>. The latter is also the case of the production and sale of timber. The sale of both timber and electricity generate genuine funds which irrigation system managers in developing countries use to reduce the system's running costs.

$$\textit{Timber production ratio} = \frac{\textit{Kilograms of Timber for Sale}}{\textit{Area Irrigated by the WUA}}$$

The timber production ratio is locally considered to be 100 kg/ha/year or US$ 6/ha/year.

$$\textit{Power generation ratio} = \frac{\textit{Economic Benefits Power Generation}}{\textit{Irrigated Area}}$$

The power generation ratio is locally considered to be 60 kwh/ha/year or US$ 3/ha/year.

The above example corresponds to a hydroelectric power plant to be installed on a main canal irrigating 80,000 ha with a duty of water of 0.6/l/s ha, an average flow of 48 m^3/sec and a 5 m difference in elevation. According to Vairani (1993), the value obtained is approximately the same as an average of the power generated by three power plants located on three main canals in different oases in the Province of Mendoza.

The ratio for timber production corresponds to the assessment of different WUAs marketing their timber annually. It should be borne in mind that the administration of an irrigation system in an oasis which sells the power it generates and the timber it produces can be very economical.

4. Conclusions

As shown in our example, for a decentralized and participatory water administration to be efficient a system of controls must be implemented that helps both the Agency and the WUAs. In the horizontal administration described there should be mutual controls, as the said controls make for a more open administration and greater water management efficiency.

With permanent adjustments, this type of administration can devise methods that will make it possible to improve water management at the regional level - especially irrigation efficiency - and, thus, to formulate guidelines for a sustainable irrigated agriculture.

Developing countries have wasted years in organizing centralized bureaucratic agencies in the belief that they could contribute to management efficiency but the DGI experience in Mendoza shows that an army of employees is not necessary. An irrigation agency's performance improves when the resource is managed by the interested parties. In this type of system performance parameters play a critical role as control mechanisms for all sectors involved.

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REMOTE SENSING, GIS AND HYDROLOGICAL MODELLING FOR IRRIGATION MANAGEMENT

M. MENENTI*, S. AZZALI* and G. d'URSO**
* *DLO Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO)*
P.O. Box 125, 6700 AC Wageningen, Netherlands
** *Univ. of Campobasso, Campobasso, Italy*

1. Introduction

The function of remote sensing (RS), in combination with other geographical data and interpretative models can be best clarified by considering how irrigation management affects the capability of farmers to react to the market environment.

In principle, the function of an irrigation system is to provide farmers with a resource which places them in a better market position. In practice this means that farmers should be able to adapt rapidly their irrigation strategy in response to the evolution of market conditions (Menenti, 1990b).

This principle clashes with natural constraints such as soil and hydrological conditions and, even more, with the constraints resulting from the increasing response time of the functional elements of irrigation management (Fig. 1). The response time of "Administrative rules", "Organization" and "Irrigation system and operation" can be decreased by efficient use of larger amounts of information. In the long run increased flexibility in these elements will by necessity lead to adapted legislation and changes in the social context of irrigation.

Past experience indicates that remote sensing data alone is of limited direct use to support irrigation management. The value of remote sensing is significantly enhanced through integration with other ancillary data in tabular or map form. Geographic information systems provide an efficient vehicle for this integration and for further data analysis with interpretative models.

The issue of the actual practical scope of remote sensing is to some extent a matter of unfulfilled promises in the early stages of remote sensing by satellites. There are examples, however, of very specific applications where the practical applicability of satellite data is beyond debate. Enforcement of land-use related regulations is a typical example. Information requirements are clearly defined and, quite often, can be met by using satellite data. Allocation of irrigation water in a broad sense is a specific case in this category.

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 453–472.

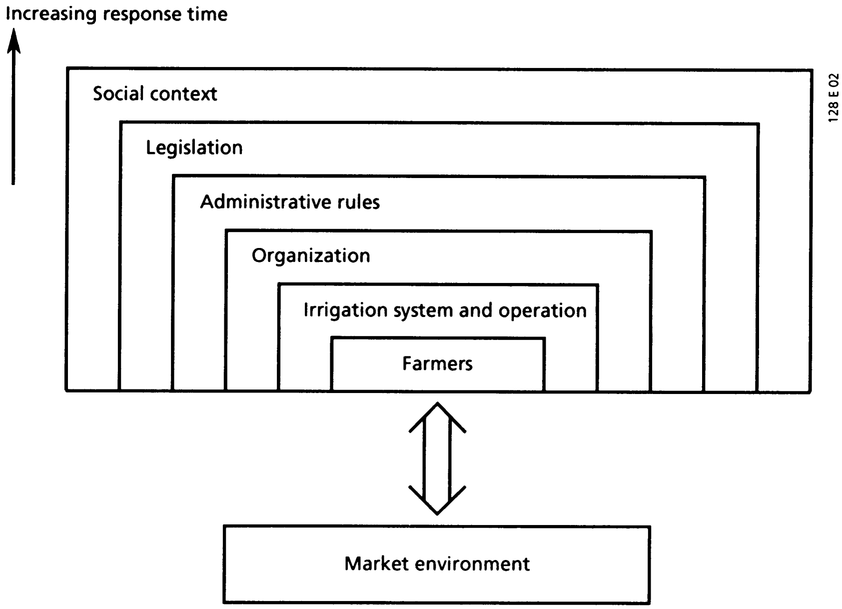

Figure 1. Conceptual scheme of functional constraints affecting the flexibility of on-farm irrigation strategy in response to the market environment

A contrast of cultures may play a role at times. Use of satellite data has a clear undertone of a technology driven, forced-upon approach. Contrariwise, irrigation has, especially in the regions where it is extensive, a secular tradition. Organization and management of large irrigated areas is the result of long-lasting, fine-tuning efforts to accommodate the conflicting requirements of farmers and water administration. It is plainly unrealistic to expect that current practices are turned upside-down just to use fancy techniques like remote sensing (Menenti, 1990 a).

A recent review of remote sensing applications in support of irrigation management was given by Vidal and Sagardoy (1994). In this paper, examples are presented of the use of high resolution multispectral satellite data to map land use and other related variables. These examples relate to the following applications:

- map crop water requirements by command area on the basis of land use;
- map performance indicators based on precise water allocation rules;
- obtain input data for distributed hydrological models of irrigation schemes.

Finally, cost estimates are given for some applications.

2. Crop Water Requirements and Crop Water Stress

2.1. CROP WATER REQUIREMENTS

The tendency to consider scheme level irrigation management as a straightforward extension of on-farm practices is still widespread and crop water requirements are often taken as the dominant objective of both design and management of irrigation schemes.

Accurate and up-to-date information on crop water requirements and on their variability within the scheme is useful even if many other aspects have to be taken into account by irrigation managers.

To map crop water requirements the most obvious approach is by mapping individual crops and subsequently by computing with agrometeorological methods water requirements by crop. This method was applied in a study on two large irrigation schemes in Italy (Menenti *et al.*, 1986; Azzali and Menenti, 1989). In many cases, such as fruit trees and vineyards, crop water requirements depend more on canopy architecture than on crop type, therefore crop mapping is a poor basis for mapping crop water requirements.

Tunuyán. This case-study in Mendoza, Argentina, has shown that individual crops could not be mapped reliably due to the extreme variability in soil cover, crop age, undergrowth, etc. (Visser *et al.*, 1989; Meuwissen, 1989). A method was developed to map crop classes, in which the crops have similar water requirements.

The procedure leading to this classification was described by Meuwissen (1989) and Azzali *et al.* (1990), who also presented detailed results. Three different maps were obtained: the map of fraction of irrigated land, the map of mean crop coefficient and the map of standard deviation of crop coefficient values. The first two maps can be directly applied to calculate crop water requirements by tertiary unit. The third map gives an estimation of under- or over-irrigating individual fields in each tertiary unit.

The reference evapotranspiration for the different crop classes in the land use map was calculated using the program CRIWAR (Vos *et al.*, 1989).

Po valley. Crop identification and mapping have been obtained in two irrigation districts located in the Po valley, Italy, by means of LANDSAT-TM images. Individual crops have been mapped by establishing a multi-temporal discrimination scheme which made use of crop labels defined in terms of different vegetation indices and overpass dates (Menenti *et al.*, 1986; Azzali and Menenti, 1989). Accurate data on crop calendar is also required to make this multi-temporal multi-indices analysis successful.

In the same area another research objective has been the determination of the variability in crop development stages (i.e. early, average, late development) using remote sensing data. This method involved the calculation of three TVI (Transformed

Vegetation Index) images from three multitemporal satellite images and the combination of the TVI images in one colour composite image. Each crop, out of six main crops, was identified by a three-colours scale indicating respectively an early, or average or late development stage. The same approach was applied succesfully by Prados Velasco (1993).

Riyadh. A study to assess the water use in the green areas of Riyadh has been performed on behalf of the Arriyadh Development Authority (ADA) (Visser, 1990).

The green areas were mapped using high resolution satellite imagery. The water requirements for all sub-haras (administrative units) within the city were calculated and compared with the volumes of water that are actually applied. Particularly, the investigation on irrigation water use was expected to show whether overirrigation was the main cause of the rising groundwater levels.

The study area (50 x 70 km) included the city of Riyadh and its surroundings. Most vegetation is planted for ornamental purposes inside the city. Only in the Wadi Hanifa agricultural crops are present.

To obtain a vegetation map of the area both LANDSAT Thematic Mapper and SPOT satellite images were used. The latter were applied in the format "multispectral and panchromatic merged on tape". By resampling of the multispectral image to the pixel size of the panchromatic one this gives an image having an apparent resolution of 10 m. To take advantage of the better spectral information provided by the TM sensor, an image was created consisting of the three SPOT bands and the TM5 band.

The results proved that the green areas were mapped rather accurately. A map of the boundaries of green areas was also produced by means of a fully automatic procedure.

The reference evapotranspiration of the two vegetation types distinguished was determined using the model CRIWAR. Besides the Modified Penman Method, the Jensen-Haise Method adapted on the basis of local measurements (Salih and Sandil, 1984) was also applied. Actual water use was compared with theoretical crop water requirements, as obtained according to both methods for all sub-haras, i.e. 560, in the study area. The final outcome of the study was a detailed data base including land use, crop water requirements, leaching requirements, actual water use and overirrigation by sub-hara, month, season and year.

Mapping of irrigated cropland is probably the most reliable and cost-effective RS-application in irrigation water management; major studies have been completed in several countries (Thelin and Heimes, 1987; Vidal and Baqri, 1994).

2.2. DETECTION OF CROP WATER STRESS USING REMOTE SENSING

A significant share of earlier literature on remote sensing applications in irrigation management focussed on early detection of crop water stress using thermal infrared measurements. The physical basis of this method are well established and can be summarized as follows (Menenti and Choudhury, 1993).

Actual evaporation from land surfaces may be observed with two types of physical measurements:

(i) direct measurement of either turbulent vapour flux by means of eddy correlation techniques or of water loss of a soil and vegetation sample by means of lysimeters;

(ii) indirect measurement through either:

a) the surface energy balance equation:

$$R_n + G + H + \lambda E = 0 \quad \left(W\,m^{-2}\right) \qquad [1]$$

where R_n is net radiation, G soil heat flux, H sensible heat flux and λE latent heat flux, i.e. the amount of energy, λ (J kg^{-1}) required in the liquid-to-vapour transition of E (kg m^{-2} s^{-1});

or

b) the water balance equation of either a soil column or an atmosphere column (e.g. Menenti, 1993).

Equation (1) expresses the balance of vertical heat fluxes at a homogeneous land surface in study of turbulent heat transfer; for non-homogeneous surfaces like partial canopies it implies some kind of definition of effective land surface properties. Regional estimates of evaporation, however, are a necessity for both water balance studies and to understand the land-surface atmosphere interaction. Direct measurement is a difficult proposition when length scales upwards of 10 km are considered, so the use of less accurate methods involving remote measurements is attractive, even if some semi-empirical relationships remain necessary.

Another manner of using Equation (1) to estimate evaporation is by casting it as a combination-type formula (Penman, 1948; Monteith, 1965). This can be done by conceiving the land surface as a one, two, four or multi-layer system (Van Bavel, 1966; Menenti, 1984; Shuttleworth & Wallace, 1985; Choudhury & Monteith, 1988; Van de Griend & Van Boxel, 1989).

A combination type of equation to compute directly the latent heat flux of actual soil evaporation, λE, can be obtained (Menenti, 1984):

$$\lambda E = \frac{s_a\, r_{ah} \left(R_n + G_E\right) + s_s\, \rho_a\, r_{sh}\, G_E + \rho_a\, c_p \left[e^*(z) - e(z)\right]}{\gamma \left(r_{av} + r_{sv}\right) + s_a\, r_{ah} + s_s\, \rho_a\, c_p\, r_{sh}} \qquad [2]$$

where s_a is the slope of saturated soil vapour pressure curve in air, s_s in soil, ρ_a is air density, c_p is air specific heat at constant pressure, e^* is saturated air vapour pressure, e is actual pressure, r_a is resistance to heat and vapour transfer in air, r_s is resistance to heat and vapour transfer between the liquid-moist air interface and the physical surface of the evaporating system, γ is psychrometric constant and G_E is soil heat flux at the evaporation front.

Note that in case the evaporation front is located at the soil surface the resistances r_{sh} and r_{sv} become zero, and equation (2) reduces then to:

$$\lambda E_p = -\frac{s_a\left(R_n + G_0\right) + \rho_a c_p \left(e^* - e\right) / r_a}{s_a + \gamma} \qquad [3]$$

where λE_p is potential evaporation and G_0 is soil heat flux at the soil surface. Stanghellini (1987) proved that a combination equation identical to Equation (2) describes correctly actual plant transpiration. The soil resistances are redefined by her then as internal resistances to vapour and heat flow from the liquid-to-vapour interface inside the leaves to the physical boundary of the leaves.

Equation (3) is a definition of potential evaporation, i.e. a case when the rate of liquid to vapour transition is not affected by liquid water flow beneath the physical boundary of the evaporating body.

Another way to obtain λE-estimators is by defining theoretical pixelwise ranges for λ E and surface temperature T_0 and subsequently interpolating by using observed T_0-values. Equation (2) is first rewritten as:

$$\lambda E = -\frac{s r_e \left(R_n + G\right) + \rho_a c_p \left(e^* - e\right)}{\left(s + \gamma\right) r_e + \gamma r_i} \quad \left(\mathrm{W\,m^{-2}}\right) \qquad [4]$$

where r_e is external and r_i internal resistance. Sensible heat flux is written as:

$$H = -\frac{\rho_a c_p}{r_e}\left(T_0 - T_a\right) \quad \left(\mathrm{W\,m^{-2}}\right) \qquad [5]$$

where T_a is reference air temperature; chosen as potential air temperature at the top of the Planetary Boundary Layer.

By substitution of Equations (4) and (5) in (1), Menenti and Choudhury (1993) obtained:

$$T_0 - T_a = \frac{\dfrac{\left(r_i + r_e\right)}{\rho_a c_p}\left(R_n + G\right) - \dfrac{1}{\gamma}\left(e^* - e\right)}{1 + \dfrac{s}{\gamma} + \dfrac{r_i}{r_e}} \quad (\mathrm{K}) \qquad [6]$$

For a given T_a, the surface to air temperature difference $(T_0 - T_a)$ is controlled by partition of net radiation R_n into λE, H and G (see Eq. 1) at the land surface. The range of $(T_0 - T_a)$ corresponding with a hypothetical change in evaporation from zero to potential rate at constant surface reflectance and roughness can now be calculated.

The upper limit of $(T_0 - T_a)$ can be obtained by taking the limit of Equation (6) for $r_i \rightarrow \infty$ (no evaporation) while the limit for $r_i \rightarrow 0$ (potential evaporation) gives the lower limit:

$$\left(T_0 - T_a\right)_u = \frac{\left(r_e\right)_u}{\rho_a c_p}\left(R_n + G\right) \quad (K) \qquad [7]$$

$$\left(T_0 - T_a\right)_l = \frac{\frac{\left(r_e\right)_l}{\rho_a c_p}\left(R_n + G\right) - \frac{1}{\gamma}\left(e^* - e\right)}{1 + \frac{s}{\gamma}} \quad (K) \qquad [8]$$

where subscripts n and 1 indicate the upper and lower limits respectively. Equations (6), (7) and (8) imply the following relationship:

$$\frac{E}{E_p} = 1 - \frac{\frac{\left(T_0 - T_a\right)}{r_e} - \frac{\left(T_0 - T_a\right)_l}{r_{e,l}}}{\frac{\left(T_0 - T_a\right)_u}{r_{e,u}} - \frac{\left(T_0 - T_a\right)_l}{r_{e,l}}} \qquad [9]$$

The ratio in the right hand side is a more general form of the Crop Water Stress Index (CWSI) of Jackson *et al.* (1981, 1988). Here Menenti and Choudhury (1993) have taken into account the dependence of r_e on the atmospheric stratification (i.e. on $T_a - T_0$). Moreover we have redefined this ratio as a pixelwise parameter since it is calculated at given surface reflectance and roughness observed at each location (pixel); they named it Surface Energy Balance Index (SEBI). Relative evaporation E/E_p is, therefore, related to SEBI as:

$$E / E_p = 1 - \text{SEBI} \quad (-) \qquad [10]$$

where SEBI is the temperature dependent term on the right hand side of Equation (9).

So far we have dealt with a horizontally homogeneous conceptual surface. To deal with heterogeneous land surfaces we have to extend the previous concepts and definitions. Actual evaporation is a simple function of surface temperature only if every other land surface property remains constant. This applies in reality to limited changes in surface conditions. We can, however, define a pixelwise E_p and a pixelwise range of $(T_0 - T_a)$ by using Equations (3) and (9) at constant surface reflectance, roughness and T_a.

This clarifies both the potential and the limitations of crop water stress detection using thermal infrared observations. As far as all environmental and canopy variables remain constant, except evapotranspiration, canopy temperature is a direct measure of reduced transpiration and, therefore, a reliable and timely indication of crop water stress (e.g. Stanghellini and De Lorenzi, 1994). In practice, this seldom applies and bi-dimensional crop water stress indices have been proposed recently (e.g. Moran, 1994) based on similar concepts as the above mentioned SEBI. See also Ben Asher *et al.* (1988); Maas *et al.* (1989).

Increasing attention is being dedicated to provide real-time crop conditions monitoring services based on the use of cheap and small platforms (helicopters, ultra-light aircrafts and even model aircrafts). This leads to timely and low-cost operations which, especially in areas of intensive high-value crops, may be attractive (Moran, 1994).

3. Assessing Irrigation Performance with Satellite Data

3.1. BASIC INFORMATION ON THE CASE STUDY

To illustrate how the use of satellite data can contribute to irrigation management, the case of the Rio Tunuyán irrigation district in Mendoza, Argentina will be described. During a number of years, investigations have been carried out in this area on using new techniques to improve irrigation management (Menenti, 1990 b). The procedure (Visser *et al.*, 1989) to obtain three performance indicators will be briefly recalled. In Table 1 the definitions of the three performance indicators are given to compute the performance indicators.

Performance indicators relating to three different water allocation policies are considered (Menenti *et al.*, 1989):
A. Allocation of surface water proportional to the irrigated area (IP1).
B. Allocation of surface water to match crop water requirements (IP2).
C. Allocation of surface water to maximize effectiveness (IP3).

In case (C) the increase of actual transpiration, a reliable indication of the increase in yield, is taken as a measure of effectiveness. Different indicators can be easily calculated by means of a spread sheet package. To compute the performance indicators satellite data can be used combined with map data in digital form and discharge measurements.

It should be noted that availability of meteorological data and of soil hydraulic properties (as required to apply by the model SWATRE, Feddes *et al.*, 1978), rather than of land use data restrict the detail which can be achieved in mapping the indicators IP2 and IP3 (Table 1). Indicators IP1 and IP2 relate strictly to the context of irrigation in Mendoza; indicator IP1 (Table 1) measures deviations from uniform water allocation.

TABLE 1. Definition of irrigation performance indices; for each index the required land use data are indicated explicitly, with their source; the ancillary data and models used to calculate each index are also indicated

Irrigation performance Index	Land use data needed	Source	Model	Ancillary data
$IP1 = \dfrac{V_{ij}/A_{ij}}{V_i/A_i}$	irrigated - non-irrigated area	satellite image		discharges
$IP2 = \dfrac{E_{p_k} * A_{ik}}{V_i}$	crops or groups having a similar K_c	satellite image	CRIWAR	discharges, meteorological data
$IP3 = \dfrac{(E_{k,w} - E_k)A_{ik}}{V_i}$	crops	satellite image	SWATRE	discharge meteorological data, soil properties

V_i = volume supplied to unit i ($m^3.month^{-1}$)
V_{ij} = volume received at unit j, within higher order unit i ($m^3.month^{-1}$)
A_i = irrigated area in unit i (m^2)
A_{ik} = area of crop k in unit i (m^2)
E_{p_k} = potential evapotranspiration of crop k ($m.month^{-1}$)
$E_{k,w}$ = actual evapotranspiration of crop k irrigated ($m.month^{-1}$)
E_k = idem, non-irrigated ($m.month^{-1}$)
K_c = crop coefficient

The current water law, approved in Mendoza in 1884, specifies that water must be allocated proportionally to cultivated land. Originally, cultivated land within each command area was obtained on the basis of yearly declarations by farmers. Accuracy of these declarations deteriorated through the years and in 1953 a law was approved to settle problems arising with crops cultivated but not declared to the Irrigation Water Board. Permanent and conditional water rights were assigned to land and since then water was allocated on the basis of the area having water rights.

Especially in the last ten years cultivated land shrank, so uniform allocation on the basis of water rights implies significant mis-allocation of water. The difference between area having water rights and cultivated area, or values of IP1 calculated with either data is a measure of this misallocation. Moreover IP1 measures whether the 1884 law is applied according to its original interpretation.

A new water law is being handled by Parliament in Mendoza; upon approval water should be allocated on the basis of net crop water requirements. In this case, compliance with the new water law would be measured by means of IP2 (Table 1).

3.2. WATER ALLOCATION ON THE BASIS OF IRRIGATED LAND

When the objective of irrigation water allocation is proportionality with irrigated land the relevant performance indicator is IP1. To obtain the value of this indicator for individual tertiary units it is sufficient to map the actually cultivated area and measure water deliveries to each unit.

The land use map was first derived from a LANDSAT Thematic Mapper (TM) image acquired in January 1986. Accuracy of landuse values was on average 6%.

Flow data were gathered in the Viejo Retamo secondary unit and converted to volumes delivered to each tertiary unit per month. Combining these data with the data on actually cultivated area by tertiary unit, the value of IP1 could be calculated for all tertiary units in the Viejo Retamo on a monthly basis. Values for September 1987 and January 1988 are shown in Figure 2. It should be added that water requirements are rather low in September in Mendoza. In January water demand is at its peak level. Water distribution seems to be more equitable at a high demand level than at a lower level. All together actual water supply in the Viejo Retamo does not seem to be that far from target delivery regarding the distribution of surface water proportional to the actually cultivated area. Monitoring of irrigated land is necessary to assess irrigation performance even when most crops are perennial, as in Mendoza.

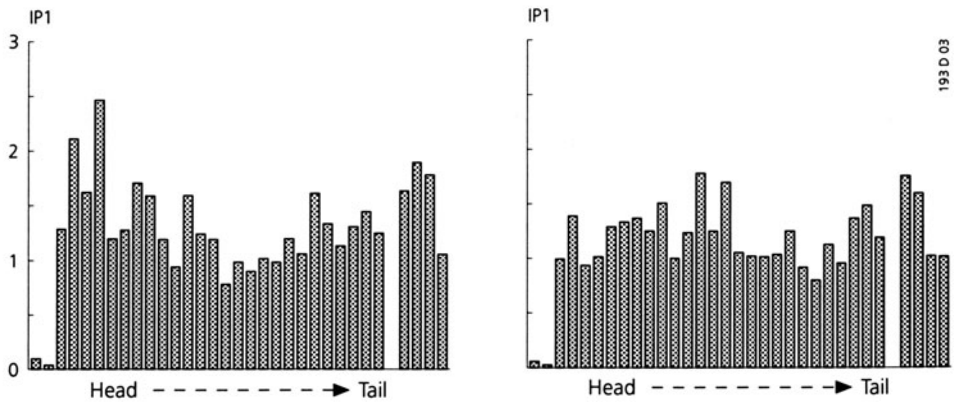

Figure 2. Values of performance indicator IP1 for all tertiary units of the Viejo Retamo secondary unit in September 1987 (left) and January 1988 (right); IP1 = 1 is the target value

3.3. WATER ALLOCATION ON THE BASIS OF CROP WATER REQUIREMENTS

In the case of the Rio Tunuyán, irrigation performance was also assessed by considering allocation policy B: "matching crop water requirements".

Subsequently the value of performance indicator 2 could be determined for all units. They are shown in Figure 3 respectively for September 1987 (low water demand level) and January 1988 (high water demand level). In September 1987 most values are less than one meaning that the volumes, actually delivered to the tertiary units, exceed the potential evapotranspiration within them. Consequently, groundwater levels in the area (Mirabile, 1985) tend to rise during the first months of the growing season. In January potential evapotranspiration exceeds the volumes that are actually applied. Part of the "deficit" will be met by groundwater supply and capillary rise causing groundwater levels in the area to fall during the months of peak water demand.

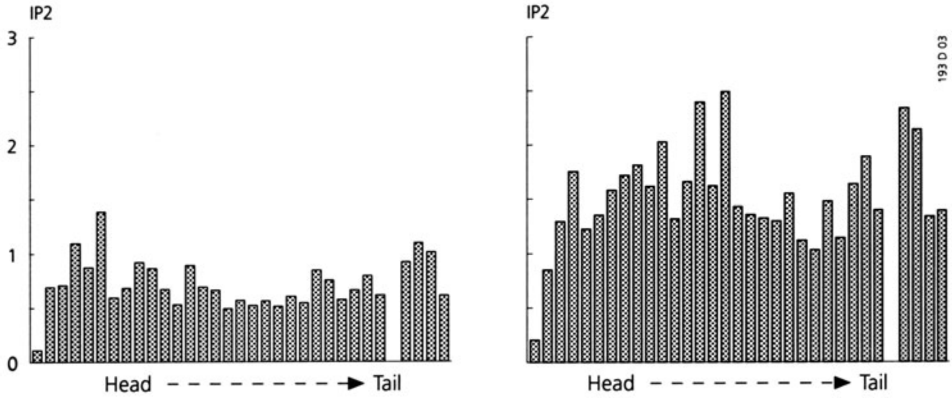

Figure 3. Values of performance indicator IP2 for all tertiary units of the Viejo Retamo in September 1987 (left) and January 1988 (right); IP2 = 1 is the target value

4. Monitoring of Drainage Conditions and of Salt Affected Areas

Satellite imagery is a straightforward approach for detection and monitoring of free water surfaces, very high moisture contents and salt deposits. So, very poor drainage conditions, major canal spills and unproductive soils can be easily detected (see e.g. Abderrahman and Bader, 1990).

Examples can be found in literature of applications dealing with several regions (Gorbachev and Shchuklin, 1987; Grave *et al.* 1987; Krapilskaya and Sadov, 1987; Vincent *et al.*, 1994; Ferrante, 1994).

Early assessment of salt affected crops is less straightforward, since observed changes in the spectral reflectances of (partial) canopies and even more so of mixed pixels have to be related to salinity conditions through ad-hoc field studies (Mirabile *et al.*, 1994).

5. Distributed Hydrological Models of Irrigation Schemes

The methods described above provide useful information on irrigated land and on irrigation performance; to identify improved irrigation management practices, however, it is necessary to compute and analyze the spatial patterns which would be produced by each management option.

This can be done using distributed hydrological models to describe the processes related to irrigation. In the study done in Mendoza, Argentina, the model SIMGRO (Querner and Van Bakel, 1989) was applied to this purpose.

This model simulates the water flow in the saturated and unsaturated zones, surface water in canal systems and the hydrological processes in a region. It takes into account the effects of irrigation and its impact on the crops water requirements.

The model SIMGRO requires the cropped area by sub-region as input. The method described above (Tunuyán study) was applied for this purpose (D'Urso *et al.*, 1992).

The nodal network was digitized and numerically overlayed onto satellite images. Next images are numerically classified using ground reference observations. Finally, fractional area is obtained by K_c value and by subregion and input to SIMGRO.

Model results can be validated for the entire system by using the model to obtain an estimation of project irrigation efficiency and comparing it with the value resulting from field data. This was done with favourable results: calculated value was 0.42, while the field data gave 0.39.

The model can be applied to study system performance under different management options. The current, rigid, water allocation rule (water is allocated proportionally to established water rights) implies that project irrigation efficiency is completely determined by seasonality in water requirements. At high water requirements (summer) project efficiency is high, while it decreases with decreasing water requirements.

A more complex analysis was done by using the performance indicator IP3 (Table 1). In Figure 4 four irrigation strategies are compared: 25%, 50%, 75% and 100% of current water supply; the analysis has been done for clusters of hydrologically similar subregions. IP3-values (marginal benefit) change considerably among clusters, indicating which clusters of subregions benefit most from water supply.

The same data can be used to identify an equitable water allocation strategy, which we may define as water allocation at constant marginal benefit, i.e. constant IP3. By taking IP3 = 0.4, for example, we should allocate 75% of current water supply to cluster 1, 50% to cluster 2, etc.

In a study done for the Nile Delta in Egypt simulation models were developed to describe the functioning of large irrigation infrastructure. In particular, a remote sensing algorithm (SEBAL) was developed converting satellite measurements of surface reflectance and temperature to estimate regional actual evapotranspiration

(Bastiaanssen *et al.*, 1992). The results obtained with SEBAL scored fairly well with the evaporation rates predicted by the calibrated model package SIWARE developed in the REUSE project (Abdel Gawad *et al.*, 1991).

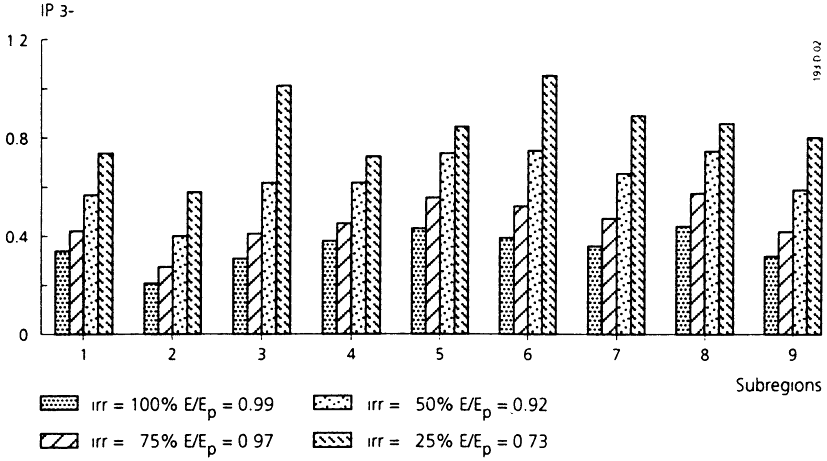

Figure 4. Values of marginal benefit (evapotranspiration-wise) of total water supply for four different irrigation strategies; results obtained with the simulation model SIMGRO

6. Water Allocation on the Basis of Farmers Preferences

The techniques described so far can be applied to identify and assess improved water management practices. Such improvements could be implemented by an Irrigation Authority having full control of scheme operation. This is generally not the case and, moreover, management of an irrigation scheme should be regarded as a service to be provided to farmers in a way optimally tailored to their needs.

There is a very significant amount of literature illustrating the fundamental importance of farmers acceptance of innovations in irrigation management. Remarkably little is known, however, about techniques to relate, in a quantitative manner, farmers' preferences to technical characteristics of the irrigation scheme and of its operation.

Knowledge of such relationships would provide a reference to design improved water management practices which meet best farmers' wishes.

This has been accomplished by applying marketing techniques to identify farmers perceptions and preferences about water distribution and to assess the utility to farmers of specific features of water distribution. A detailed description of the approach and of the results of a case study in Mendoza, Argentina, was given by Baars and Van Logchem (1993) who found that farmers *perceived* an alternative water distribution method as much better than the current one on the perceptual dimension "control" and to a lesser extent on the dimension "sufficiency". The current system was *perceived* as easier to use and less expensive.

Preference analysis showed that farmers attach the highest importance to "sufficiency", much less to "control", while they do not consider "ease of use" and "expenses" important (at least in the conditions of the Tunuyán area). Note that "*Preference*" is a higher order evaluation than "*Perception*". The latter relates for farmers' evaluation of product characteristics, while the former (preference) is the importance attached to each perceptual dimension.

Finally, utility functions were obtained for the features "rotational interval", "flow rate" and "new water allocation rule" (i.e. on-demand within some limitations). Three relatively homogeneous clusters were obtained having the same utility function for each feature. Since the clusters relate to spatial patterns, this information can be used to optimize water distribution to command and sub-command areas in the scheme in a way which maximize total utility.

Particularly, a dominant discriminant of clusters is the percentage of vegetable crops in relation to vineyards and the percentage of abandoned land by farm. This aspect of land use can be easily quantified by means of satellite images, which therefore are helpful to design and implement a client-oriented irrigation scheduling. A canal scheduling procedure has been developed which applies these principles (Schakel, 1993; Benjamins, 1994).

7. Management Issues

7.1. COST ESTIMATES OF INDIVIDUAL APPLICATIONS

Aspects of management issues involve first of all analysis of cost estimation of investments for a considered project. Here some costs are given for four applications already mentioned in this article.

Mendoza program (1984-1987). This program included six sub-projects where eleven Argentinian institutions and one Dutch institute have been involved. The project was partly funded from the ordinary budget of the participating institutions and partly by external agencies, both national and international. Twenty people were directly involved. The analysis of investments and running costs of the program indicated that operational costs were a rather small fraction of investments. The total project outlays amounted about US$ 400,000 of which $ 280,000 for investments, $ 14,700 for satellite images and $ 101,600 for services. Out of the service outlays only $ 2000 have been available for actually operational costs, such as data processing, field work (involving 11 test sites), analysis of 200,000 km^2 study area etc. Consequently the output of the entire project was greatly limited by the restricted operational funds.

Costs per hectare. Some of the projects allowed a direct estimation per hectare. The Riyadh project involved a cost per hectare equal to 0.23 ECU.

In India a mission on the use of satellite remote sensing technology evaluated the economic viability of monitoring irrigation performance using a geographic information system/remote sensing software. It turned out that a unit cost will be about 0.03 ECU per hectare per year, assuming that only 100,000 ha are irrigable within an area covered by a single satellite image and that data are of no use outside the command areas (Menenti and Meijerink, 1990). This estimate assumes a 10-year lifetime of equipment and it includes costs of developing and/or adapting specific remote-sensing applications.

In Italy, the identification of the actual crop cultivated area allowed a straightforward comparison between the cost of applying satellite data with the resulting benefit. In this area water fees are assessed according to crop type: rice is the most expensive, fees are due also for spring-summer crops, while no fees should be paid for growing wheat. The here described application would cost 20,000 ECU for a TM quarter image. Since the irrigation water charges amount to some 80 ECU per hectare per year. the identification of only 250 ha erroneously declared would pay the cost of the application.

Impact of the cooperative effort in Mendoza (1984-1993). The cooperative work started in 1984 did result in the establishment of an active users' community, as proven by the publication output (quantity and diversity), newly established cooperative links and additional support received in a variety of forms from state, national and international organizations. At the present stage additional resources (to the normal budgets of institutions) are determinant for the productivity of the community, but not of its continuing existence.

The project-wise funding of the entire operation has been hovering around 50,000 US$ per year, on top of the usual budget of the institutions and of the initial investment to acquire computing resources.

7.2. ECONOMIC BOUNDARY CONDITIONS

A rather simplistic definition of 'remote sensing research environment' will be proposed and the situation of Egypt, India, Argentina and the Netherlands will be compared.

The simplistic view is that a remote-sensing research environment is made up of a dedicated scientist, a small computer, a satellite image and a research institution with some resources to cover operational expenses. The comparison will be based on four indicators defined in Table 2.

7.3. REMOTE SENSING RESEARCH ENVIRONMENT IN EGYPT, INDIA, ARGENTINA AND THE NETHERLANDS

The country-wise comparison has been done on the basis of 1991-values and the results are given in Figure 5. It should be noted that the y-axis scale is logarithmic, which means that in some cases IRE2, IRE3 values differ by 1 or 2 orders of magnitude. For example, the IRE3-value is 15 for Egypt means that the price of a single TM image is equal to the salary that our public sector scientist would receive in 15 years. This compares with an IRE3-value of 0.3 in the Netherlands. It is self-evident that it is much harder to consider a necessity acquiring a TM-image in Egypt than in the Netherlands.

Another interesting result is that the values of all the indicators are rather similar in Argentina and the Netherlands. A note of caution about the IRE3-value for India: the National Remote Sensing Agency (NRSA) sells satellite images acquired in India at a much lower price, close to the royalties paid to the satellite operator. Accordingly the IRE3-value would be close to Netherlands', when using NRSA prices.

TABLE 2. Definition of indicators of research environment in Less Developed Countries (LDC)

Indicators of research environment	Definition	Remarks
IRE1 or Index of dispersion	Wp/Ws	to be applied on a university graduate with 10 years professional experience
IRE2 or Index of accessibility to computing devices	Ppc/Ws	Ws same as in IRE1; reference PC i.e. IBM-AT, its price related to the last five years on basic configuration
IRE3 or Index of accessibility to satellite data	Ptm/Ws	Ws same as in IRE1; price of LANDSAT-TM full scene on CCT according to EOSAT price list; prices applied by NRSA (India) or INPE (Brasil) might also be considered
IRE4 or Index of institutional operability	Bd/B	Bd should include resources allocated to project activities and not to fixed expenditures

Wp = yearly wages in the private sector
Ws = yearly wages in the public sector
Ppc = price of a reference PC
Ptm = price of a LANDSAT-TM scene CCT
Bd = yearly actual non-fixed expenditure for institutional operations
B = yearly budget

8. Conclusions

The linkage between numerical simulation models, remote sensing and geographical information system has been shown to be useful towards the improvement management of irrigation. On this matter we would just add the following statements:

- remote sensing applications in irrigation management should be defined and undertaken on the basis of precisely identified management problems, taking into account the regulations and traditions of local irrigation communities;
- problem tailored land use information obtained with satellite data can solve critical bottle-necks in the enforcement of water allocation rules through performance monitoring.

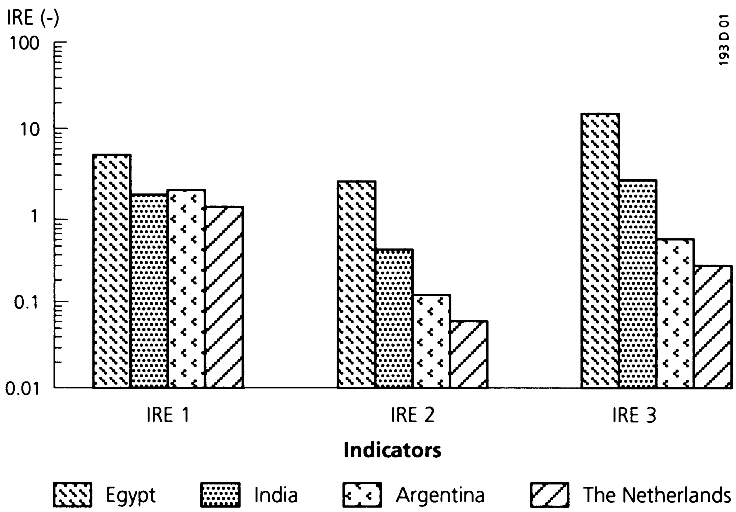

Figure 5. Values of indicators IRE1, IRE2 and IRE3 in Egypt, India, Argen- tina and the Netherlands; values in 1991

9. References

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REGULATION AND CONTROL IN IRRIGATION SYSTEMS

J. GOUSSARD
Irrigation and Water Supply Engineering Adviser
28 rue Gay-Lussac
38100 Grenoble
France

1. Introduction

1.1. SCOPE

The purpose of the present paper is to show how improved control methods for irrigation water delivery systems, especially canal systems, can contribute to better sustainability of irrigated agriculture and of water resources utilization.

In a first part, the control concepts and techniques presently available are reviewed from the angle of operational flexibility and responsiveness to water demand. A second part brings out some research and development tracks that appear especially promising /or necessary. The conclusion lays stress on essential actions to be taken for spreading knowledge and application of efficient control methods.

1.2. REASONS FOR IMPROVING WATER CONTROL

«World-wide irrigation efficiency is estimated to average less than 40 percent, which means the bulk of water diverted for agriculture never benefits a crop. Although some of the "lost water" returns to streams or aquifers, where it can be tapped again, its quality is often degraded as it picks up salts, pesticides and toxic elements from the land» .

We can add to the above quotation from Postel (Postel 1992) that, even if the "lost water" can be re-used, the money spent to capture, divert, store, convey and deliver it has been absolutely wasted.

In fact, especially in canal systems, which largely prevail over pipe systems as explained later, most of water losses and wastes can be due to poor flow control in conveyance systems, resulting in spillage, and to poor control of deliveries, leading to overconsumption.

In addition, many problems related to the sustainability of irrigated agriculture, such as the efficient use of water by the plants, the use of poor-quality water for irrigation,

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 473–491.

soil salinization and waterlogging concerns, prevention of pollution from fertilizers and pesticides, make it necessary to apply improved on-farm irrigation scheduling methods.

This implies that water deliveries at the farm gate be both reliable and flexible in time, duration and flow rate, and consequently that the delivery system should respond to variations in water demand as shortly as possible. Reliability and flexibility of deliveries are also essential for crop diversification and cultivation of high-yield varieties, as may be required to provide a decent income to farmers or to compensate for a reduction of water resources allocation to agriculture.

On the other hand, reliable and equitable service to users is a pre-condition to develop a climate of confidence among farmers, as well as between farmers and irrigation agency, leading to cessation of practices such as misappropriation of water, vandalism, bribing agency's operators. Moreover, such a climate is essential for effective payment of water charges and for the success of other measures beneficial to water management and project economy, such as the organization of water-users associations participating in system management, operation and maintenance (Goussard 1993, Plusquellec *et al.* 1994).

2. General Considerations

2.1. PROPER CONTROL SYSTEM SELECTION (Plusquellec *et al.* 1994)

Whatever the nature, size and location of the project, the design of the control system should be firstly based on a proper definition of the operational goals in terms of anticipated service level. In this phase the following factors should be assessed : total seasonal allocation, frequency, rate, duration, and timeliness of deliveries, flexibility in changing the schedule or in ordering water, reliability of service, consistency of flow-rates during delivery. All above factors must reflect the specific conditions of the project with regard to climate, crops and soil.

Above considerations will lead to the choice of a convenient delivery scheduling method (rotation schedule, central scheduling, arranged schedule, limited-rate demand) and of the delivery control mode (flow-rate or volume).

Next and final step consists in selecting a control method that should be consistent with the above service requirements, feasible with regard to the local socio-economic conditions and the existing infrastructure, as simple as possible and preferably robust, i.e. with some capability of adaptation to changing conditions.

2.2. DISTINCTIVE FEATURES OF CONTROL METHODS

The control methods applicable or currently applied to irrigation systems are very numerous, as resulting from multiple combinations of the following factors:

- degree of responsiveness to demand variations (from nil for proportional control to high for downstream control),
- degree of automation (local or remote manual control, automatic control),
- degree of control centralization (distributed control, centralized control),
- type of control equipment or structures (passive, hand or motor-actuated, self-operating).

2.3. PRESSURE-PIPE SYSTEMS AND CANAL SYSTEMS (GOUSSARD 1993)

The difficulties of achieving responsive, spillage-free operation are quite different for pressure-pipe systems and canal systems.

Owing to their ability to transmit pressure to distant points with virtually no time lag, pipelines can immediately respond to variations in demand at the offtakes ; they have no evaporation or seepage losses, there is no possibility of spillage, at least with closed systems. Water deliveries can be easily measured in volumes, which allows introduction of volumetric water charges, itself a means to incite farmers to optimize their water consumption while leaving them maximum freedom. However, for systems supplied by pumps, which cannot adapt to large flow variations by themselves, overall system responsiveness requires pump automatic control or at least strict operating rules.

With canal systems, the situation is exactly opposite :

- the transient phenomena are very long, and flow variations must be anticipated;
- as flow-rate and depth are inter-related, the regulators, offtakes and turnouts require frequent and tricky adjustments ;
- as available head is low, volumetric measurement is virtually impossible and flow-rate control approximate only.

Nevertheless, due to a comparatively low initial cost, canals are the only solution that can be considered in most developing countries. Anyhow they remain the only water conveyance mode economically practicable for long distances and for flow-rates over some m^3/s.

3. Canal Upstream Control

3.1. DEFINITION

A canal is said under upstream control when the flow entering it through the head structure varies according to water availability or is controlled according to a pre-defined schedule based on anticipated water needs, while the cross regulators, if any, can only distribute the incoming flow or pass all or part of it onto downstream, with no possibility of influencing that incoming flow.

3.2. GENERAL FEATURES (Ankum 1993, Buyalsky *et al.* 1991, Goussard 1992, Goussard 1993, Zimbelman 1987)

In counterpart to simple operation and relatively low investment costs, operational flexibility and responsiveness to variations in actual water demand are basically poor, since you can eliminate neither the time lag between head regulator adjustments and their effect at distant points that may be several ten kilometres away, nor the discrepancies between anticipated water needs and actual water demand. Consequently there is a virtually inescapable mismatch between supply and actual needs, which results either in short deliveries or in water wastes through excess deliveries or spillage, both primarily affecting the tail end of the system.

However, that mismatch can be significantly reduced in using one or several of the following means :

- applying proper operational procedures, possibly with the help of a simplified canal simulation model ;
- applying local automatic control of levels, or centralized control, either manual or automatic ;
- providing the system with intermediate temporary storage capacities in the form of buffer reservoirs or reservoir reaches ;
- remotely monitoring the status of the system, especially at its tail end and at the buffer reservoirs , if any ; establishing a proper water-ordering procedure, or improving the existing one, with special regard to ordering frequency and advance notice time ;
- improving the prediction of water demand through computerized processing of stored, recent or real-time information on crops, weather conditions and/or system status, together with the water orders.

With upstream control, water supply is in the hands of the water authority, which is then in a position to restrict overall water consumption, as necessary in case of short water resources or regular overconsumption.

3.3. FIXED PROPORTIONAL CONTROL

This method, aiming at equitable distribution of an available or pre-defined flow, consists in dividing the flow incoming at each branching point into pre-determined fixed proportions. Widely used in India and Pakistan, it is consistent with rotational scheduling only.

In counterpart to maximum simplicity (no adjustments, no communications required), the system is absolutely rigid and unresponsive. Expected equity seldom is a reality, since there is no way to compensate for changes in physical canal conditions and successive faulty divisions may be cumulative ; there is no way either to adapt to changing cropping patterns. In addition, the wide variations of water depth with the flow-rate make offtake control uneasy and are detrimental to canal bank stability.

For the above drawbacks, the method should be avoided as much as possible, and in any case used only beyond the point from which no other solution is applicable. Some flexibility can be obtained in using adjustable flow-dividers and on-farm storage ponds.

3.4. DISTRIBUTED MODULATED UPSTREAM CONTROL

3.4.1. *General*

With this method, the flow allowed to the canal through a gated head regulator according to anticipated water needs is controlled further downstream by cross regulators distributed over the canal length, and working and operated according to a local target.

Contrary to a still common error, this target should not be a flow-rate, that cannot be easily measured and mastered, but an upstream water depth to be maintained constant, which is simple to achieve and allows proper supply conditions and flow-rate control at nearby upstream offtakes.

Besides the possible improvements related to operational storage capacities and head regulator operation (cf. 3.2 above), the quality and easiness of control vary with the type of cross regulators used, i.e. depending upon whether upstream water levels are controlled by fixed or adjustable weirs, manually-operated or automatic gates.

3.4.2. *Distinctive Features Related to Cross Regulator Type*

Fixed weirs. Long-crested weirs (transverse, diagonal or duckbill type) are the simplest, however very efficient means to maintain upstream levels nearly constant over a wide range of flow-rates.

To restrict the crest length required for a specified maximum variation of the upstream level, the weir can be combined in parallel with undershot gates to be operated for large flow changes only. A gate should also be installed at the lower point of the structure to flush away silt deposits.

Stop-Logs and Manually-Operated Overshot Gates. The hydraulic features of stackable stop-logs and movable weirs such as Rominj gates and drop-leaf gates are similar to those of fixed weirs, but with the facility of crest elevation adjustment, which can be used to vary the target level or to minimize upstream level variations.

When applied to upstream level control, overshot gates require less frequent adjustments than undershot gates but, unless the available differential head is more than half the upstream depth, they require wider openings for the same flow capacity.

Manually Operated Undershot Gates. Hand or motor-actuated plane-leaf gates, generally of sliding type, are extensively used as regulators all over the world for their simple design and construction. Radial gates are slightly less simple, they require longer receiving structures but much smaller operating forces.

The frequency of adjustments as well as the flow capacity required for the gates proper can be greatly reduced in passing a part of the incoming flow over wing weirs working in parallel with the gates.

Automated Motor-Actuated Gates. Automation of conventional gates through local electric or electronic automatic controllers linked to level and gate-position sensors is an attractive way to modernize existing manually-operated systems by eliminating the hazards of human operation.

However, the following requirements must be considered prior to applying this type of automation :

- reliable power supply must be made available at every regulator, which may be very costly ;
- the control hardware must be consistent not only with the very severe conditions proper to any irrigation project, but also with the technical level of the operation-and-maintenance personnel and the local availability of spare parts ;
- the control software should be designed with special regard to stability and robustness of control ;
- operator interfaces should be specially user-friendly, i.e. not requiring a specialist in programming for routine adjustments of the control parameters.

In addition, measures should be taken to detect and remedy any operation failure (monitoring and alarm system, emergency remote control and hand operation).

For the above reasons, local electric automation has been applied mostly in developed countries.

Automatic Self-Operating Gates. Self-operating constant-upstream-level gates generally are radial gates either linked to a buoyant counterweight moving in a controlled-leak side well supplied from upstream, or, more often as simpler, integrating an upstream float and counterweights.

Such gates are very sturdy and reliable, they require no power supply and only infrequent mechanical maintenance. In counterpart the initial overall cost may be higher than with electric automation, depending upon the availability of reliable power supply. Though generally lesser than for electric automation, level control accuracy is quite acceptable. For gates with integrated floats, the target depth can be adjusted only within centimetres, which requires a cautious determination of the longitudinal water profiles at the canal design stage and a careful on-site height-setting of the gates.

Constant-upstream-level gates with integrated floats have been successfully applied to a number of project all over the world for decades, especially in West and South Europe, North Africa and Middle East.

3.5. SCHEDULED CENTRALIZED UPSTREAM CONTROL

In this method, the regulators are remotely controlled from a master station. Operating orders are generated on a daily basis by a computer processing the water orders, to be received with 1-2 days advance notice, and data on the actual status of the canal, provided by a remote monitoring system. The computer software includes a complete mathematical model of the canal, or simpler equivalent transfer functions, plus a control algorithm depending upon the control logic applied, i.e. the conditions to be met by volumes and/or levels in each canal pool. Orders are transmitted manually or automatically for implementation to remote terminal units (RTUs) located in the vicinity of the regulators and directly controlling them.

In addition to RTUs, the method requires a comprehensive monitoring and communication system, together with a well-trained operation-and-maintenance staff. The reliability of the whole control system essentially depends upon the reliability of the communication system. The advantage over distributed automatic control is that regulators are moved simultaneously or in a co-ordinated way, which considerably reduces the response time of the canal.

Scheduled centralized upstream control is specially suitable, technically and economically, for large and long feeder or conveyance canals, as shown by its main typical applications, all located in the Western U.S.A. (e.g. California Aqueduct and Central Arizona Project).

4. Canal Downstream Control

4.1. DEFINITION

Downstream control consists in operating the head and cross regulators so that each canal pool and the canal as a whole be continuously in a position to immediately and fully answer any change in downstream and lateral water demand.

4.2. GENERAL FEATURES (Ankum 1993, Buyalsky *et al.* 1991, Goussard 1992, Goussard 1993, Plusquellec *et al.* 1994, Zimbelman 1987)

Downstream control requires a real-time closed-loop automatic process to ensure immediate and adequate reaction of the regulators to demand changes and, as far as possible, some temporary storage capacity in each pool to compensate for the inescapable time lag between regulator action and effective correction at a point that may be distant.

Flexibility and responsiveness are thus obtained without almost no need of communication between the successive levels of operators and users. As responsiveness is however limited by the maximum flow capacity of the canal, the design of each canal section should be based on a proper estimate of the most probable maximum demand from the adjacent laterals and downstream section, which itself depends upon the control method applied to the next lower level of the system.

Except for a special configuration of the main canal (see 4.4 below), the implementation of the most flexible and responsive delivery scheduling, i.e. in practice limited-demand deliveries, requires that downstream control be applied from the system head to the farm turnouts. When this is not feasible for cost reasons or else not desirable with regard to farmers' behavior and/or limited water resources, as is often the case, a good compromise between operational flexibility and mastery of consumption consists in combining downstream control of main and possibly secondary canals with upstream control of lower-level canals.

The concept of downstream control covers various logics and techniques. The respective distinctive features and application fields of the main ones are set out hereafter.

4.3. DISTINCTIVE FEATURES OF THE MAIN DOWNSTREAM CONTROL METHODS

4.3.1. *Distributed Downstream Control for Level-Top Canals*

This method, also called close downstream control, consists in maintaining a constant water depth just downstream from the head regulator and each cross regulator. The water profile in each pool pivots about the constant-depth point at the upstream end, providing a substantial operational storage volume between the sloping water line at maximum flow and the horizontal one at zero flow.

The regulator gates can be either conventional gates with automatic controllers or automatic float-operated gates, with the same respective advantages and disadvantages as those of similar gate types used for upstream level control.

The only drawback of the method is the necessity of level bank tops, which in practice restricts its application to canals with a longitudinal lope of maximum 20 to 30 cm/km for construction cost reason

Close downstream control has been widely applied in France, North Africa and West Africa, and to a lesser extent in various countries, e.g. in the U.S.A. and Indonesia.

4.3.2. *Distributed Downstream Control for Sloping Canals*

Distant downstream control methods have been developed to apply the concept of downstream control to sloping canals, especially existing canals previously under upstream control, without raising the canal banks while keeping the simplicity of distributed control. Such methods consists in controlling the water profile in each canal pool by the regulator located at its upstream end so that either the water depth at its downstream end or the water volume within the pool be maintained nearly constant, while answering water demand at the best.

With the first option, as operational storage capacity in the reach is virtually nil, control software designers come up against the difficulties of reconciling the conflicting requirements of quick response, accuracy and stability ; buffer reservoirs, if feasible, can only make control easier.

The problem is not so critical for constant-volume control, but the canal bank tops must be level over the downstream half of the pool.

In fact the matter of distributed downstream control for sloping canals is still in the development phase. To our knowledge, the only operational on-field applications are the Corning Canal in the U.S.A. (constant-level control, ELFLO + reset type) and the Sahel Canal in Mali (constant-volume control, BIVAL type) ; other control algorithms are being tested on either canal simulation models, physical scale models (Cal-Poly, U.S.A., CARDD type) or real canal (Canal de Provence, France, PIR type).

4.3.3. *Real-Time Centralized Control*

The principle of the method consists in using a centralized real-time computerized process to maintain the water levels and/or volumes over the system in such a dynamic status that any expected or unexpected variation in demand , and even any unforeseen event, could be immediately and satisfactorily answered. The process includes the following tasks :

- virtually continuous data collection and data transmission to the master station for monitoring, control and storage purposes ;
- recurring data processing (from every 10 minutes to every few hours) generating control instructions ;
- immediate transmission and implementation of the above instructions.

To minimize operational storage volumes and level variations, the system is operated with some anticipation of the future changes. Finally the process is a combination of an open-loop control based on anticipated water demand and real time data, very similar to centralized scheduled control, and of a closed-loop control correcting the deviation of the actual status from the target status in real time.

The method can be applied to complex systems including not only canals, but also rivers, reservoirs, pipelines, pumping stations, hydraulic power plants. Full automation and centralization result in minimum constraints on the operating staff : even large and complex systems can be managed by only one operator whose tasks are limited to supervision, checks and, as the case may be, emergency manual remote control.

In counterpart, for cost and reliability reasons, it should reasonably be applied only to large, long and/or complex systems, and only where the conditions for proper management, operation and maintenance of the highly sophisticated hardware and software required can be met.

The leaders in development and application of centralized real-time control are the Société du Canal de Provence (Provence Canal in France and Rocade Canal in

Morocco), and the Compagnie d'Aménagement des Coteaux de Gascogne (Neste System in France).

4.4. COMBINED UPSTREAM AND DOWNSTREAM CONTROLS

The method consists in applying upstream control to the upstream section of the canal and downstream control to its downstream section. The control hardware and software for each section are respectively the same as for pure upstream and downstream controls, but a buffer reservoir or reservoir reaches must be provided at the shifting point to compensate for the mismatch between supply, controlled from upstream according to anticipated demand or to a schedule inconsistent with irrigation, and actual demand from the downstream section.

The system is less expensive than if totally under downstream control, while flexibility and responsiveness are nearly the same, at least for the downstream section.

Related-levels control , i.e. co-ordinated "breathing" of successive reservoir reaches can be achieved through automated conventional gates, or float-operated gates known as mixed gates.

Combined control is specially suitable for canals with an initial steep-slope section followed by a low-gradient section, as also for canals where inflows cannot be modulated in consistency with demand (e.g. supply from an hydraulic power plant, or from a pumping station operating with large discharge steps or preferably using off-peak power).

Typical applications of combined control are the Friant-Kern Canal in the U.S.A. and the Doukkala Canal in Morocco, both with buffer reservoirs, the Kirkuk-Adhaim Canal in Iraq and the Bas-Rhône Canal in France, these last with reservoir reaches and related-levels control.

5. Control of Pressure-Pipe Systems

5.1. GENERAL

As previously explained, a closed gravity pipeline is responsive by nature. However, to reduce the pipe pressure rating of the lower parts as well as the pressure variations resulting from flow-rate variations, it is often necessary to divide the line into several sections linked by valves or structures controlling the pressure in the adjacent downstream or upstream section.

On the other hand, pumps with manual on/off control are not much responsive to demand variations, whereas a simple pipe has no operational storage capacity. Therefore responsive operation of a collective pumped irrigation system requires installation of a buffer tank or reservoir and/or automation of the pump control.

5.2. PUMPS DIRECTLY SUPPLYING A CLOSED PIPE SYSTEM (Coite 1992)

5.2.1. *Control Principle*

Pumping station control is based on a proper gradation of pump sizes so as to minimize the mismatch between water demand and pumping capacity, and on the relationship linking together the discharge, output pressure and speed of each pump.

It consists in maintaining the operating point of each pump within discharge and pressure limits consistent with pump efficiency and cavitation risks. This can be achieved in starting and stopping the pumps according to pre-defined criteria, or re-circulating a part of the discharge, or else varying the speed of one or several pumps.

These methods are briefly reviewed hereafter, in an order of increasing efficiency and sophistication. It can be considered that the most simple ones are all the more suitable since the operation-and-maintenance personnel is less skilled, the discharge capacity lower, the total yearly operating time shorter, the variations of flow-rates smaller and more progressive, and the surrounding conditions more severe.

5.2.2. Various Methods

Semimanual Control. It consists in letting the output pressure freely vary with the discharge within pre-defined limits. As a rule, pumps starts are manual, at least for the first unit, and stops are automatic (relays connected to a pressure sensor or a flowmeter).

If the pipeline pressure must be kept within narrow limits, this control mode can be associated with constant-downstream-pressure control through an in-line automatic throttling valve.

Control by Recirculation. It consists in by-passing a part of the overall discharge from the output side back to the suction side, using a valve automatically controlled according to pressure, flow-rate, or both.

This method allows very large variations in demand with a single pump or a few large identical units, but much energy is wasted and cavitation problems may be critical for the by-pass valve.

Automatic Control with a Pressure Tank. The unceasing starts and stops occurring with semimanual control for wide and frequent variations in demand can be avoided in installing between the pumps and the pipeline a pressure tank acting as a buffer capacity. Such a tank is also useful for anti-surge protection and pressure-sustaining in case of short-duration power outage.

As a rule, control is based on pressure thresholds. However, to minimize the large tank volume required (often several ten m^3), which increases with the average discharge of the pumps under control and the minimum allowable time interval between pump stop and re-start, it is advantageous to install small "jockey" units delivering 15% to 40% of the discharge of the larger units, which are then controlled according to pressure thresholds.

Automatic control of this type is generally achieved through a programmable controller connected to a pressure sensor and a flowmeter.

Control through Variable-Speed Units. As compared to sequencing several constant-speed units with incremental discharge steps, the use of variable-speed units allows continuous, more accurate matching between pump output and water demand.

Variable-speed control has become feasible at a reasonable cost owing to the development of electronic power equipment. The electronic variator is connected to an automatic controller programmed to maintain the output pressure constant or else to relate it to the flow-rate according to a pre-defined equation (e.g. pressure proportional to squared flow-rate).

The method can be combined with recirculation or jockey units to prevent variable-speed units from working at too low a discharge (for pumps) or too low a speed (for motors). Though not necessary in theory, a pressure tank, then of low capacity, is still recommended for anti-surge protection and emergency constant-speed operation.

5.3. CONTROL OF GRAVITY PIPE SYSTEMS (Goussard 1992, Zimbelman 1987)

5.3.1. *Closed and Semiclosed Systems*

Maintaining the responsiveness of a closed pipeline in spite of its division into sections can be easily achieved in installing at each junction point some device automatically keeping the pressure close downstream at a constant or nearly constant value.

A first option consists in using pressure-reducing valves, either self-operating or motor-actuated under local or centralized automatic control. The main drawback of the solution is the inescapable leakage in zero-demand conditions which will cause the pressure to rise up to the upstream static head. Overpressure can be avoided in installing pressure-relief valves. But, in addition to the resulting spillage, prolonged leakage of pressure reducers and prolonged working of relief valves are not recommended for cavitation risks.

A better and safer option is the semiclosed system, in which the tail end of each section is fitted with an automatic valve discharging in a free-surface tank at the head of the following pipe section, and maintaining its water level within limits. The automatic valves can be motor-actuated or float-operated. The intermediate tanks must be carefully sized to avoid emptying and overflowing upon respectively sudden call and sudden cut-off of maximum flow. The semiclosed design can be applied to high-pressure mains as well as to low-pressure tertiary systems, possibly supplied from a canal.

5.3.2. *Open Systems*
In open systems, the pressure in the pipe section upstream from a junction point is controlled from this point by an overflow-baffle set within a standpipe open to the atmosphere. Such systems are very similar to canals under upstream control with fixed weirs. Their poor flexibility can be improved in using re-regulating reservoirs. They are subject to surges and flow instability caused by trapped air.

As the height of overflow-stands is necessarily limited, the method is suitable only for low-pressure and low-gradient pipelines. In practice it has been mostly applied to tertiary systems supplied from canals and used for surface irrigation, e.g. in North Africa and the U.S.A..

5.4. GRAVITY PIPE SYSTEM SUPPLIED FROM PUMPS THROUGH A RESERVOIR

Such a system consists of a pumping station lifting water to a surelevated reservoir or tank, which itself supplies a gravity pipe system, generally closed or semiclosed type.

The operational reserve formed by the storage capacity of the reservoir or tank greatly contributes to overall system flexibility and responsiveness, especially in easing pump control. In practice, pumps can often be manually controlled according to anticipated demand and possibly using remote monitoring of reservoir storage status. A second option, leading to maximum responsiveness, is to automatically control sequential starts and stops of the pumps according to reservoir status.

6. Flow-Rate Control at Turnouts and Outlets

6.1. CANAL TURNOUTS (Goussard 1992, Goussard 1993, Plusquellec *et al.* 1994)

When considering the difficulties of flow-rate measurement in open channels, it is clear that control of farm turnouts and of offtakes supplying sub-systems under upstream control should be based on a constant, adjustable flow-rate. Three functions should then be performed : (1) on/off, (2) flow-rate adjustment and control, i.e. setting and maintaining the flow-rate at the desired constant value, and (3) flow-rate measurement (Plusquellec *et al.* 1994).

When the range of upstream water level variations do not exceed 20% of the average available head, a simple undershot gate properly calibrated is perfectly suitable for all three functions, since the flow-rate corresponding to a fixed setting will not vary by more than ± 5%. For slow or infrequent larger level variations, flow-rate measurement and adjustment are still feasible with an acceptable accuracy (± 7%), but require the reading of level scales and the use of a chart or table. Control methods based on two gates (so-called "constant-head orifice offtakes") or a movable weir, though often used, are too much sensitive to level variations and must consequently be avoided.

In practice, the only control device that is nearly insensitive to wide head variations is the baffle distributor, or module, which delivers a nearly constant flow (typical accuracy of ± 5%), adjustable by steps, in spite of substantial variations of the upstream level, however within specified limits. Where upstream level variations exceed this permissible range, constant-flow control can be achieved by a constant-downstream-level gate followed by either calibrated gates or modules.

6.2. PIPE OUTLETS

In high pressure systems, which supply water for pressure irrigation, small diameters allow volumetric measurement of deliveries through propeller meters. A typical farm outlet equipment then includes a valve, possibly a pressure reducer, a discharge limitor and a propeller meter.

For low-pressure systems, which supply water for surface irrigation, the problem is similar to that of free-surface turnouts, but no satisfactory solution has been found yet. The discharge can be roughly estimated from the assessed head and the number of opening turns of the outlet valve (gate valve, alfalfa valve), but it may widely vary with the location of the outlet along the line and the overall water demand. Prototypes of head-insensitive outlet valves have been developed and even successfully tested, but too high a cost has impeded any significant on-field application until now (Goussard 1992).

7. Research and Development Prospects

When considering the wide range of concepts and equipment that have been developed to improve technical and economical performances of irrigation projects, it may be thought that the matter has been exhausted. In reality, besides the fact that available techniques are not currently applied on a global basis for ignorance, misunderstanding or conservatism, it is still necessary to improve existing hardware and software and to fill gaps that still remain, using advanced concepts and tools where appropriate.

7.1. USE OF SIMULATION MODELS

Until recently, simulation models of canals in steady and unsteady conditions have been mostly used for hydraulic design. Now, with the development of versatile, user-friendly programs that can be run on micro-computers, simulation is about to become a common tool for improving canal operation through three different ways (Cemagref 1992).

7.1.1. *Improvement of Control Strategy*

Simulation of operation of an existing canal in normal and critical conditions allows deeper knowledge of the system behaviour and, through a test-and trial process, selection of an appropriate control strategy. On the other hand, true "operation simulators" that would be used to train operators on everyday operation of complex manual systems and emergency manual control of centralized automated systems are currently under development (SCP 1991).

However, adapting and calibrating a model to an existing system remain a very time-demanding task, hence the need for developing still more versatile models and some simpler and quicker standard calibration procedures.

7.1.2. *Integration in Control Process*

Canal mathematical models are an essential component of the software of modern centralized control. Complete models can be used in the open-loop control methods (scheduled centralized control), but not in the closed-loop real-time methods, because of the short recurrence period of the process. In this case, simplified models in the form of linear transfer functions must be used ; however, at the design stage, a complete model is required to define, adjust and test such transfer functions.

7.1.3. *Development of New Controllers*

A number of new control algorithms and controllers have been recently developed or are currently under development, especially for distributed downstream control of sloping canals (Cemagref 1992, Rousset and Baume 1992, SCP 1991).

A simulation model is required at three stages of the development :

- identification of the transfer functions representing the canal behaviour ;
- determination and refinement of the transfer functions and control algorithm to be included in the software ;
- prototype operation tests in simulated conditions.

Such operation tests can also be useful to compare the performances of various controllers placed in similar conditions.

7.2. APPLICATION OF AUTOMATION THEORY AND TECHNIQUES

7.2.1. *General*

The credit of the recent or on-going developments in this field is due to hydraulic engineers who have realized that automation theory and tools, which have been developed in industry and aeronautics for several decades, might well bring satisfactory solutions to arduous problems they were facing.

Benefits expected from this approach are :

- optimization of operational performances
- rationalization and optimization of on-field adjustments of controllers, replacing the current empirical practices by an analysis of measures ;
- developing more efficient solutions for the control of complex systems.
  Some examples are briefly presented hereafter.

7.2.2. *Regulation through Pole Placement*

An important step in the design of a modern controller is the definition of such a transfer function that the target value of the controlled variable be reached with enough accuracy and stability.

Such conditions for accuracy and stability can be expressed by conditions to be met by the poles of the overall transfer function (i.e. the roots of its denominator). With the classical approach, the form of the controller transfer function is firstly chosen, and its parameters are then adjusted so that the above conditions be met. The pole-placement method consists in firstly choosing proper values for the poles and then deriving the controller transfer function (Cemagref 1992, SCP 1991).

The method is specially suitable wherever delayed effects of control are to be considered, a problem that cannot be satisfactorily answered by classical controllers.

7.2.3. *Optimal Control*

Optimal control aims at minimizing a criterion that may be complex. For the purpose, the dynamic behavior of the system is represented by two matrix equations :

- a status equation expressing the future status of the system in terms of the present status vector, control vector and disturbance vector ;
- an output equation expressing the present output vector in the same terms as above.

The matrix representation makes it possible to deal with systems where the control, output and disturbance include several components.

Starting from an initial pre-defined status, optimal control design consists in finding a sequence of control vectors minimizing the selected criterion, which is generally expressed in terms of quadratic deviations of the output and control vectors. Mathematical derivation of the condition results in a series of matrices representing the control (Cemagref 1992).

The interest of optimal control lays on one hand in the concept itself, i.e. minimizing a multi-parameter criterion, on the other hand in the ability to master systems with multiple inputs and outputs.

7.2.4. *P.I.R. Control*

P.I.R. control (from the French "Proportionnel, Intégral et Retard", i.e. "Proportional, Integral and Delay") aims at eliminating instability resulting from the time lag between regulator action and its effect at a distant point. It uses a "Smith predictor", i.e. a transfer function allowing calculation of the anticipated future effects of regulator action.

In a classical feedback controller, corrective action is calculated from the instant deviation of the variable from the set point. In a P.I.R. controller, corrective action is based on the deviation of the anticipated future value from the set point, corrected by the difference between actual instant value and simulated instant value integrating the modelled delayed effects of past actions.

Such a controller type has been recently developed by the Société du Canal de Provence, France, and is currently under on-field testing (Cemagref 1992, Rousset and Baume 1992, SCP 1991).

7.2.5. *Use of Decouplers*

The purpose of the decoupling technique is to avoid instability that may be caused by dynamic interactions between automatic regulators in series.

For example, in the case of distant downstream control through two regulators in series, decoupling will consist in operating a regulator not only according to the deviation of the level it controls, but also so as to compensate for the expected effects of the reaction of the other regulator to this action. Decoupling can be partial (additional signal to the next upstream or downstream regulator) or complete (additional signals in both directions).

The method has not yet be used on the field, but it has been successfully applied to stabilize distant downstream level control (EL FLO type) on a test scale model canal in Cal-Poly, CA, U.S.A. (Cemagref ed. 1992).

7.3. HARDWARE DEVELOPMENT AND IMPROVEMENT

7.3.1. *Local Controller Hardware*

Local controllers used up to now are of four types : do-it-yourself devices, small personal computers, programmable controllers designed for industry, multitask units specially developed for water applications. The first ones are not marketable, the second ones must be protected from the severe conditions encountered on most irrigation schemes, the two last ones are often too much powerful, complicated or costly for extensive application to distributed automation.

Consequently, it appears desirable that specialists in control software design, in electronic hardware manufacturing and in irrigation engineering meet together in order to define technical specifications for a local microprocessor-based controller that would be compact, sturdy, user-friendly and of a reasonable cost, and could be programmed with both classical and newly developed control algorithms, especially those suitable for distributed downstream control of sloping canals.

7.3.2. *Distant Level Control through Float-Operated Gates*

In areas where power supply is not available or reliable, downstream control can be achieved only through float-operated gates with level-top canals, which may be unfeasible for cost reasons. However, it should be possible to use float-operated gates, either existing types to be adapted, or new types to be developed, for downstream control of sloping canal in governing their hydro-mechanical operation according to inputs from remote points through a low-power control system with battery back-up.

We can only incite irrigation engineering companies, gate manufacturers and controller designers to go more deeply into this idea.

7.3.3. *Constant-Discharge Outlet Valves*
As mentioned under 6.2, some prototypes have been developed, but no significant on-field application has been made, mainly for cost reasons. Manufacturers of irrigation valves should be urged to turn such prototypes into standard pieces of equipment, readily available on-the-shelf at an attractive cost.

8. Conclusions

When considering the large variety of concepts, methods and equipment available for proper control of irrigation systems, one can only wonder why low project efficiencies, deceiving performances, negative environmental effects, premature failures, rigid scheduling and unreliable water deliveries are still common.

In fact, besides administrative and financial constraints, the main cause for the slow progress of improvements in this field is a lack of knowledge and understanding of available techniques, combined with an ill-founded, though natural, resistance to changes, especially in countries where irrigation has been practised for decades if not for centuries. It should be also noted that engineering of irrigation systems is generally left to civil engineers only, whereas proper design also requires inputs from specialists in hydraulics, on-farm irrigation, agronomy, social sciences, environment and, as the case may be, automation. Such multidisciplinary teams are not easy to set up everywhere.

It is then essential that all people who are conscious of the necessity of efficient water control in irrigation systems, and who detain and master some pieces of the relevant know-how, do their utmost to initiate, develop, participate in, or support any action aiming at disseminating knowledge, improving education and training at all levels, from the University to the field, transferring technology, inciting decision makers to changes, involving the farmers in the decision process and, as the case may be, revising abnormally constraining administrative or financial rules.

Such actions are a must to win the challenge for sustainability of water resources and irrigated agriculture in spite of an increasing competition for water and a lack of new land.

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REMOTE CONTROL AND MANAGEMENT OF IRRIGATION DELIVERY SYSTEMS

P. KOSUTH
Cemagref, Irrigation Division
361 rue J.F. Breton
B.P. 5095
34033 Montpellier Cedex 1, France

1. Introduction and Basic Considerations on Irrigation Delivery Systems

The main purpose of an irrigation system is to deliver water to users in a viable, appropriate and reliable way.

Besides social, economical and managerial organisation aspects, technical skills still play a key role in ensuring the long term functioning of the system: a correct initial design, an efficient operation and a regular maintenance. Experience and literature show that there is a close interrelation between design, operation and maintenance.

The aim of this paper is to analyse the complexity of irrigation canals operation process, to present the tools that already are operational and to draw possible lines for future improvements in this matter.

2. When Poor Operation of Irrigation Canal Networks Endangers the System Sustainability

Various examples can illustrate the fact that poor operation induces poor performances and in some cases endangers system sustainability.

Simplified operation modes limit the economical performance and the financial return of the system. Rigid operation modes (for example rotational distribution), though easier from the manager point of view, have poor results on farmers practice. They induce both water losses and risks of waterlogging when water is not needed by crops, and damageable constraints on farmers if they want to grow sensitive crops (as vegetables).

Case: (Baume et al. 1992, IIMI 1989, Kosuth and Rey 1992, Rey et al. 1993)

Kirindi Oya Irrigation System in southern Sri Lanka illustrates this situation. The right bank main canal is 30 km long with a head dischargre of 10 m3/s and a

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cropping area of 3300 ha mainly with paddy rice. Operation is led through 18 gated regulators and 42 gated offtakes. Delivery is organized on the base of an imposed schedule with occasional adjustments. Rigid operation of the canal and limitations in available water resource hardly allow to reach a cropping intensity higher than 100% (versus a 150% forecast at the design stage) on paddy cultivation. At the same time efforts towards crop diversification, as an alternative to paddy, are made impossible by the low flexibility of delivery. There is no way but a change in the operation mode.

Vulnerability of operation to external perturbations (fluctuations in head flow, unauthorized water offtakes,...) **decreases the reliability of water delivery, inducing security behaviours** at each actor's level: farmers ask for more water than they really need to minimize the impact of a potential failure of the delivery, canal operators use security coefficients when transmitting farmers' demand to the manager's level in order to limit potential complaints,... This leads to water loss and poor benefits from of the resource.

Case: (De Leon Mojarro et al. 1986, Kosuth and Rey 1992)

La Begonia Irrigation System in Mexico (State of Guanahuato) is a 8000 ha system with diversified crops: alfalfa, wheat, corn, onions, tomatoes, fruit trees,... The main canal is 35 km long with a maximum capacity of 12 m3/s, 35 gated regulators and 120 offtake gates. The command area is divided in 8 sections each being operated by a "canalero". Water delivery is organized on the base of farmers' demand: farmers have to go to the main office before Friday evening if they want water for the next week; they declare the plots they want to irrigate and pay for the irrigation in relation with the plots area. A flow pattern in the canal is then decided by the manager for the next week, with a constant head flow and constant flows at the limits between sections. Water delivery within each section is then programmed by the corresponding canalero, respecting imposed input and output flows of the section. The canalero then indicates to each farmer the day and time when he will get water, and operates the various gates to achieve his delivery plan.

Various perturbations affect the canal functioning, the more noticeable one being daily fluctuations in the head flow of the canal due to water extractions in the river by irrigating farmers between the dam and the canal head structure. These fluctuations affect water flows and levels in the canal. Arguing on the poor reliability of water flow, farmers ask for prolongation of their irrigation period, thus delaying the whole irrigation schedule. In order to face this misorganization and lack of reliability, farmers tend to use tubewell water increasing the pressure on the aquifer that is already overexploited with a water level drop close to 3 m/year.

At this point a better operation of the canal and counterreaction to perturbations is the only way to keep control of the whole system.

The **ability to adapt the operation mode to changing context and targets** is a key for sustainability of a system. During the life of an irrigation system operation mode has to evolve from initial design constraints (ex. high flows and velocities to prevent siltation) to new constraints and targets (ex. limitation of the flows to limit waterlogging).

Case: (Bandaragoda and Badruddin 1992, Bhutta and Kijne 1992, Kosuth and Rey 1992).

The last example, taken in Pakistan, is an illustration of the link between design, operation and maintenance.To face siltation risk and minimize maintenance costs, design of irrigation canals in Pakistan aimed at maintaining high velocities using constant high flows. One indirect (maybe should we say direct) effect was large amounts of water entering the plots and causing water logging, water table rise and salinization. Deficiencies in canal operation and maintenance lead to paralysis of the canal network external fringe thus penalizing irrigation efficiency when not decreasing the total irrigated area.

Nowadays a new challenge is to limit water flows in canals to spare water for downstream Indus. Operation has to find an equilibrium point and procedure between high flows to prevent siltation and low flows to spare water, in the limit of constraints imposed by design

These three examples enlighten how operation can be a decisive node in the overall irrigation system sustainability.

3. The Complexity of Irrigation Canals

One should not underestimate the fact that irrigation water delivery systems, mainly irrigation canals, are complex physical systems thus making difficult to elaborate (and even more difficult to implement) an accurate operation strategy.

The complexity of irrigation canals is due to several characteristics:

- their **size and spatial extent** ranging from tens to hundreds of kilometers. On large scale systems the whole canal network can reach more than one thousand kilometers. The size makes it very difficult for a manager to have an overall perception of his system. It can even make it difficult for an operator to know what his neighbour has been doing.
- their **time-dependent behaviour**. The first aspect of this dynamic behaviour is the varying time delay between an upstream operation and the corresponding answer in different locations of the system. Another aspect of this dynamic behaviour, often underestimated, is the fact that transient flow takes place most of the time, leaving only short periods for steady flow. As an illustration, measurements made by IIMI on Kirindy Oya Right Bank Main Canal (Sri Lanka) during 1991/1992 on a 19 weeks' period showed that steady flow periods accounted for less than 20% of the time. Nonetheless, most part of operation rules are generally elaborated under a steady flow hypothesis.
- the **multiple local operations and their interactions**. Gates along the irrigation canal network are operated more or less simultaneously and generally

independently by various operators, thus inducing downstream and even upstream (though with less intensity) interactions that can lead to reinforced fluctuations in water levels and flows.

- the **variety of perturbations** ranging from external perturbations (rain, fluctuations in head flow,...) to internal perturbations (unauthorized gate movement, deficient local operation, ...).
- the **variety of operational targets**. This variety of targets generates additional complexity: equity, flexibility, security of ditribution, siltation prevention,... and requires additional rules.

This complexity is generally responsible for either poor operation with water level fluctuations, unreliable deliveries and subsequent security behaviours by users that ask for more water than needed in case they would not be satisfied, or rigid operation with a minimum number of gate movements and water delivered according to an imposed water delivery schedule, even when not needed by farmers.

Any improvement in the canal operation requires on one hand an overall perception of the system and understanding of its behaviour, and on the other hand some tools to analyse the efficiency of the operation rules, quantify their impact on the system behaviour and test improved sets of rules.

We will present briefly three types of tools that proved to bring substantial advance in canal operation: data bases, simulation models and automatic control.

4. Data Bases and Management Information Systems

The first priority when facing a complex problem is not necessarily to introduce complex and sophisticated tools. It is first to get a better understanding of the problem.

In the case of irrigation canals, poor operation is often linked to poor monitoring and poor (if existing) data analysis before decisions. A lot of irrigation systems were planned and designed to be managed and operated with regular measurements, sometimes with a measurement staff, and then evolved progressively dropping measurement, due to costs and implicitly admitted unusefullness. Decisions are taken with a very limited information, the main criteria of intervention often being complaints from users.

On such systems the general feeling is "we have a good operation efficiency" untill external changes (changes in price of water, shortage of water,...) put in light the management and operation deficiencies.

Hence introducing, implementing and sustaining a management information system can have an important impact on water delivery efficiency. Its success will depend on various factors as: managers' and operators' motivation, simplicity of data collection and transmission process, closed loop between collected data, its analysis by the manager and corresponding modification of operation. These three aspects are clearly interwoven.

IIMI, using IMIS (Kosuth and Rey 1992, Rey et al. 1993), FAO, using CIMIS (FAO 1993), Hydraulic Research Wallingford, using INCA (FAO 1993) and others have experience in introducing Management Information Systems.

The following aspects are underlined by Rey et al. (1993) in the experiment led by IIMI in Kirindi Oya (Sri Lanka):

- the diagnosis preceding introduction of the Management Information System focussed on three main questions:
  - are management decisions based on reality ?
  - are management decisions based on performance analysis ?
  - is the logic of management technically apropriate ?
- analysis of the answer with the manager led to the organization of a data collection system and communication network (all by manual intervention);
- hydraulic data (water levels and gate opening at each structure) are recorded twice a day by gate keepers, summarized in a standard format and handed over on the same day to the manager; these data are converted into discharges, stored in a computerized database (IMIS) and displayed in the manager's office on a board;
- this board together with measured and targeted discharges, cumulative volumes delivered at each offtakes,... focuses the attention of the manager, stimulating timely control of deliveries.

The first part of this management support intervention was implemented during 1991/1992 wet season in Kirindi Oya. As a result, water distribution at the offtakes was roughly looked into by the manager on a daily basis. A significant reduction of consumption was observed during the season (0.2 m), and field staff showed an increased accountability, linked with the greater responsiveness of the manager to the measured field conditions.

In addition the collected data offered an increased source of knowledge on the canal hydraulic functioning.

Complementary long-run experiments are needed to assess the viability and the influence of Management Information Systems on water delivery efficiency, and to give guidelines on the way to introduce them in the management process.

5. Use of Simulation Models to Analyse the Operation of Irrigation Canals.

5.1. WHAT CAN YOU DO WITH (OR ASK TO) A SIMULATION MODEL ?

Simulation tools offer new ways to analyse and understand the functioning of canals and the impact of operation rules, due to the fact that they facilitate a comprehensive time and space representation of the dynamic.

In fact mathematical models for open channels flows have been developped since the 1960s, mainly for research and for design purposes. They were used by skilled engineers on specific hardware.

The main evolutions that have led to present tools (ASCE 1993, *Cemagref* 1992) are:

- evolution of computers that allow widespread diffusion of the tools
- development of user-friendly interfaces
- development of tools specific to irrigation canals and their particulars (offtakes, control structures, operations,...)
- development of methodologies to address specific operational problems

5.2. THEORITICAL BASES (*Cemagref* 1992, Chow 1988, Mahmood and Yevjevitch 1975, Miller and Yevjevitch 1975)

An irrigation canal is a succession (or a network) of reaches, offtake structures (gates) and control structures (gates, weirs,...). Its functioning is not only from upstream to downstream as direct understanding would let think, but also from downstream to upstream when structures configuration or moving influence the upstream water profile.

The topology and numerotation of nodes and reaches is particularly crucial for the simplicity of further use of the model.

Flow in reaches is represented by Saint-Venant equations

Continuity Eq.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

Dynamic Eq.

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2 / A)}{\partial xt} + g.A.\frac{\partial z}{\partial x} = -g.A.S_f + kq.V$$

Flow rates at structures are represented by specific equations:

$$Q_{off} = f(h1, h2, W)$$

depending on hydraulic conditions (free flow, submerged flow,...), e.g. for a totally submerged orifice: $Q = \mu'.L.\sqrt{2.g}.(h1 - h2)^{1/2}.W$

where
x abscissae (m)
t time (s)
A water cross-section area (m^2)
L width of opening (m)
W height of opening (m)
Q flow rate (m3/s)
g gravity acceleration (m/s^2)
z water surface elevation (m)

h1 upstream water level (m)
h2 downstream water level (m)
Sf canal bottom slope (m/m)
V water velocity (m/s)
μ' orifice coefficient

Mathematical models solve these equations through various numerical analysis methods (implicit or explicit) using a time and space discretization.

5.3. PRACTICAL IMPLEMENTATION OF A MODEL

The implementation of a model is done in 3 steps:

- the **description of the canal network**, which requires topographical and geometrical data for the description of reaches and structures,
- the **calibration** which requires hydraulic data (flows and water levels measured in different locations for a set of flow conditions) and consists, through an iterative or direct process, in determining the hydraulic parameters that make simulation results as close as possible to real measurements.
- the **validation** using new sets of hydraulic measurements. Validation is not a binary process leading either to adoption or to refusal of the model. It is mainly the way to quantify reliability of the model results: for example a model can be suitable to analyse response types and trends but not to predict precise values of variables. It should then be used for the only applications for which it is reliable.

Major problems encountered result from approximate knowledge of the topography that people try to compensate through calibration.

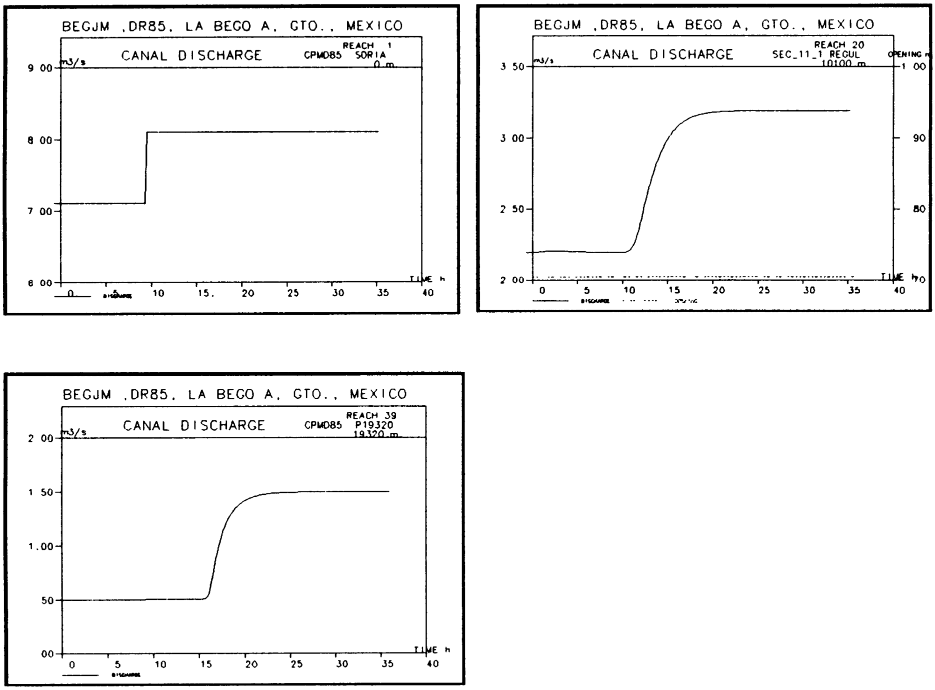
5.4. APPLICATION OF THE MODEL

We give here an example of a simulation model application on La Begonia Irrigation Canal in Mexico (De Leon Mojarro et al. 1992, Kosuth 1993). First applications asked for by the manager are generally about physical properties of the canal: lagtime and capacity.

5.4.1. *Analysis of Time Delays Along the Canal*

This application is aimed at determining time delays between changes at the head of the canal and the response in different locations along the canal. The head flow increases of +1 m3/s at 10h00.

The three graphs in Figure 1. illustrate the average delays:
0.0km-10.1km: av. delay: 4 hours
10.1km-19.3km: av. delay: 8 hours



Figures 1. Time delays along the canal

5.4.2. *Maximum Discharge Capacity of the Canal and Limiting Sections*

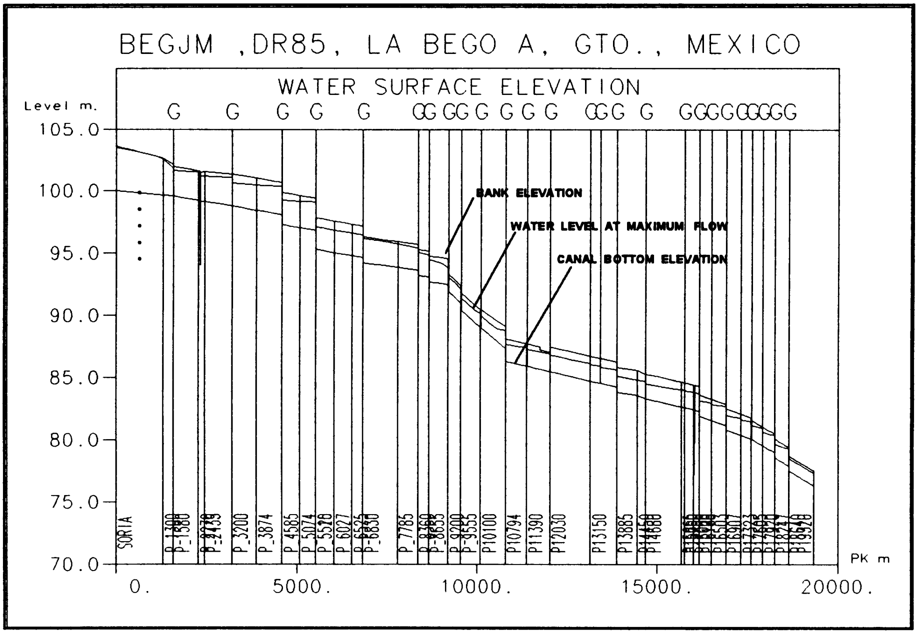
The second application was the concern about knowing the maximum discharge capacity in different locations along the canal, to identify limiting sections where rehabilitation works could reinforce this discharge capacity, and to determine, for a targeted capacity reinforcement, how canal embankments should be consolidated.

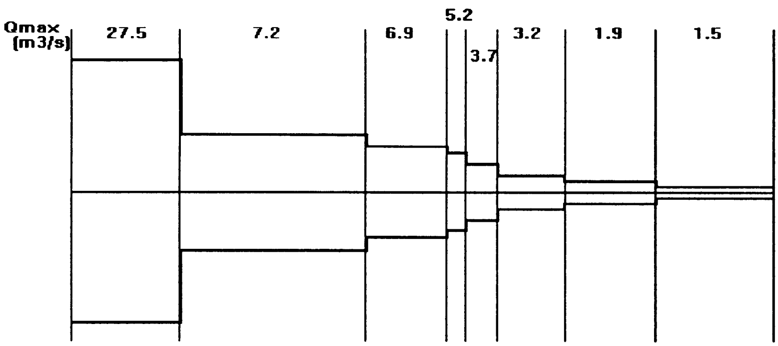
Figure 2 illustrates the results about maximum discharge capacity along La Begonia Canal as obtained through the model.

Next applications deal with the canal operation, first as a help to determine correct gate settings for various distribution plans, then as a tool to identify deficient operation procedures and test improved ones.

5.4.3. *Computation of Gate Openings for a Given Delivery Plan in Steady Conditions*

The following table, resulting from the model computation, indicates the gate openings at the offtake structures as well as at the control structures, for a given distribution plan along the canal, between point 0.000 and point 10.100:





Figures 2. Maximum discharge capacity in La Begonia Irrigation Canal (Mexico)

TABLE 1. Gate openings at offtake structures and at control structures for a given delivery plan. (GO1, GO2, GO3)

	Type	Off	Q	W	Imp	P	W		Go1	Go2	Go3		Q	Qmax
													8.3	27.5
1.300	I.D.	x				0.000							8.300	27.5
1.575	G			x		1.100	0.58						7.200	7.2
1.580										1.29	2.00		7.200	7.2
2.270	O.F.			x		0.000							7.200	7.2
2.435	G			x		0.000	NO						7.200	7.2
3.195	G			x		0.000	0.00						7.200	7.2
3.200									0.69	1.40	0.00		7.200	7.2
3.874	G			x		0.800	0.35						6.400	7.2
4.580	G			x		1.200	0.29						5.200	7.2
4.585									0.12	1.00	0.00		5.200	7.2
5.074	G			x		1.300	0.29						3.900	7.2
5.515	G			x		0.000	0.00						3.900	7.2
5.518	G			x		1.800	0.28						2.100	7.2
5.520										0.24			2.100	7.2
6.027	G			x		0.000	0.00						2.100	7.2
6.525	G			x		0.000	0.00						2.100	7.2
6.825	G			x		0.900	0.19						1.200	6.9
6.830										0.26	0.00		1.200	6.9
7.785	G			x		0.000	0.00						1.200	6.9
8.355	G			x		0.000	0.00						1.200	6.9
8.360										0.38	0.00		1.200	6.9
8.650	G			x		0.000	0.00						1.200	6.7
8.655										0.32	0.00		1.200	6.7
9.195	G			x		0.000	0.00						1.200	5.2
9.200										0.29	0.00		1.200	5.2
9.550	G			x		0.000	0.00						1.200	3.7
9.555										0.42	0.00		1.200	3.7
10.095	G			x		0.000	NO						1.200	3.2
10.100										0.36	0.00		1.200	3.2

As an illustration:

- a 5.2 m3/s discharge at point 4.585 requires openings at the three gates of the control structures of respectively 0.12, 1.00 and 0.00 m.
- a 0.9 m3/s discharge at the offtake located in point 6.825 requires an opening at the offtake gate of 0.19 m.

5.4.4. *Test of present operation procedures under external perturbations*

If the tool gives accurate results, the manager starts being confident and wants to adress specific problems he faces on the canal.

One of the first problems addressed on La Begonia canal is the damageable influence of daily fluctuations of the head discharge due to pumping in the river between the dam and the canal intake. Downstream users on La Begonia Canal complain that they receive less water, while upstream users argue that they themselves suffer from these fluctuations, occasionaly receiving less water and asking for an increase of their irrigation duration to compensate for low flows.

Analysis of present operation. The first step of the approach consists in a detailed understanding of the operation mode, through discussions with the operators. Enquiries allowed to determine the main rules applied in La Begonia:

- weekly organization of the delivery on each section (independently one from another) with constant input and output flows.
- delivery from downstream to upstream on each section; delivery unit of 0.1 m3/s
- main changes of offtake and control structures at 8h00, additionnal change at 15h00.
- supposed proportional relation between change in opening and number of delivery units (for example + or - 0.03m at an offtake gate to deliver + or - 0.1 m3/s)

Delivery planning. The following Table 2 gives an example of delivery organization by the "canalero" at the section level.

TABLE 2. Example of weekly Delivery Planning on section n°7, La Begonia Irrigation Canal (Mexico)

SEC.7	WEEK 1													
X		MO		TU		WE		TH		FR		SA		SU
0.000	7.5	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
1.300	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
1.575	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
1.580	6.9	7.2	7.2	7.2	7.2	7.2	7.2	7.0	7.0	7.0	7.0	7.0	7.0	7.0
2.270	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.435	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.4	0.4	0.4
3.195	0.2	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
3.200	6.5	7.2	7.2	7.2	7.2	7.0	7.0	6.8	6.8	6.6	6.6	6.4	6.4	6.4
3.874	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0
4.558	0.0	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.4	0.4	0.4
4.585	6.5	6.5	6.5	6.5	6.5	6.2	6.2	6.0	6.0	6.0	6.0	6.0	6.0	6.0
5.074	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.515	0.0	0.3	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6.5	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0

The planning of delivery on section n°7 takes into account constant upstream flow (8 m3/s) and constant downstream flow (6 m3/s). We can observe that delivery is organized from downstream to upstream, offtake at 5.074 being served before 3.195. Closing of gate 5.515 from 0.3 m3/s to 0 m3/s on Wednesday morning is balanced by opening of gate 3.195 from 0 to 0.2 m3/s and opening of gate 3.874 from 0.1 to 0.2 m3/s. Control structures 3.200 and 4.585 are moved to fit the new discharge pattern.

Simulation, diagnosis and improvement of operation. The next Figures 3 and 4 illustrate the simulation of operation for a whole week, each "canalero" moving the gates (offtakes and control structures) to match his delivery program and to face perturbations (daily fluctuations of the head flow between 8 and 7 m3/s). The graphs left concern the « **current operation mode** », while those on the right represent « **improved operation mode** ».

Simulation of current operation: In a first step let us concentrate on the graphs on the left, i.e. the current operation mode.

The three graphs (left of Figure 3) respectively show the discharge at the limit between sections 5 and 6 (targeted constant discharge of 3.5 m3/s), between sections 6 and 4 (targeted constant discharge of 2.5 m3/s) and finally at the downstream end (targeted constant discharge of 0.5 m3/s).

Daily fluctuations of the head flow rate (upstream end of the canal) are still sensitive along the canal, despite numerous corrections by the operators. Oscillations keep discharges far from their targeted value.

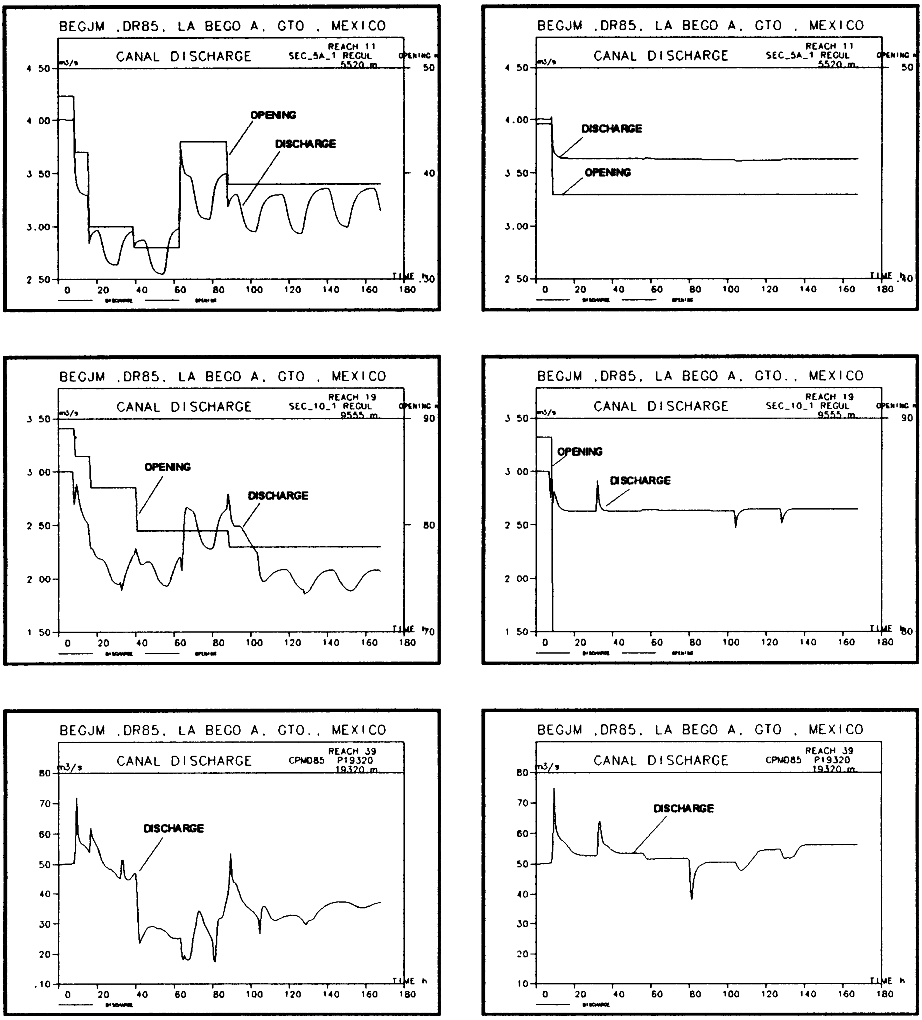
The four graphs on the left of Figure 4 indicate values of offtake discharges respectively at points 3.195, 9.195, 17.915 and 18.635. The deficit between effective and planned delivery are -2%, -20%, -45% and +5% respectively.

Diagnosis: Fluctuations and corrections by operators tend to transfer the deficit to tailend users. But errors in the gate setting position add other perturbations enable last offtake (18.365) to receive more than its share.

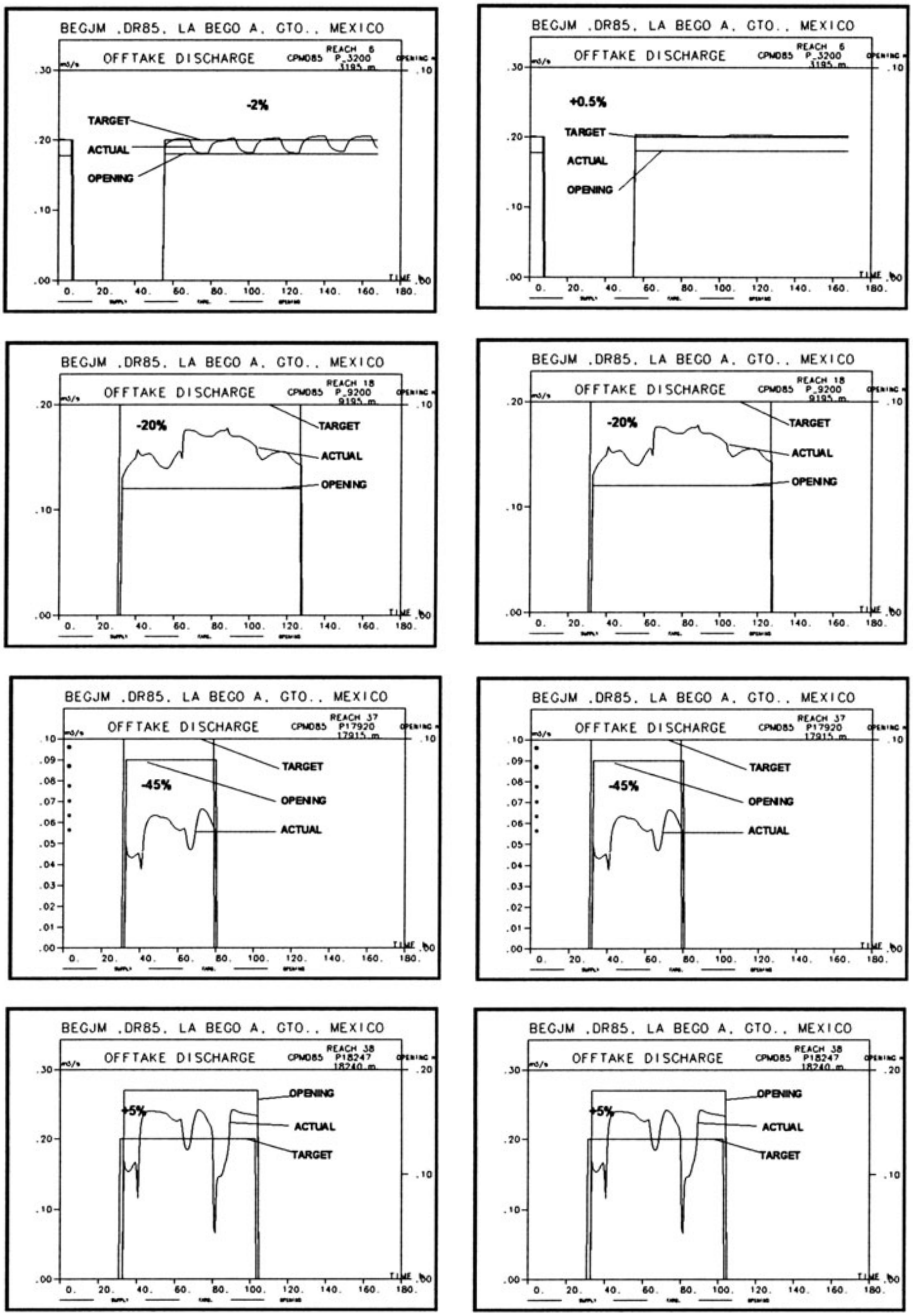
This diagnosis is clearly not meant to replace a field measurement campaign and data analysis. It is a complementary way to analyse the impact of current operation rules.

Improvement of operation rules: Having identified the main perturbations we can propose an improved operation mode using a regulation of the head discharge and a set of accurate gate openings for given targeted flows at offtake structures. Graphs on the right side of Figures 3 and 4 present the simulation results with these improved rules.

By comparing left and right columns one can appreciate the potential improvement of water delivery:
- targeted discharges at offtakes are reached in a satisfactry way (+/- 3%),
- cross-structures require far less changes in gate positions,
- water distribution is equitable, perturbations being spread among the users without penalty on the downstream end users.



Figures 3. Canal discharge and cross-structure opening at points 5.520, 9.555 and 19.320 during a 7 days scenario. Left: with current operation rules. Right: with improved operation rules



Figures 4. Offtakes at points 3.195, 9.195, 17.915 and 18.240 during a 7 days scenario. Left: with current operation rules. Right: with improved operation rules

6. Automatic Control of Irrigation Canals

Automatic control of irrigation canals came as an answer to system complexity and needs in water saving and distribution flexibility. First applications of automatic float-operated gates to level control in irrigation canals date back to the mid-1940s and were extensively used in France and North Africa in the 1950s. Electric / electronic automatic control developped from the 1960s, first in industrialized countries (France, U.S.A.,...) (Buyalski 1991, Goussard 1993).

In the various situations electric / electronic automatic control did not appear directly as an alternative to manual operation. Its introduction was done in several steps:

1. **Installation of sensors and teletransmission of data** to a centralized office: this was mainly aimed at limiting the costs of salary and transportation, and at allowing a permanent monitoring of the system and fast detection of perturbations.
2. An illustrative exemple was the installation of sensors along canals or rivers till the downstream end, directly linked to the dam where operators could regulate head discharge
3. **Installation of electric gates and remote control** to operate gates from the central office: this was aimed at limiting the costs of salary and transportation, and allowing rapid intervention on the system.
4. **Introduction of automatic control** of the gates, aimed at optimizing complexifying systems, and eventually at limiting costs of salary.

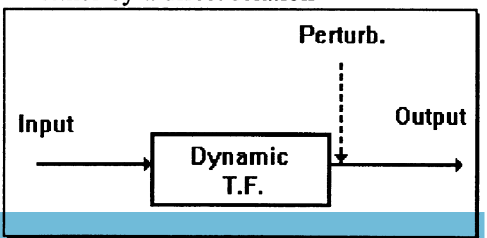
6.1. BASIS OF AUTOMATIC CONTROL (Dieulesaint and Royer 1990, Kosuth 1994)

Numerous research works have been led during the past decade throughout the world on the introduction of automatic techniques to open channel hydraulic systems (Chevereau 1991, De Leon Mojarro 1986, Deltour 1992, Kosuth and Hurand 1991, Malaterre 1994, Reddy 1992, Rodellar *et al.* 1993, Sawadogo *et al.* 1993) . There are various techniques, but the procedure is always in 2 steps:

6.1.1. *Dynamic representation of the system*

The first step of the automatic approach (system analysis) consists in determining a simple representation of the system dynamics. There are mainly two groups of dynamic representation:

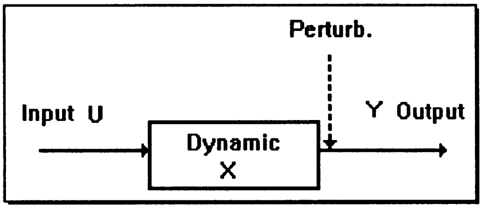
- either by a direct relation



$O = TF.I + P$

where
TF is the "transfer function" between input and output
I is the input (for exemple upstream flow)
O is the output (for exemple downstream flow)
P is the perturbation (for exemple offtake)

- or by a state-space representation



$$\begin{cases} X(t+1) = A.X + B.U + B'.P \\ Y = C.X + D.U + D'.P \end{cases}$$

where
X is the state vector
U is the input (ex. upstream flow)
Y is the output (ex. downstream flow)
A, B, B', C, D, D' are matrices

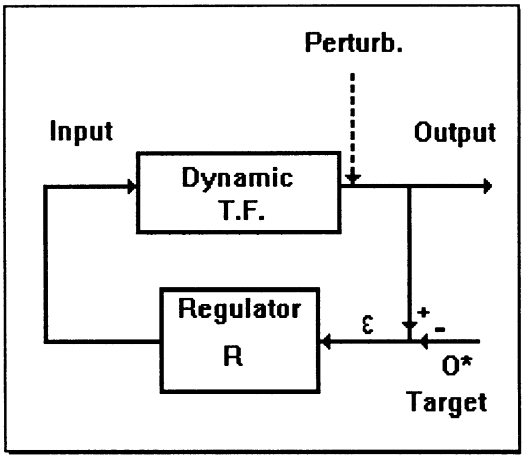
In both cases the transfer function or the state space equations can be determined from measured field data (Kosuth and Hurand 1991) or from physical knowledge of the system, for example Saint Venant equations in the case of canals (Malaterre 1994).

6.1.2. *Synthesis of regulators*

The « regulator », from the viewpoint of automation specialists, is the automatic control procedure (generally an algorithm) that will calculate the accurate command to reach a targeted output, depending on the measured output and the targeted output.

Synthesis of a regulator requires to determine the regulator that will ensure some properties of stability (damping of perturbations) and precision (exact return to targeted output). In the state space approach the optimal command technique allows, besides stability and precision, to determine the regulator that ensures a minimal value of the "cost function".

Transfer Function or Polynomial Approach: simple (for example P.I.D. Proportional, Integral, Derivative controler) and satisfactory for local control.



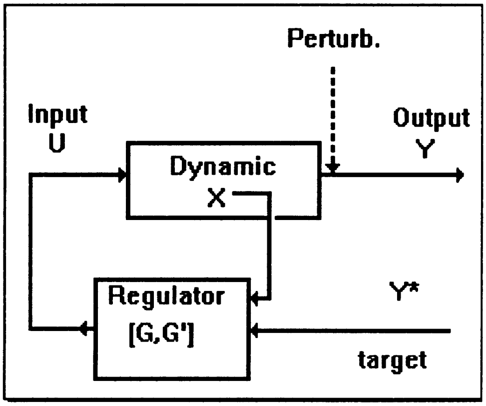
Relation between output, target and perturbation:

$$\boxed{I = R.(O - O^*)}$$

$$O = \frac{TF.R}{1 - TF.R}.O^* + \frac{1}{1 - TF.R}.P$$

R is determined so that $\frac{TF.R}{1 - TF.R}$ satisfies certain conditions of stability and precision

State Space Approach, Optimal Control: closer to optimality and better suited to complex systems



Optimal Control:

$$U = G.X + G'.Y^*$$

G et G' are matrices determined to minimize a cost function J on the time interval [1..N]:

$$\min_{U}\left(\sum_{i=1}^{N}\left[(Y_i - Y_i^*)^2_{QY} + (U_i - U_i^*)^2_{QU}\right]\right)$$

Graphs in Figure 5 show performances of an Optimal Controller on a 5-reach canal, facing unexpected demands at offtakes in several locations along the canal.

6.2. FUTURE OF AUTOMATIC CONTROL FOR IRRIGATION CANALS

With decreasing costs of sensors and information transmission devices, increasing salary costs, complexification of systems, increased need for flexibility, optimality and efficiency in distribution, it is the author's belief that there will be a growing demand for the introduction of simple, and progressively more complex, automatic control on irrigation canals.

Application of downstream control to existing sloping canals presently under upstream control is one of the most promising field.

7. Conclusion and Prospects for the Future

The sustainability of any water resource management policy depends on administrative mechanisms, socio-economical balance and technical reliability. This paper focusses on the latest.

To face the complexity of irrigation canal operation, managers must use appropriate tools. Experience in the implementation of Management Information Systems and in the use of Simulation Models demonstrate their rich potentiality and their accuracy for the improvement of irrigation canals management. They give access to a better knowledge of the physical functioning and allow monitoring and diagnosis of problems as well as test of improved operation rules.

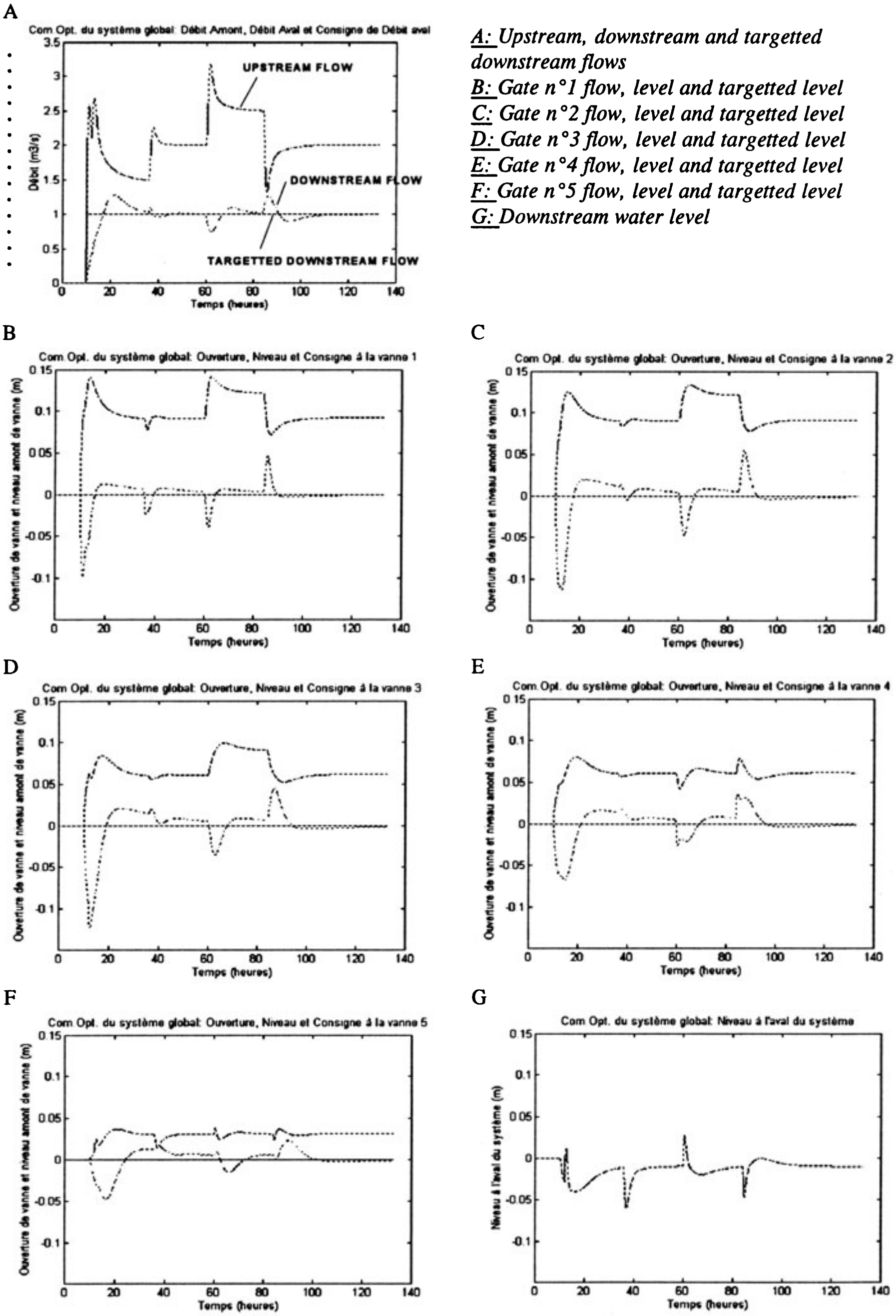


Figure 5. Optimal control on a 5-reach canal facing unexpected demands at several offtakes

The experience is still too limited to give reliable ideas on the process through which the managers are the more likely to appropriate these tools. To propose guidelines for users we need further implementations with assesment of their real impact on water management efficiency, as well as viability in the manager's decision process.

Management Information Systems are likely to find their place in a close future.

Simulation Models require more skills and should first be transfered to skilled engineers that can provide a technical support to managers to solve specific problems.

Interaction between Management Information Systems and Simulation Tools is under study in different places (IIMI, Cemagref, HR Wallingford,...).

Automatic Control Techniques, though still sophisticated, could rapidly show to be the most efficient and reliable way to operate complex large scale systems, allowing fast reaction to perturbations, increased flexibility and optimal control over water delivery. The two main goals of research in this field are to offer a clear perspective both on the existing techniques and on the guidelines to direct choice when introducing automatic control on a given system.

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PART VII

CAPACITY BUILDING

ROLE OF CONSULTING SERVICES

J. HENNESSY
Chairman - Water Group International
Sir Alexander Gibb & Partners Limited

1. Introduction

"Human beings are at the centre of concerns for sustainable development..." (Principle No. 1, Rio Declaration, June 1992).

This primal realization parallelled the development of economic theories which currently suggest that **knowledge**, together with **capital** and **labour**, is an economic production factor. Accordingly, it is now widely accepted that the rate of development which can be sustained by a given community is directly related to the available capacities of its people and its institutions.

Thus the importance of Human Resource Development (HRD) and capacity building is now beginning to be better understood but urgent priority attention is needed to identify site -specific and cost effective processes to successfully implement the requisite education, training and technology transfer functions.

This paper describes how consulting services add **real value** to the community's (stakeholder's) assets.

2. The Project Cycle

In World Bank terms, the project cycle comprises identification, preparation, appraisal, negotiation, presentation, implementation and supervision and evaluation. However, the project cycle descriptors used by many basinwide stakeholders for water resource developments will be conceptualization, planning, design, procurement, construction, commissioning, operation and maintenance, rehabilitation and modernization/re-fashioning and, in some cases, decommissioning. In all cases, the services of experienced water resource specialists/irrigation managers, operators, planners, system maintainers, engineers, economists, agronomists, researchers and social scientists are needed to join forces with the farmers for successful implementation.

In industrial and developing countries alike, such services are regularly provided by private sector consulting firms, research organizations, universities and in-house

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professional/management teams acting either individually or collectively. To find the optimal mix of external/internal inputs to match the dynamic needs of catchment stakeholders, is the key to sustainable success.

3. The Knowledge Base - AGENDA 21

The United Nations Conference on Environment and Development (UNCED; "The Earth Summit") held in Rio de Janeiro in June 1992 was the culmination of the worldwide action programme designed to inform, guide and assist the world community to address the Global Environmental challenges of the 1990's and beyond. Of particular significance was the publication of **Agenda 21** which provides a framework for Sustainable Development into the 21st Century. For the term "Sustainable" the adoption of the FAO (1989) definition of "Sustainable Agricultural Development" is recommended: "Sustainable development is the management and conservation of the natural resource base and the orientation of technological and institutional change in such manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development (in the agriculture, forestry and fisheries sectors) conserves land, water, plant and animal genetic resources, is environmentally sound, technically appropriate, economically viable and socially acceptable."

Agenda 21 is a non-legally binding agreement which was signed at the Earth Summit. It presents an environmental action plan for both industrial and developing countries for the next decade and into the 21st century. **Agenda 21** comprises 40 chapters (800 pages) on subjects as diverse as the role of indigenous peoples, sound management of toxic chemicals and international legal instruments. The basic tenets of **Agenda 21** (and its precursor the Dublin International Conference on Water and the Environment; ICWE January 1992) are that development and environmental sustainability are inseparably linked, that human beings are at the centre of concerns for sustainable development, and that alleviation of poverty and provision of adequate food and sanitation are priority objectives. And further, that new levels of co-operation (global partnerships) among States, various sectors of societies and people are needed so that the requisite skills, technologies and resources are appropriately shared and applied.

Chapter 18 of **Agenda 21** deals with the "Protection of the Quality and Supply of Freshwater Resources" and inter alia deals holistically with water resource management issues. The Chapter incorporates the main conclusions of the ICWE and is underpinned by the Guiding Principles of the Dublin Statement (January 1992) viz:

Principle No. 1 - Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment.

Principle No. 2 - Water development and management should be based on a participatory approach involving users, planners and policy makers at all levels.

Principle No. 3 - Women play a central part in the provision, management and safeguarding of water.

Principle No. 4 - Water has an economic value in all its competing uses and should be recognised as an economic good.

In terms of specifics, **Chapter 18** comprises an introduction and seven programme areas:

1. Integrated water resources development and management
2. Water resources assessment
3. Protection of water resources, water quality and aquatic ecosystems
4. Drinking water supply and sanitation
5. Water and sustainable urban development
6. Water for sustainable food production and rural development
7. Impacts of climate change on water resources

Overarching **Agenda 21** is the Rio Declaration comprising 27 Principles of which those following relate directly to HRD, capacity building/technology transfer:

Principle No. 1 - Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature.

Principle No. 4 - In order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it.

Principle No. 9 - States should co-operate to strengthen endogenous capacity-building for sustainable development by improving scientific understanding through exchanges of scientific and technological knowledge, and by enhancing the development, adaptation, diffusion and transfer of technologies, including new and innovative technologies.

Principle No. 21 - The creativity, ideals and courage of the youth of the world should be mobilized to forge a global partnership in order to achieve sustainable development and ensure a better future for all.

4. Appropriate Water Management (AWM)

In September 1993, the Global irrigation and drainage community comprising around 750 participants from 65 countries met in The Hague, The Netherlands for the ICID XVth Congress. The Congress addressed the theme "**Water Management in the Next Century**" and concluded with The Hague ICID Declaration comprising a ten-point Action Plan centred on the worldwide adoption of **appropriate water management**, defined as: "those cultures, methods, systems and techniques that provide a socially and environmentally acceptable level of service or quality of product at the least economic cost"; "accordingly, **Appropriate Water Management** - or Development - is not necessarily low tech or labour intensive forms of management for example, but rather is the selection and adoption of the right solutions to meet the developmental needs in a particular environment, but sustainably."

The ICID Action Plan includes, inter alia, the following specific items:

N° 1: ICID will promote new programmes for water savings in agriculture to enable the release of water for other emerging high priority uses;

and

N° 10: Programs will be undertaken to exchange appropriate technology among national committees, planners, designers and managers of irrigation systems.

These examples demonstrate that international NGO's (non-governmental organizations) such as ICID contribute constructively to the "knowledge base" and to the effective transfer of the technologies and experiences involved (i.e. "Lessons Learnt").

5. A Water Ethic

Most professionals are governed in their work by rules (codes) of professional conduct set by relevant professional (qualifying) bodies or institutions. For example, in the UK the well-known definition of civil engineering (1827) - "being the art of directing the great Sources of Power in Nature for the use and convenience of man", is embodied in the Charter of the Institution of Civil Engineers (ICE). Similar definitions and codes exist in other countries which underpin the professional training programmes established for the transfer of technology (experience) from the mature practitioners to the newly graduated engineer. Thus capacity building is well served by such institutions.

In addition to the professional institutions/learned societies, there exist national/international organizations which govern the working practices of professional firms. In the case of Consulting Engineers (CEs) the applicable bodies are, for example, the Association of Consulting Engineers - ACE (UK) and FIDIC (Fédération Internationale des Ingénieurs Conseils) internationally. FIDIC/ACE set the rules of conduct for CEs which include, inter alia, that member firms be independent of any manufacturing/contracting interests; that the fees paid by the client represents the sole remuneration of the CE for the particular services; and that the CE provides the requisite services to the client with full objectivity and in a fiduciary capacity (i.e. the position of complete trust).

FIDIC has 56 Member Countries, of which about a half are either developing or newly industrialised countries. Transfer of Technology has, therefore, been a priority activity for the past 20 years and more. Likewise, it was accepted over the past decade that **"Sustainable Development"** issues called for explicit attention and guidance. Accordingly, in 1990 FIDIC issued their "Policy Statement on Consulting Engineers and the Environment" (see Annex 1). The Policy Statement gives positive commitment to environmental sustainability and, for example, calls on CE's - "to take appropriate action, or even decline to be associated with a project, if the client is unwilling to support adequate efforts to evaluate the environmental issues or to mitigate environmental problems".

In addition to the professional institutions/representative bodies/NGO's, many other community groups have made constructive contributions to the "**Sustainability debate**". Especially noteworthy is the "Last Oasis" (Sandra Postel, Worldwatch Institute, Washington D.C. 1992) where the author argues the need for "**A Water Ethic** - a guide to right conduct in the face of complex decisions about natural systems we do not and cannot fully understand.

The essence of such an ethic is to make protection of water ecosystems a central goal in all that we do".

The understanding and acceptance of such a Water Ethic embodying commitment to **Agenda 21** and **Appropriate water management (AWM)** is the essential pre-requisite for those involved with sustainable irrigated agricultural production. It is, therefore, strongly recommended that the "knowledge base" of each member of the "water resources utilization team" should explicitly include the "Water Ethic" expertise alongside that of the conventional engineering, agronomic, socio-economic, financial and other disciplines. Or, put another way, it is suggested that only professionals/managers who have adequate knowledge and experience of the "Water Ethic" be permitted to hold leadership roles in sustainable water resources development.

This priority item will require especial attention in technology transfer/capacity building programmes both at national and international levels.

6. The Role of Consulting Services

The fundamental purpose of Consulting Services is to **add value to the client's assets** (be they **capital**, **labour** or **knowledge**) through the provision of advice and services. The services may comprise activities pertaining to any or all phases of the "project cycle" including "hands-on" management support as may be necessary. This applies to all consulting service sectors - e.g. management, financial, engineering, project management, agriculture, research, training etc. in industrial and developing countries alike.

Science, technology and management expertise are increasingly becoming internationally shared commodities, and ideally a free international market should exist in the services sector. This is already an established practice between North America and Europe and client bodies -public or private - benefit from having the best experience available in the market place. For example, the importation of Dutch expertise on polders and drainage enabled the agricultural development of low-lying East Anglia (UK) to proceed in the 17th Century. Other examples abound and to this day the best managed enterprises maintain the keenest interest in the technological development of their competitors, be they national organizations or private companies. It is, therefore, accepted that technology transfer is an ingredient for success but the question remains - how to achieve it?

From the client's standpoint, the considerations include:

- the technologies needed to be transferred; from where; to whom; how; and when?
- can the task be achieved (cost-effectively) by available in-house resources?
- If not:- whether to employ national or international consultants as individuals, (seconded or direct hiring) or as teams from consulting firms, research groups or others.

The main issues concerning the client's decision will include:

- Does the client already operate a continuous system of training for all levels of management and staff and accept that such training is an essential component and cost in any successful enterprise?
- Does the client subscribe to improving career prospects to retain staff by supporting HRD programmes for graduate staff to achieve chartered professional status and/or post-graduate degrees?
- To what extent does the client already engage Consulting Services to assist with the ongoing development programmes and/or the "management of change"?
- Are the needed services available locally, nationally or internationally?
- If international services are required, does the client have the means to meet the foreign exchange costs?
- Does the client know of and accept the Water Ethic.
- Typical specific issues arising from case studies in developing countries highlight:
    - lack of awareness of those involved in the planning and development process of the potential environmental consequences of such developments and especially so in the irrigation and drainage sectors.
    - lack of effective communication between those involved in the development process and the concerned farming communities (regardless of gender).

For national/regional governments, an overarching issue is the extent to which the technological/managerial expertise should be readily available nationally rather than internationally. Whilst it is generally accepted that it is not essential for all nations to possess, say, space-technology or all hi-tech industrial processes, it is also accepted that a nation's "knowledge base" is a prime capital asset. The problem is greatest for developing countries where, for example, it is reported that in Sub-Saharan Africa there are only 2.5 graduates in science and engineering disciplines per 100,000 inhabitants compared with 95 per 100,000 in developed countries. For developing countries the additional issue to technology transfer is, therefore, the urgent concurrent growth of indigenous capacity and the related institutional reforms necessary for success.

Taken either individually or collectively, the above-listed issues represent a formidable challenge, especially for developing countries. The scale and the urgency of the needs is such that individual TA assignments will prove inadequate. Thus considerably increased funds are required to be allocated by governments/international agencies to the HRD/Training/capacity building function.

It is concluded that, in the short term at least, the services of international consulting firms will be needed to help the developing countries take action "today" to provide for a better "tomorrow".

However, there are severe constraints which inhibit effective international technology transfer today including, inter alia:

- Inadequate funds allocated for transfer of technology and capacity building functions.
- The increasing practice of awarding consulting assignments based on financial considerations alone. This adversely impacts on the quality of the staff engaged and the services rendered.
- Inadequate priority given to the transfer of technological activity when scoping the project task definition.
- Reduction in the number of longer term assignments (say 12 months plus) which markedly reduces the opportunities for effective on-the-job training etc.

Accordingly, the leading consultants adopt forward strategies to meet the challenges of AD 2000 by adopting a mixed menu of sustainable improvements such as:

- Continued Improvement of the efficiency of the services rendered.
- Adoption of task specific quality plans prepared for each and every activity.
- Improvement in the training of the consultants' personnel so that they are properly equipped to undertake transfer technology/capacity building functions.
- Continue to persuade client bodies/funding agencies about the importance of making explicit and suitable allocations of funds and other resources on each and every task.
- Continue to lobby through professional organisations such as FIDIC, for the adoption of the selection of consultants based on value assessment, i.e. combination of quality and cost. For successful transfer of technology, the financial element in the value assessment should not exceed 15% of the selection criteria.

In selecting the consulting firm the criteria should include:

- Direct experience of the project cycle for water resource management developments in developing countries.
- Record of training and technology transfer experience with developing country nationals.
- Critique of the consultants existing in-house "own-staff" training programmes.
- Ideally Quality Assurance Accreditation according to ISO 9001.

- Direct experience of the particular country/region.
- Track record of working with client counterparts and effecting "on-the-job" technology transfer.
- Track record of joint-venture and other co-operative associations with developing country consultant firms and organizations.

7. Conclusions and Recommendations

- For any given community, the achievable rate of sustainable water resource development depends crucially on the available capacities of its people and its institutions.
- Education, training, human resources development (HRD) and technology transfer are interlinked means of capacity building.
- Technology transfer remains of especial importance to developing countries for redressing (partly) the widening "knowledge gap" between North/South peoples.
- Sustainable irrigated agricultural production depends upon the lifetime inputs of leaders and managers who adopt the holistic approach - i.e. comprehensive and intersectional -combined with the full commitment to practise according to the Water Ethic (i.e. **Agenda** and **Appropriate water management**).
- Declining investment in the irrigation sector since 1980 has led to a marked reduction in effective technology transfer.
- The use of consulting services in the "Project Cycle" is an important opportunity for the meaningful transfer of the technologies and experiences involved.
- Many leading international consulting firms significantly add value to the assets of their clients and the communities at large by:
    - providing specifically designed technology transfer services to the client's staff
    - providing on-the-job training opportunities for the client's personnel
    - providing and/or facilitating project specific workshops and seminars for the "in-country" participants
    - using the consultant's visiting specialists and resident team to give "state-of-the-art" lectures/discussions aimed at sharing international "Lessons Learnt" experiences
    - working with national co-consultants which results in the development and establishment of effective national consultancy firms
- Giving opportunities for professional development, i.e. for engineers, accountants and others to proceed to Chartered status (UK terminology) in the course of their on-the-job experience and training; this is provided either "in-country", in the consultant's home offices or both.
- Capacity building within the client's organisation which would include inter alia:
    - Understanding of Rio Declaration, **Agenda 21** and its impact on the community at large
    - Understanding of individuals responsibility not only to their specific responsibilities but also to the community at large

  - Understanding and practice of the holistic approach to sustainable development
  - The acceptance of the reality that "Lessons Learnt" from other environments can have direct bearing in the specific area

- By assisting nationals to establish national offices representing professional bodies, learned societies and trade associations as may be locally relevant.
- To date, far too many water resource developments (developing countries) have relegated technology transfer to an ad hoc activity, poorly defined and with wholly inadequate funding allocations.
- For successful technology transfer, the essential ingredients include:
  - clear definition of the task
  - well designed and site-specific (i.e. also people-specific) transfer programmes
  - full acceptance by the public sector authorities that technology transfer is an important activity in its own right
  - definition of mechanisms to monitor progress and measure achievements
  - allocation of adequate funds to meet the costs involved
- Technology transfer consulting services will continue to be greatly needed to support the developing country authorities enhanced attempts to accord with **Agenda 21** precepts. The efforts of professional representative bodies (such as FIDIC for Consulting Engineers) to achieve commonality of understanding and purpose between the client bodies, funding agencies and consultant groups, deserve enhanced priority by all concerned.

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ANNEX 1
FIDIC POLICY STATEMENT ON CONSULTING ENGINEERS AND THE ENVIRONMENT
(approved by FIDIC Executive Committee in June 1990)

The Endangered Environment

There is a growing awareness that the earth cannot continue supporting increases in population and consumption. Mankind is threatening its own existence, in addition to that of many other forms of life, through global pollution and excessive consumption of limited resources.

Engineers have contributed to the quality of life through the provision of better water supplies and sanitation, and by the development of natural resources, food, energy and communication and transportation systems. These advancements have contributed to rapid population growth and environmental problems.

Consulting Engineers and the Environment

Consulting Engineers accept the challenge of the endangered environment. Because of their professional training and background they have a particular role and obligation towards the protection of the environment. Engineers should provide leadership in achieving sustainable development -development that will meet the long term needs of future generations of all nations without causing major modification to the earth's ecosystems.

This role of the engineer should result in:

* Careful evaluation of the environmental benefits and adverse impacts of proposed projects
* Conservation of energy
* Reduction in the use of non-renewable resources and increased re-use of materials
* Reduced waste production through improved industrial processes, better transportation and distribution systems and recycling of waste products
* Sound agricultural and other land-management practices
* Restoration or improvement of damaged land, polluted water supplies and disturbed ecosystems
* Effective transfer of environmental knowledge and experience

Ethics and Responsibilities

Worldwide steps are required to protect and improve our environment. The effort must involve government, the public and private sector.

Consulting Engineers are trained and experienced in handling complex problems. They should combine their traditional skills with broader applications of physics, chemistry, biology and other disciplines to lead inter-disciplinary teams directed at achieving acceptable environmental solutions.

Observing a code of conduct is a fundamental part of the profession of a Consulting Engineer. The goals of Consulting Engineers should include a commitment to achieve sustainable development. Consulting Engineers should give the highest priority to the short term and long term welfare, health and safety of the community. They should consider regional, global and cumulative effects of projects in addition to local effects.

Therefore, FIDIC recommends as follows:-

GENERAL ACTIONS

Each Consulting Engineer should:

* Keep informed on global environmental trends and issues
* Discuss environmental problems with professionals from other disciplines
* Provide information to clients, the public and government about environmental problems and how adverse effects can be minimized
* Become involved in organizational activities, including assistance to governmental authorities that promote the protection of the environment.
* Encourage and promote appropriate environmental laws and regulations
* Actively support and participate in all forms of environmental education
* Promote research and development relevant to protecting and improving the environment

PROJECT ACTION

Consulting Engineers should:

* Recommend that environmental studies be performed as part of all relevant projects. Such studies will normally require a multi-disciplinary approach
* Evaluate the positive and negative environmental impacts of each project. This evaluation might be based on a preliminary review of available information or on the engineer's experience. They should evaluate the basic functions and purposes behind a project. They should suggest alternatives to their clients if environmental risks emerge
* Develop improved approaches to environmental studies. Environmental effects should be considered early in the planning process. Studies should evaluate the long term consequences of environmental changes

* Make clients aware that engineers can reduce, but not always eliminate, adverse environmental impacts. The legal and financial responsibilities of all parties should be clearly defined.
* Urge clients to prevent or minimize the adverse environmental effects of projects in all phases -initial planning, design, construction, commissioning, operation and de-commissioning.
* Finally, take appropriate action, or even decline to be associated with a project if the client is unwilling to support adequate efforts to evaluate the environmental issues or to mitigate environmental problems.

PROFESSIONAL TRAINING REQUIREMENTS

J. FEYEN
Institute for Land and Water Management
Katholieke Universiteit Leuven
Vital Decosterstraat 102, B-3000 Leuven
Belgium

1. Perspectives on Irrigated Agriculture

Productivity in agriculture must grow rapidly to keep food supply in balance with the ever increasing demand. Demand for food is controlled by the expansion of the world population (the current world population of 5.3 billion will increase to 8.4 billion by 2025) and the change in the demand (from grain to a meat-based diet) (MacKenzie 1994). It is estimated that in the developing countries over the next 30 years, a large increase in grain production of around 150% must materialize, or from 1.067 to 2.555 billion tons, to meet the projected food demand (Yudelman 1993). Table 1 gives a summary of the expected growth in population and food demand in the developing (LDC's) and the developed countries (DC's) over the period 1992 and 2025. The calculations are based on the study of Yudelman (1993) and FAO 1993.

Some of the need can be met by expanding the area under rainfed cultivation, but the availability of good new land is scarce, and or its geographical location is not ideal. In particular there is limited land available in Asia. The small contribution from increased land area to past production increases argues that suitable land is not easy to find, and that increasing yields per ha on established fields is more cost-effective. In addition, the yield level on rainfed land is often controlled by available water, which may be inadequate or irregular in supply. Therefore, on rainfed land the benefits from additional inputs are often low and as a consequence farmers are reluctant to invest in them. As such, it is uncertain how far grain yields on rainfed lands of the developing world can be increased in a sustainable way beyond the present level of 1 to 1.5 tons/hectare/year. Being so, then the yield increase has to come from the expansion of the irrigated area or through increased productivity per unit area of irrigated land. Table 2 gives an estimate of the grain yield the irrigated area has to produce, so that food supply meets demand in the year 2025. In Table 2 it is assumed that in the rainfed areas over the next 30 years the productivity of cereals in the LDC's will rise from 1.5 to 2.0 tons/hectare/year, whereas a rise from 4.0 to 7.0 tons/hectare/year is expected to occur in the DC's. Furthermore, it is assumed that some expansion of the irrigated area, an estimated increase of 1% per year for the coming 30 years, will

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occur (Jensen *et al.*, 1990). The ratio between the land area covered by cereal and non-cereal crops for the LDC's and the DC's was derived from FAO (1993). The analysis in Table 2 reveals that grain yields of the irrigated area in the LDC's has to rise from 4.40 to 6.00 tons/hectare/year and in the DC's from 6.00 to 9.00 tons/hectare/year, if a balance between world food demand and supply is to be reached by the year 2025. If the previous is materialises, the irrigated area, representing roughly 20% of the total cultivated land, will produce 50% of the world global production of cereals. In addition, the data in Table 2 suggest that the DC's remain an important food supplier to the LDC's.

TABLE 1. Expected growth in population and food demand in the developing and the developed countries between 1992 and 2025

Region	1992			2025		
	(1)	(2)	(3)	(1)	(2)	(3)
LDC's	4,074	262	1,067	7,078	361	2,555
DC's	1,211	736	891	1,336	800	1,068
World	5,285	371	**1,958**	8,414	431	**3,623**

(1): population in millions
(2): average consumption of cereals in kg/person/year
(3): demand for cereals in million tons

TABLE 2. Estimate of the required productivity of cereals on irrigated land in the year 2025

	1992				2025			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
LDC's								
irrig.	609	173	0.80	***4.40***	1,152	240	0.80	***6.00***
rainfed	431	599	0.48	1.50	645	672	0.48	2.00
total	1,040	772	0.55		1,797	912	0.55	
DC's								
irrig.	307	64	0.80	***6.00***	641	89	0.80	***9.00***
rainfed	611	608	0.25	4.00	1,185	682	0.25	7.00
total	918	672	0.30		1,826	771	0.30	
World								
irrig.	916	237			1,793	329		
rainfed	1,042	1,207			1,830	1,354		
total	**1,958**	1,444			**3,623**	1,683		

(1): total yield of cereals in million tons
(2): cultivated area in million hectares
(3): ratio of land area cultivated with cereal and non-cereal crops
(4): average yield of cereals in tons/ha/year

Although at a first glance an average production rate of cereals of 9.00 tons/hectare/year under irrigation and 7.00 tons/hectare/year under rainfed conditions in the DC's might be unrealistic, one should realize that when all current technologies of fertilizers, water supply, pest control, and management are used in full, the maximum yield for a single crop of cereal is about 10 tons per hectare. In the developing countries similar potential yield levels are achievable, from two crops per year and with well controlled growing conditions. In China for example, one might easily find 5.00 tons/hectare wheat followed by 7.50 tons/hectare corn. In practice, the average yields over a large area will always be somewhat smaller than this, and the practical limit for full intensification under irrigated condition in the DC's therefore is estimated at 9.00 tons/hectare/year and 6.00 tons/hectare/year (for 2 crops) in the LDC's. Lower average yields over a large area in the LDC's are envisaged due to the more difficult and adverse growing conditions in many of these countries. Average annual yields, at a regional scale on properly managed irrigated land, of 6.00 tons/hectare are currently being obtained in some parts of the Punjab and Egypt.

2. Constraints on Irrigated Agriculture

Evaluations of irrigation projects have emphasized that many do very poorly, and that most projects are operating well below their potential as defined to justify investments (Le Moigne *et al.*, 1989). The major constraints responsible for the general low performance of irrigated agriculture and the decrease in the rate of expansion of the total irrigated are:

* rising capital costs for the construction of new irrigation capacity (about US* 2,500 per hectare in Asia to US* 7,500 per hectare in Africa for medium-sized systems (IBRD, 1982);
* insufficient funding for recurrent expenditures (the total annual investment in irrigation required for the maintenance of the irrigation infrastructure is estimated at US$ 10 to 12 billion) (World Bank/UNDP, 1990);
* lack of systematic plans for maintenance and management practices (IPTRID, 1993);
* lack of cooperation between the managers and operators of the water system and the water users (Vander Velde, 1990);
* increased scarcity of water and competition for the same source of fresh water by other sectors of economic activity (irrigation in the developing countries uses up to 80% of available fresh water) (Postel, 1993);
* increase in waterlogging and degradation of the resource base, through salinization of the soil (integration of drainage facilities increases the cost of new irrigation schemes by more than 10 percent) (Smedema, 1993);
* increase in health hazards to people living in irrigated areas through propagation of vector-borne disease (WHO, 1992); and
* rising impact of upstream activities in the catchment area of the irrigation system (such as deforestation, cultivation without soil conservation measures, and overgrazing) adding eroded soil in dams and canals; and downstream impacts induced by the irrigation system on water quality (both surface and groundwater) (Brouwer, 1993).

The combination of all these shortcomings results in inequitable, inadequate and unreliable water distribution and inefficient use of water. The foregoing not only results in a total low output of the system but contribute to increased social tensions among the farmers, and environmental and health concerns.

For the irrigation sector to achieve its goal, irrigated agriculture has to become more productive, efficient and sustainable. Given the long list of constraints the total task facing the irrigation sector is truly a formidable one, a task that can only be accomplished successfully by extensive advances in irrigation-related activities such as training, research, development and management. Training and research curricula in irrigation must address all key problems. Such a broad agenda and such a huge area require the work of many schools and research institutes, both in the developed and the developing countries. Given the relatively short period (30 years) available, training in irrigation need to be considerable and more effective than in the past.

3. Training Needs

The need for training in irrigation has been echoed at various national and international conferences. For example, at the 13th International Congress on Irrigation and Drainage in Morocco in 1987, 33 papers on irrigation water management training were presented by authors from 33 countries. Participants reached several conclusions, from which the Economic Development Institute (EDI, 1989) of the World Bank summarized the five main conclusions concerning training as:

* programmes should be based on an assessment of the needs for training and developed in line with organizational objectives;
* programmes should comprehensively and systematically enhance the skills needed by management, operating, maintenance, and administrative staff;
* initial training of project operating and maintenance staff should be completed before new works are commissioned;
* water users and their associations should be considered when developing new training strategies; and
* training programmes should be conducted as close to the field as possible.

Training programmes can be conveniently divided into five main groups: (i) professional training programmes for irrigation engineers, agriculturalists and other relevant professionals; (ii) technical training programmes for irrigation and agricultural technical assistants; (iii) vocational training programmes; (iv) on-farm or on-the-job training programmes; and (v) informal training programmes for water users (farmers), community leaders and other relevant nontechnical personnel. This paper concentrates on the course profiles and means for academic programmes. The latter can be subdivided into long-term programmes (graduate and postgraduate programmes), short courses, workshops and conferences, and programmes for continuing education.

4. Professional Training Programmes

4.1. GRADUATE AND POSTGRADUATE PROGRAMMES

Professional training at graduate and postgraduate level must begin with providing a thorough understanding of the biophysical and non-biophysical aspects of the irrigation process and the crop production system. Academic programmes in the field of irrigation must address more than only the engineering disciplines. There is ample evidence to suggest that the failure of irrigation schemes can, among other factors, be attributed to defective or inadequate academic training. The emphasis on engineering sciences in many traditional training programmes is a manifestation of such inadequacies. Similarly, it is unrealistic to expect agriculturalists and other non-engineering professionals to appreciate the complexities and problems associated with water abstraction, storage and conveyance systems without a fair knowledge of the basic engineering principles behind an irrigation system. Furthermore, it can be questioned if engineering and agricultural dimensions to academic training are a sufficient guarantee that professional training in irrigation is adequate.

Since the main shortcomings in irrigation find their origin in the social behaviour of farmers, communities, water user associations, irrigation agencies and public institutions towards water use, academic training programmes in the field of irrigation also ought to pay attention to aspects such as:

* rural household and community behaviour towards water use (the behaviour of rural households and individuals within the households by gender and age, emphasizing the differentiation across household types, etc.);
* community behaviour, particularly with respect to the management of common property resources, the cooperation at grassroots organizations and the role of local structures of authority;
* the behaviour of intermediary organizations, such as water users associations, farmer-managed irrigation systems and cooperative organizations with respect to issues of turnover and privatization of water management, and of complementary institutional reforms as the government pulls back from the delivery of services, including service cooperatives, credit unions, technical assistance services, etc.; and
* public finance and investment priorities, planning techniques for the intersectoral allocation of water, property rights and the legal foundations of water contracts, the development of water markets and water pricing as mechanisms for the allocation of water, regulatory agencies for the performance of water markets and the determination of water fees, regulation of pollution and incentives for sustainability, the broader policy framework determining the structure of incentives and constraints, and long run dynamic forces such as population growth and global environmental change.

Today, it is believed that a balanced irrigation course should blend the agricultural and engineering sciences associated with irrigation with appropriate organizational and managerial skills. Furthermore, such a course must be based on hydrologic system synthesis or simply on the systems approach, by which irrigation is perceived as a sub-system of a much larger hydrological system. Academic training programmes should also focus on the relation between the system performance and the planning, design, construction and operation aspects (Jensen, 1991). In addition, a key component of such a course should be the application of microcomputers, software packages, information systems engineering and expert knowledge.

Rangeley (1986) noted that the advances in appropriate irrigation technology and scientific understanding of the soil-plant-water relations have had little impact on the performances of irrigation schemes and projects, particularly in the developing countries. Similarly, management science has advanced greatly during the past few decades, but its application to irrigation system management is greatly lacking, even in the DC's. One major reason for the poor diffusion and effective use of such knowledge and advanced technologies is the inadequacy and inappropriatness of many training programmes.

There are several MSc (2- and 1-year) courses and 1-year Postgraduate Diploma programmes in the field of irrigation, irrigation engineering, irrigation agronomy, irrigation water management, soil and water, and water management all over the world. Most of these are available in universities and institutions in Western Europe, North America, South America, and the Middle East. A survey of some graduate and postgraduate training courses in irrigation show that besides the biophysical aspects the non-biophysical aspects are gradually, although slowly, incorporated in their curricula.

Depending on the orientation of the organizing institute (Faculty of Engineering, Faculty of Agricultural Engineering or Agronomy, School for Business and Administration or the Faculty of Sociology), either the engineering, agricultural or managerial and organizational aspects of irrigation are emphasized in teaching. The number of truly interdisciplinary university training programmes in the field of irrigation is very small. Slowly are social issues associated with irrigation and environmental effects of irrigated agriculture being incorporated in the curricula of the more traditional engineering oriented training programmes. So far, few programmes have topics that explicitly address the problems of health and water pollution associated with irrigation projects. In those programmes, also little is covered about the pains of socioeconomic adjustment peasant farmers go through when resettling and adopting new technology.

The low number or absence of academic training programmes in the developing countries, where most of the irrigation is not only practiced but badly needed, is a striking fact. The primary reasons for this are the lack of human and financial resources. Unless these countries get the financial resources to establish and run universities and departments in an appropriate and cost-effective way, and the newly established schools provide an advanced level of learning, students of the developing countries will continue to pursue graduate and postgraduate learning in the developed countries.

The drawbacks associated with most professional training programmes in the developed countries can be summarized as: (i) educational programmes are still discipline oriented, and the programmes are rare that really embrace the engineering and non-engineering aspects in their curricula; (ii) programmes in irrigation at universities pay often little attention to the technical, managerial, economical and social aspects of irrigated agriculture; (iii) professional training programmes are slowly moving towards a 'systems' approach; (iv) academic programmes in irrigation have the tendency to overemphasize the use of information technology at the cost of field work; (v) too little training is designed to improve general management of projects as a production system; and (vi) trainees are seldom exposed to interdisciplinary teamwork.

4.2. SHORT COURSES, WORKSHOPS AND CONFERENCES

Apart from the regular training programmes in irrigation, there are several international short courses (SC), workshops (WSHOP), conferences (CONF), seminars (SEM), congresses (CONG), symposia (SYMP) and exhibitions (EXH) organized every year. Some objectives of these courses, workshops and conferences are: (i) to provide intensive refresher courses in irrigation to ease the exchange and dissemination of new improved irrigation technologies; (ii) to exchange information on the performance of irrigation systems; (iii) to draw up coordinated strategies for regional and international irrigation developments; and (iv) to act as forums on which ideas and knowledge from professionals in different fields can be blended for more successful and sustainable irrigation systems.

A compendium of international SC, WSHOP and CONF on irrigation and related topics for 1992 and 1993 was prepared by Louis Berger International, Inc. and Water and Power Consultancy Services (India) Ltd. (LBII/WAPCOS, 1992). The topics covered in the compendium were divided into 13 main groups (water resources, irrigation engineering, climate and environment, irrigation management, general management, human resources development, computer applications, irrigation project analysis and evaluation, communications and extension, water quality, management information system, waste water irrigation and energy use and conservation) which are not exclusively unrelated. The total number of SC, CONF, WSHOP, SEM, CONG, SYMP and EXH was 329 for 1992 and 115 for 1993.

Although data are available for two years only, which might be too short to draw general conclusions, the data show the following trends:

* the general dominance of SC on general management and computer applications, followed far behind by SEM and CONF;
* an almost complete lack of interest for SEM, CONF and WSHOP;
* water resources engineering, followed by environmental issues receive as much importance as irrigation engineering;
* the low score of waste water irrigation and energy use and conservation probably shows the low priorities these areas receive in irrigation; and

* the medium score of irrigation management, general management and human resource development shows that considerable effort is being made to address these important irrigation-related issues at international forums.

Given the recent boom in number of SC on microcomputer applications at the international forum, the following paragraphs probe a bit deeper on the reasons why these types of SC are highly requested for. The introduction of microcomputers in the field of irrigation, as is the case in other areas, opens unknown territories, presents new opportunities and makes it possible to achieve substantial advances in the modeling of various processes and the analysis of alternative design, operation and management scenarios, far beyond what was imaginable a few decades ago.

The introduction of microcomputers, general and specific software help to better understand and solve project related issues such as: optimal planning, design, operation and management; accurate and timely prediction and monitoring of water source hydrography, canal flow and soil water conditions; accurate and timely collection and processing of agricultural, hydrological and meteorological data as a basis for accurate, timely, effective and equitable application of crop required water and fertilizers; thorough understanding of the soil-plant-atmosphere continuum as a basis for dynamic simulation and prediction of the status of soil water and solutes and crop yield; better assessment and control of the impacts on the environment and human health.

The widespread use of computers and the vast development of computer software has significantly changed the traditional approach in education, research and practice in many engineering fields, of which irrigation is no exception. Whereas in the past, many efforts have been spent on the number crunching and drawing making, today an irrigation engineer equipped with a good knowledge of computer use can free himself from such tedious and labourious tasks, and concentrate on the more judgemental and intuitive aspects of planning, design, operation and management. This presents an unprecedented opportunity to irrigation education by way of expanding the depth and breadth of theoretical and abstract ideas and subject matters that can be treated in classroom.

Furthermore, computers enable instructors to show to students how knowledge from diverse disciplines can be pulled together through the use of integrated models, which concatenates single or multiple processes. In addition, the recent inclusion of concepts of expert systems and systems analysis techniques in curricula of training programmes is only a few of the many collateral benefits, to irrigation and drainage education, obtained from the use of computers. Also they make easy the interpretation and, mainly, the extension of research findings. However, it is noted that the introduction of the computers has led to a decreased interest in data collection and field work. Computer uses to be appropriate require extensive field and laboratory data, and a good understanding of the processes controlling the performance of irrigation systems and irrigated agriculture.

4.3. CONTINUING EDUCATION

Professionals have typically lengthy formal education with clearly defined education levels usually of bachelors and frequently of master status. Their education follows a broadly standardized structure. Continuing education is important to them in keeping them abreast of developments in methodologies and technologies and in providing less formalised training that concentrates on the practical application and aspects of irrigation, which are not well covered in formalised education. Significant too is the role of continuing education in development of the interpersonal and managerial skills necessary to allow professionals to develop within an organisational team and ultimately, with experience, become the manager of such a team. The importance and value of continuing education for professionals is being increasingly recognized. Even an optimal composition of the staff requires upgrading of skills because of scientific and technological progress, increasing requirements of the enterprise, competition among companies, different responsibilities of public service, etc.

According to Van der Beken (1993) continuing education aims at improving the effectiveness of the organisation by increasing the quality or the quantity of the output and the image of the organisation. In a commercial organisation this may directly translate into an increase in profits. For a research or academic organisation this may enhance the ability to win research funding. In a government organisation, better public service, reduced costs and hence reduced public expenditure may be the goal of more effective operation. In contrast to formal education, continuing education cannot follow the same pattern and needs to be individually tailored. The methods of continuing education can vary from on-the-job training to classroom-education, open learning, workshops, specialty conferences or self-learning. The techniques used range from elementary material, textbooks and printed material, correspondence and self-instruction material, multimedia techniques to advanced learning technologies (such as computer aided instruction or -learning).

The enterprise or organisation is greatly responsible for monitoring its staff to recognise at an early stage those who need further training and which skill is to be enhanced. The role of the enterprise is to identify the objectives and the type of training programme needed, to put the necessary funds aside, and to generate the interest of the potential trainee. The latter can be achieved by offering incentives (e.g. promotion or higher salary). The success of continuing educational programmes also strongly depends on the interest, commitment and dedication of the employee. Full harmony between the interest of the trainee and the objectives of the organisation can only be achieved through the adequate choice of the content and form of training.

Programmes of continuing education, also in the field of irrigation, are becoming increasingly popular in the developed countries. However, they are very few in the developing countries, mainly due to lack of funds and interest of the enterprise or organisation. In addition, there is the temptation of the organisation to suggest to the trainee that he/she himself should initiate continuing education in order to save money. Furthermore, the developing countries have not yet full recognized the benefits of continuing educational programmes as a means to improve the performance, motivation and dedication of ageing staff.

5. Training Means

How much money and time should a country or a project devote to training programmes in irrigation, is an extremely difficult question to answer. The amount of training resources needed for a country or a project varies according to the specific needs and budget of the country or project authorities. According to EDI (1989) private corporations dealing with rapidly changing technology may devote over 20% of their administrative budget to improving the performance of their staff. Irrigation departments suggest 3 to 5% of staff time devoted to improvement is appropriate. According to Jensen (1991), each such case may be unique, but the bottom line is that funds should be specifically budgeted and allocated for management and staff training, and that external funds are appropriate for precommissioning costs and to establish facilities and training capacity for continuing operations. Jensen (1991) further argues that recurrent costs be considered as an integral part of the costs of operation and maintenance.

Training means are a major stumbling block behind ineffective training programmes in developing countries. This is generally due to endemic economic hardships experienced by developing countries. On the other hand, the problem is exaggerated by misguided and wrong priorities prevalent in developing countries which tend to starve irrigation of the much needed funds for training programmes. One way of solving the problem is to reinvest part of the irrigation profits into irrigation training programmes. This can be a realistic source of funds for training programmes at farm and community level, but will seldom be of help for the funding of professional training programmes.

6. Conclusions

There is a need to formulate and implement training and research activities on both national and regional basis if the several urgent and practical problems in irrigation are to be solved. In so doing, one should try to avoid repeating the 'old' mistakes and shortcomings of former training programmes and opt for interdisciplinary curricula of programmes, under which the right blend of engineering, agronomy, economics and social sciences are pursued. In addition, attention should be given to modern technologies, such as information and computer sciences, operational research and expert knowledge in those programmes. At the same time, particularly when training is provided in the regions where irrigation is practised, one should not forget to devote a sufficient amount of time to field training.

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NORTH-SOUTH COOPERATIVE RESEARCH ON SUSTAINABILITY OF WATER RESOURCES UTILIZATION IN AGRICULTURE

M. CATIZZONE
Scientific Officer
European Commission
Directorate General XII, STD3 Programme
200 rue de la Loi, B-1049 Brussels, Belgium

1. Research with Developing Countries (CDs) and European Commission (EC)

The European Commission (EC) has, since 1983, initiated scientific relations with DCs in order to strengthen research capacities in DC's and European Union on themes and problems related to development.

Scientific cooperation with Developing Countries (DCs) began with a programme "Science and Technology for Developing Countries" (STD). A few years later this was followed by the "International Scientific Cooperation" (ISC) initiative and more recently by the "Avicenne" programme.

STD is a thematic research programme, which aims are to improve living and health conditions in DCs, but ISC addresses research needs identified bilaterally by the EC and individual countries in Asia, Latin America and the South Mediterranean. Avicenne was created to build up scientific activities specifically focused on Mediterranean issues and on shared perspectives for North Africa, Middle East and Europe relations.

The common objective of these EU research programmes was the promotion of a framework of mutual understanding, encouraging cooperation between research teams. Its main instrument is joint research projects where scientists of DCs and EU are "forced" to pool their research capacities in a complementary way.

Many but not all DC's have skilled scientific teams and well-equipped research institutions. Nevertheless the synergy generated through collaboration in jointly identified, prepared and implemented research activities is undoubtedly reflected in a better focused and higher quality research effort, in addition to improved cost-effectiveness.

These research initiatives have been created to stimulate researchers to concentrate on problems which are of mutual interest and which address issues present in DCs. They are not "donations", and for this reason they are subject to highly competitive

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evaluation/selection procedures. Only projects considered scientifically original and of the highest quality, while satisfying the criteria requiring team integration, can be funded.

The three programmes supported somewhat different scientific areas but in all of them water was unanimously considered as a basic, important and specific field of research cooperation.

1.1. STD AND WATER RESEARCH IN AND FOR CDS

The STD (CEC/DG XII,1993) reference framework has evolved in its ten years life. The first STD aimed at raising the interest of the researchers, in Europe and in the South, integrating them in a workable partnership. The first STD worked on (inter alia) problems linked to dams and large irrigated perimeters, and other aspects of water use in agriculture. This approach was developed in the second STD (1987-1991) and research contracts were concentrated on irrigation for the control of salinity and improvement of soil fertility; minor constructions (dams, micro-catchment lakes, drainage, etc..); improvement of irrigation techniques (drip, underground, etc...); problems linked to the irrigation (sedimentation, lowering of the water table, weed control, evaporation); traditional irrigation systems and its transformation/ improvement; computer simulation and modelling of irrigation system performance using also remote sensing.

For the third STD programme (1991-1994) a more specific reference framework was created and water use and management in DCs considered as a complex entity involving cultural, socio-economic and legal factors.

This concept also emphasizes that the improvement of traditional methods of water conservation and water harvesting should be considered as a starting point in the analysis leading to an agriculture which is sustainable and profitable to farmers.

It has been recognised that research for developing countries has to be planned having in mind the various partners involved and the need to promote non-destructive use of key natural resources. This holistic and evolutionary approach gave due weight to resource-poor farmers who traditionally have not seen their technological needs sufficiently well addressed.

It has become evident that researchers need to take into account the ethnographic environment where research results are going to be used and consider local systems of problem solving. Solutions and recommendations must be understandable to decision makers and adapted to local conditions.

In STD3, we are looking for new interdisciplinary research approaches which try to understand the causes and mechanisms maintaining underdevelopment and not only to look for solutions to specific technological problems.

The STD3 reinforced its impact with supporting measures such as coordination meetings and the promotion of research activities in particular fields. In this context, a specific workshop was held by STD3 in Lisbon in October 1991 which produced "Research Agenda on irrigation, drainage and water related issues in DCs". The participants drew the attention of all interested people the following research themes :

- modern irrigation methods made appropriate to the least developed technological context;
- decision support systems at various levels;
- transnational river basin management for multiple water uses and environmental protection;
- water management with diminished authority;
  a) integration of the social and natural resource policy context of irrigated agriculture;
  b) management and design interaction in relation to community dynamics and local managerial capability;
  c) assessing and managing third party effects of irrigation water abstraction and use;
- monitoring and evaluation of irrigation and drainage systems;
- if and when to use water; deficit irrigation;
- development of a working interface between irrigation research and practice;
- environmental sound and affordable practices for sustainable agricultural production.

This comprehensive research agenda for cooperation with DCs on irrigation, drainage and water related issues must be considered as a first step towards a much broader discussion amongst an expanded number of experts in the international research community.

1.2. THE ISC SCHEME

Water is the subject of a number of projects supported in the different countries covered by the ISC (CEC/DGXII, 1992) scheme (Asia, Latin America, Mediterranean). For example, water is a research priority in Mexico and is reflected in the joint activities carried out in the framework of the scheme. Research projects include novel approaches to water treatment, hydrological studies and the fate of agrochemicals in aquatic ecosystems.

In other countries water-related projects include biological monitoring of rivers, weather forecasting research and studies of climatic change. In general, it has been found that the ISC scheme has permitted European scientists access to new environments, intellectual as well as physical, and at the same time has enabled their expertise to be employed in a collaborative way on research problems faced in third countries. In this way benefits have accrued to science and scientists on both sides.

1.3. THE AVICENNE INITIATIVE

This research action created in 1992 (CEC/DGXII, 1993 "Avicenne"), concerns

Science and Technology cooperation between the EU and the Mediterranean third countries in two main areas of mutual interest and regional impact : the environment and health.

Since its beginning water research was specially supported in relation to the improvement and conservation of water resources, desalination and establishing the location of water resources.

With the action launched in 1993, there was a specific emphasis on water resources management. In this framework, water is defined as a limited and vulnerable resource, essential to support life, to promote economic development and to preserve the environment : it should therefore be considered as an item of vital, social and economic importance. In the Mediterranean Basin countries, there is considerable pressure on this resource, not only in arid or semi-arid regions but also in higher rainfall areas. There is very fast demographic growth in the region. The current development model of industrialized countries generates excessive consumption of natural resources and particularly of water. The existing and fast-growing competition between different sectors for the use of water (domestic needs, agriculture and industry) underlines the need for well researched policies and technologies aiming at preventing resource wastage and/or increasing its efficient use :

The area covered by the research contracts awarded in 1993 concerns :

- the characterisation, evaluation and classification of water resource (hydrology, water cycle, dynamics etc...). This includes both freshwater and Mediterranean Sea water;
- definition and development of scientific methods for the control and surveillance of water resources (including underground water, fossil water and the Mediterranean Sea). Assessment of the extension of pollution of these resources;
- new techniques to develop a greater end-user efficiency by various consumer groups (domestic, agricultural, industrial), depending on qualitative and quantitative needs. Planning of the rational utilisation of water resources;
- treatment processes for waste water and its regeneration after use. Development of appropriate physical, chemical or biological techniques to separate contaminants from waste water of industrial, domestic or agricultural origin, enabling its reutilization;
- water conservation and storage techniques;
- prevention of contamination in underground water, particularly by agrochemicals and industrial wastes.

2. Elements for the Debate

The European Commission has acted in a wide and international context, with the aim to incorporate the DC researchers, jointly with the European ones, in the international effort for rationalising water use.

Many of the researchers working in EC research projects were requested to attend international meetings and symposia where they valorized the experiences conducted through the EC research programmes.

In the meantime the international context for water use and research was clearly redefined (Dooge 1993). A new milestone was the "International Conference on Sustainable Development" in January 1992, in which for the first time water is declared a "economic good". The four principles of the Conferences, better known as "Dublin Statement", claimed:

- **Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment.**
- **Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.**
- **Women play a central part in the provision, management and safeguarding of water.**
- **Water has an economic value in all its competing uses and should be recognized as an economic good.**

These "simple" principles have produced almost a revolution in the actions related to water. They are also incorporated in the "Mediterranean Chart for Water" (October 1992).

In the same time, the World Bank (September 1993) was identifying a new approach to water resources management. Called "Comprehensive Framework" (see Fig.1). The scheme provides a conceptual approach to water combining the presence of : multiple actors, multiple criteria, multi-integrated levels, policy instruments, and impediments. In other words interested people, experts, researchers, decision makers, politicians have to be aware of the scheme and its interaction if they want to achieve the objectives of a sustainable development.

If Dublin was the first new milestone, the UN Conference on Environment and Development in Rio de Janeiro (June 1992) was the finalization of a comprehensive framework for all activities related to environment and development (ICSU 1992, Blaike 1989).

It is important to recall principles 1 and 5 of the UNCED Declaration that claim:

"Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature."

"All States and people shall cooperate in the essential task of eradicating poverty as an indispensable requirement for sustainable development in order to decrease the disparities in standards of living and better meet the needs of the majority of the people of the world."

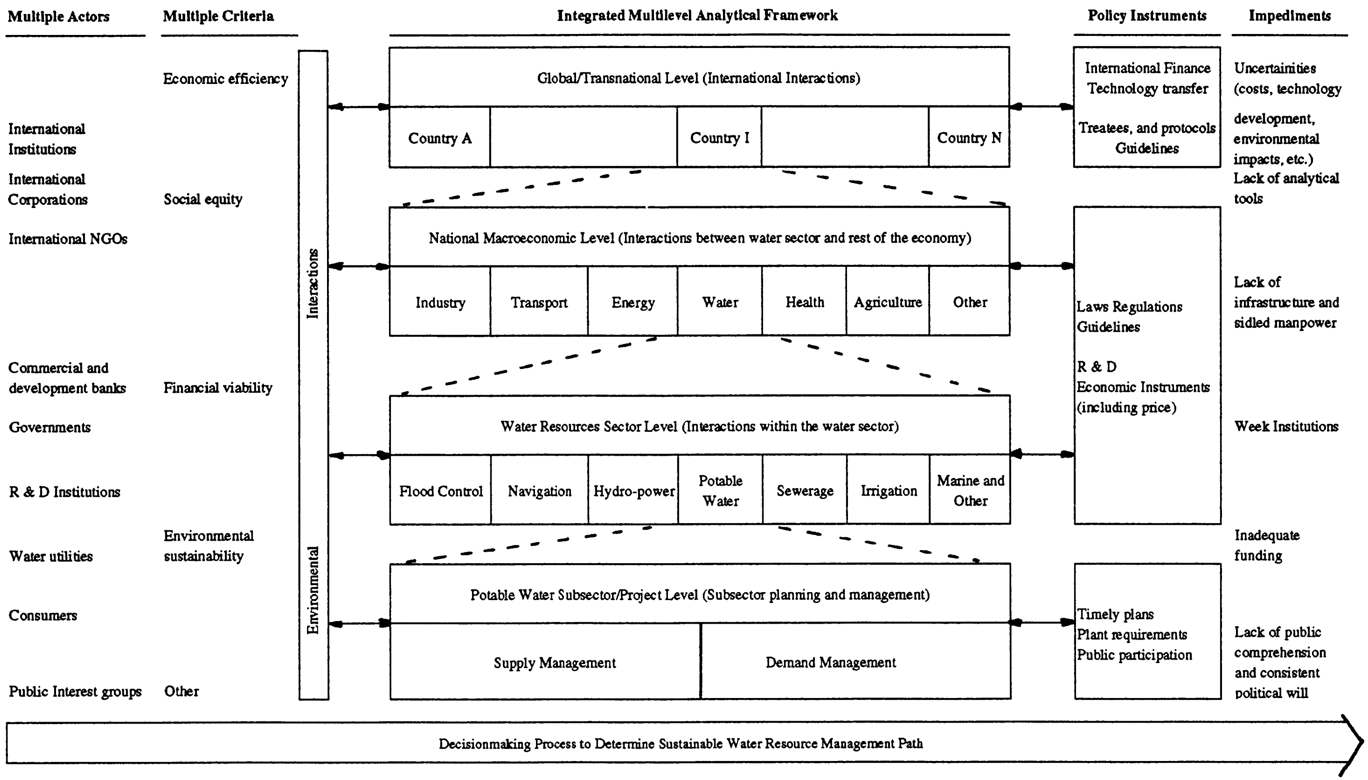

Figure 1. Conceptual Framework for Comprehensive Water Resources Management (The World Bank, 1993)

How to take care of these principles in conducting our researches on water and sustainable development ? How to take care of eradication of poverty and how to put the human beings at the centre of the research activities ? Consequently, how to modify our research methodologies and parameters on water and sustainability ?

These questions involve the international/national bodies and the water researchers.

A test of how to implement Rio's principles is the "Convention to Combat Desertification" (November 1993), still in negotiation. The originality of the Convention lies in its language. Behind the already known planning at local-national-regional-international levels, the need for an integrated approach able to reduce debts, dependencies and in the same time to eradicate poverty (see Fig.2) is clearly indicated.

3. Eradication of Poverty

What does eradication of poverty mean ? It is possible to represent this schematically as a "Vicious Circle" (see Fig.3).

- Human degradation affects all DCs as well as many countries defined as industrialized (in recent international documents the words "poor" and "rich" are increasingly used to distinguish the two realities of development).
- Poverty means backwardness, recognition of which implies an endeavour to escape from a degraded situation.
- Automatically, this endeavour produces emigration, chaotic urbanization, and other consequences including religious fanaticism, radicalism, nationalism, racism, rejection and other drastic reactions against the weakest section of the population as violence and slavery.
- Meanwhile, the rich industrialized world has adopted in many cases a short-sighted vision of the "vicious circle", considering the DCs either as a potential market (advantage of which can be taken to export pollution and use made of cheap labour intensive production), or to which its own way of life may be exported as a means of preserving its present leading position (but this is accompanied by the unwanted aspects of corruption, speculation and unproductive revenues).
- The only possibility of survival for the population in many DCs is linked to (over) exploitation of own natural resources, which are mostly limited and not easily renewable. This inevitably produces deforestation, land degradation, loss of fertility, major extensions of urbanization, loss of biodiversity, all of which result in more poverty and increased human degradation.

INTERNATIONAL CONVENTION TO COMBAT DESERTIFICATION
(Still in negotiation)

Art. 4
General Obligations

In pursuing the objective of this Convention, the Parties shall :

a) adopt an integrated approach addressing the physical, biological and socio-economic aspects of the processes of desertification and drought;

b) give due attention, within the relevant global and regional bodies, to the situation of affected developing countries with regard to international trade, marketing arrangements and debt;

c) integrate strategies for poverty eradication into efforts to combat desertification and mitigate the effects of drought;

d) promote cooperation among affected country Parties in the fields of environmental protection and the conservation of land and water resources, as they relate to desertification and drought;

e) strengthening sub-regional, regional and international cooperation.

Figure 2. Rio de Janeiro principles to combat desertification

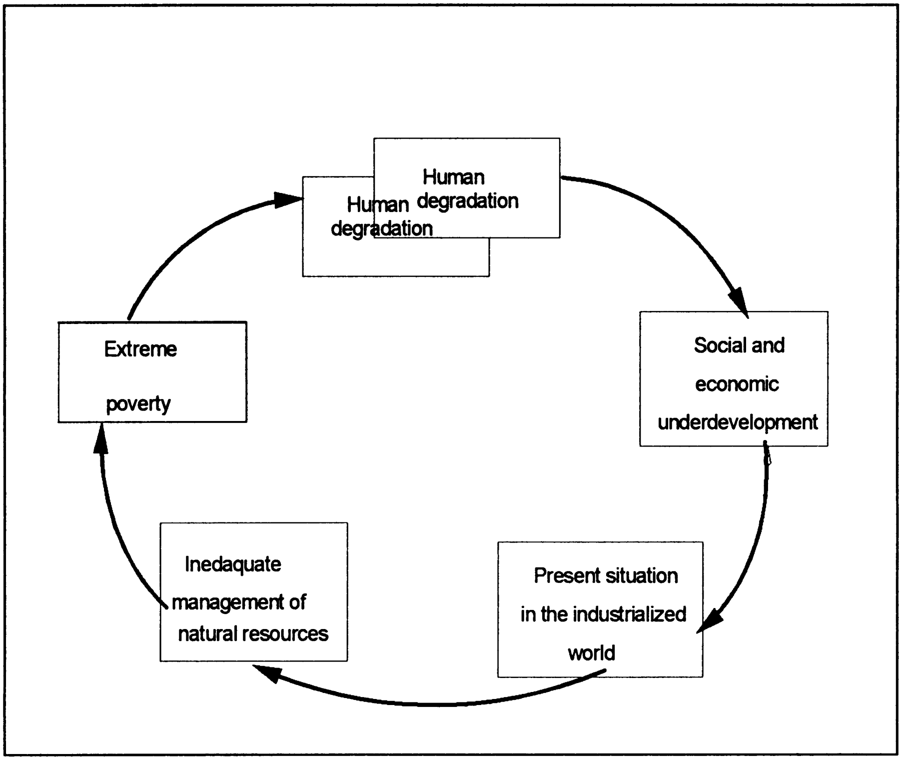

Figure 3. The vicious circle of underdevelopment, poverty and human degradation

With these points in mind, it is evident that it is necessary to develop a new paradigm with which to respond to challenge of the world survival (Chambers 1993). A major effort is required of researchers, because they must provide new and safe ways to use world resources. Researchers are asked to translate the principle of "sustainable development" into pragmatic actions. This new scenario causes the researchers to re-define their role and their on-going research activities to carry out the necessary scientific work. They are now forced to go far beyond their disciplinary limits to get rid of old biases and to create a new open conceptual framework (Funtowicz and Ravetz 1990).

Some researchers already started this new approach to research. One example could be the University of Laval (Calkins *et al.* 1992), which tried to define a methodology able to measure "happiness" (see Fig.4). It can be considered as a new tool for integrating new science and normal disciplines.

4. The International Context

If the UNCED in Rio and the "Statement" of Dublin created the new basis for research and development concerning water, the international bodies still consider the researchers in a closed configuration (Williamson 1992).

World Hydrological Cycle Observation System (WHYCOS), Global Terrestrial Observation System (GTOS) (Heal *et al.* 1993), Global Climatological Observation System (GCOS), Committee on Earth Observation Satellites (CEDS), Global Resource Information Database (GRID) (UNEP 1993), etc.. are acronyms of different activities using basically the same approach for monitoring the "natural" resources of the planet. Their context does not fully take into account the recommendation of the UNCED conference.

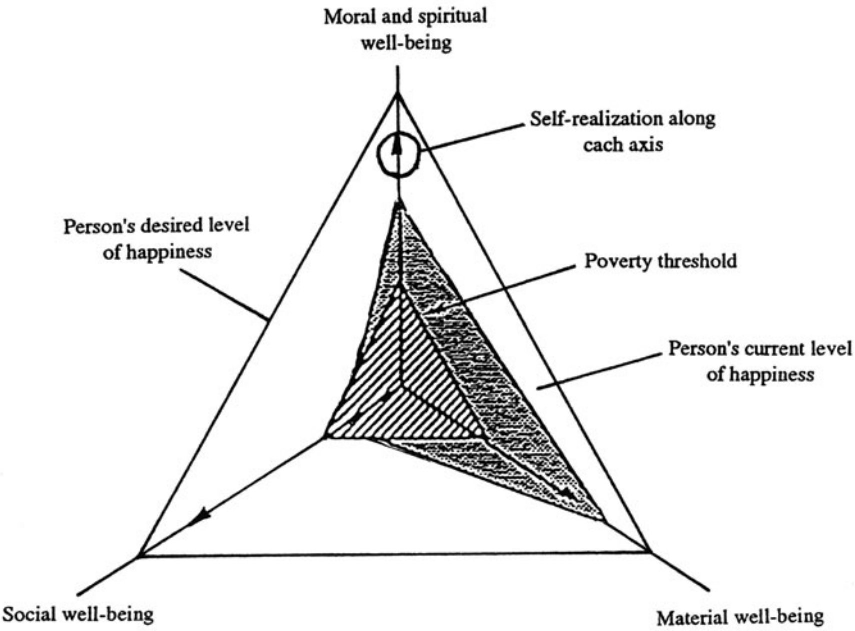

Figure 4. A person's self-realization, happiness and poverty threshold (Calkins *et al.* 1992)

In fact the physical elements of the ecosystems are in this way monitored but human components, especially in DCs, are still the weak points to be incorporated. Moreover the DC participation is still marginal and passive. The DC partners are considered recipient of decisions taken in an external context. Rarely it is recognized that the local knowledge can actively indicate scientifically sustainable actions for development.

The gap between local and foreign researchers is not more in the scientific knowledge, but in their capacity of dialoguing with local people.

A deep change in mentality is required, this means different way to act. It must be recognized that the industrialized life style is not considerable as "sustainable" for all the planet. This implies a more realistic vision of people research capacity. For example if a village's life is measured through the quantity of grains that is able to produce, it is possible to reach the conclusion that it is under the minimum level of nutrition. But if all the village's activities are considered globally, it could be possible to find out that a impressive quantity of people's labour and time is spent in unremunerated activities able to cope with the ecosystem (fishing, collecting of natural edible grasses, production of tools used for exchange, etc...). This provides a positive picture with a useful and sustainable integration between man and environment.

What are the key elements to be analyzed to improve the life conditions of the population in this context is the key question, that needs the synergistic analysis and action of researchers and development actors.

A real "dialogue" is possible only if the interest that lay behind the formal relationship is clear. The concept of "Mutual Interest" in research should become the common matrix for both participants. The interest can be direct (use a resource), indirect (reduce emi/immigration), or opposite (deforestation). If we want to use rationally the world resources we should not forbid their use to DCs. On the contrary, we should indicate where and how to use them in a possible sustainable way and, if their use is not sustainable, indicate alternative actions or the costs to be supported by the international community for not using that resource.

5. Conclusion

The international evolution for mono-disciplinary into a multi/disciplinary research and from "research for creating researchers", to "research for creating sustainable development" allowed the EU research programmes to incorporate better their own endeavour in the international concern on the sustainable development.

The world is running faster than research programmes. Luckily it is becoming easier to get in touch from Europe with researchers in Latin America, Asia or Africa. The new researcher generation is able to use easily the new communication tools and the concept of "laboratory without walls" is already a common reality.

The future EC research programmes will cope with these new identities hoping to create stronger synergy with the research capacities existing at DCs and international levels. The focus will continue in how to improve the dialogue with the DC researchers and how to allow a better dissemination and implementation of the research results and the way to implement it will be in agreement with the new international context developed in recent years.

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TECHNOLOGY TRANSFER FOR SUSTAINABLE WATER RESOURCES DEVELOPMENT

M. SMITH
Senior Officer Irrigation Management
Water Resources , Development and Management Service
Land and Water Development Division
Food and Agriculture Organization of the United Nations
Rome, Italy

1. Introduction

Irrigation has played a major role in the increase of agricultural production. Presently 245 million ha or 17% of the total arable land in the world are irrigated providing 35% of food production. To sustain the ever-increasing world population, production from irrigated land needs to provide 45% of the total food requirements by 2010 (FAO 1993a).

There is reason for concern about meeting these targets as growth of irrigated areas has been considerably reduced (from 2.3% annually to 0.8% at present) due to the shortage of suitable land and water resources and an exponential increase in costs for new irrigation developments. Furthermore, the performance of many irrigation schemes is disappointing as a much lower productivity has been achieved than originally planned and as substantial areas are affected by poor maintenance or problems of waterlogging and salinity (FAO 1990, Smith 1994).

Given the limitation to further expansion of irrigated lands, an important part of the water needed to satisfy future food requirements will need to be covered by a more efficient and sustainable use of irrigation water (FAO 1993b). The introduction of more efficient water management techniques has, however, proved to be a major bottleneck.

The introduction of appropriate irrigation techniques and practices both at scheme and farm level will require a major focus, in which not only the technique and technology itself will be important but much more the process of introducing the technology into the farmers' fields .

In the following, the various aspects of technology transfer in irrigation will be further evaluated focusing in particular on technology transfer at farm level. The various types of programmes used to introduce improved water management practices will be briefly reviewed, while the different aspects which are important in the technology

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 553–568.

transfer process will be evaluated based on FAO's experience in the on-farm water management development programme in Indonesia.

2. Technology Transfer Programmes in Irrigation

The importance of introducing efficient and sustainable use of water for irrigation has been recognized for a considerable time and a range of technologies has been developed to improve water use efficiency at farm and system level and to ensure the sustainability of the irrigation system (FAO 1990). Such improvements typically include system improvements by canal lining and regulating structures, appropriate field irrigation methods, the development of irrigation water delivery models at field and system level, salinity control measures and drainage systems, crop diversification and intensification programmes. Various research institutes and numerous projects have developed and tested a range of potentially promising approaches and technologies.

Even if the results have proven their value and relevance in the experimental field or pilot area, their application and adoption in the farmers' field have been often disappointing.

Unless an adequate mechanism and appropriate procedures are established to introduce, test, demonstrate and adopt the use of promising new techniques at system and field level, most efforts to achieve a greater sustainability water resources utilization are doomed to fail.

Unfortunately, too few irrigation scientists are interested, trained or given the means to become involved in the often cumbersome procedures of introducing new techniques in the field. This problem is particularly pronounced in developing countries, where the educational level of farmers and field staff and the lack of a practical approach of irrigation specialists have proved to be major constraints.

Over a range of years and in a range of projects and programmes worldwide, both in developing and developed countries, efforts have been made to introduce better water management techniques at farm level. Four different categories of such technology transfer programmes may be distinguished:

- the agricultural extension approach,
- the on-farm water management approach,
- the participatory water users approach,
- the irrigation research approach.

2.1. AGRICULTURAL EXTENSION PROGRAMMES

Over the last 25 years considerable efforts and resources have been put into establishing agricultural extension systems and most countries have introduced an extension system for disseminating new agricultural technologies to farmers, including irrigation (Swanson *et al.* 1990).

There is no doubt that agricultural extension has played a crucial role in the often impressive increase in agricultural production, in particular in irrigated agriculture, where the introduction of new high-yielding varieties, fertilizers and pesticides and the provision of credit for purchase of agricultural inputs have been highly successful (Contado 1990).

Although irrigation and water management figure prominently on the list of essential inputs to enhance agricultural production, inputs have been limited mainly to the installation of irrigation facilities by the irrigation department. The extension service seldom takes new irrigation techniques and technologies as a topic to be introduced through its extension programme. One reason is that the agricultural extension services, already short of adequately trained subject matter specialists, have in general no or few staff adequately trained in water management, even in cases where water management is recognized as an essential element in agriculture.

Another important reason is that in many cases the irrigation department, responsible for irrigation development but often situated in a different ministry, is considered the competent agency for these types of activities. Irrigation departments like to construct, however, and little experience and interest exist in these departments to become involved in the cumbersome process of farmers' training, while inter-departmental competition often excludes the extension service from effectively participating in an irrigation technology transfer programme.

2.2. ON-FARM WATER MANAGEMENT PROGRAMMES

In the 1970's already, the need for efficient water use at farm level was fully realized, as serious salinity and waterlogging problems (Pakistan, Egypt) and water shortage problems arising from new settlement schemes (India, Latin America, Far East) required urgent solutions.

A number of on-farm water management projects were implemented in several countries with the specific aim of introducing better water management techniques and practices at farm level (Smith 1981) . Among them may be mentioned in particular the on-farm water management programme in Pakistan initiated in the 1970's with the financial and technical assistance of USAID in Pakistan (Kango 1981). This programme successfully introduced new water management techniques such as canal lining, improved regulating structures and field levelling and gave due attention to the participation of farmers and the promotion of water users' associations.

The command area development programmes in India and Bangladesh and a range of small-scale irrigation programmes worldwide all had important components of on-farm water management development, where the introduction of new irrigation technologies played an important role.

For various reasons, however, in many of the on-farm water management programmes the main emphasis was left on the physical aspects of irrigation development.

Construction of canals and pumps and field levelling implemented by engineers and construction companies formed the core of activities. Systematic efforts to ensure and sustain the introduction of improved water management practices were unfortunately few.

2.3. WATER USERS' PARTICIPATORY PROGRAMMES

Rural development projects, initiated in many countries over the last 20 years, have often been linked with the introduction or rehabilitation of irrigation facilities and have highlighted the importance of the participation of farmers in the technical development process as a condition for success. Low performance of irrigation projects was increasingly linked with inadequate involvement of farmers in the design and implementation process (Scott *et al.* 1993). The establishment of water users' groups or water users' associations (WUA) as a representative body for farmers evolved as the more successful procedure to involve farmers and to secure their cooperation and participation in the irrigation development process.

The transfer of responsibility to farmers' groups of at least part of the operation and maintenance of the scheme became an important additional consideration for the promotion of the WUA, as the increasing burden for operation and maintenance of the irrigation system on public funds proved increasingly difficult to maintain. Realizing the financial independence and satisfactory performance of traditional irrigation systems, governments, with support from donors and lending organizations, have increasingly promoted the establishment of water users' associations in transferring management and maintenance responsibilities to the users with the double aim of reducing public expenditures in irrigation and improving the performance of the irrigation systems by a greater farmers' involvement (Vermillion and Johnson 1993).

Good results have been reported from areas where farmers, mostly under specific pilot programmes and with adequate socio-technical support, have been able to form viable water users' associations.

Expanding such programmes successfully on a wider and national scale has proved to be a more difficult task. Sustained support to farmers'' associations, a strong legislative framework and a consistent national policy are essential conditions to bring about a sustainable transfer of responsibilities on a national scale.

The main emphasis in the water users' programmes has been on the institutional and management aspects of the associations; less attention has been paid to the introduction of good water management techniques as part of the effort to transfer responsibilities to the farmer-controlled irrigation system.

2.4. IRRIGATION RESEARCH PROGRAMMES

The main tasks of irrigation research institutes and projects lie in the development of appropriate techniques and technologies in irrigation and water management. Where researchers are also purposely involved in the process of introduction of the techniques in the farmers' fields, they can play a very successful role in the process of technology transfer.

This process of adaptive research where new technologies are tested and adapted to local conditions and the farming system should be seen as an essential aspect of irrigation research.

The beneficial role of involving research and educational institutes in the technology transfer is successfully applied in the USA where universities may assign their staff the triple task of research, teaching and extension (Axinn 1988). Here the essential link between research and extension is fully exploited as the researcher is directly confronted with the need for appropriate technologies and the constraints adopting these at field level. The benefits are clear for both parties, as farmers will directly profit from new research findings while the researchers will be confronted with realities and problems in the farmers' field and direct his research efforts to solve these problems.

Large irrigation and water authorities may also employ their own research staff, ensuring that the adoption of new technologies is integrated into the development of new techniques and technologies.

Commercial firms, providing agricultural inputs to irrigated agriculture, including irrigation equipment, or producing commodities from irrigated agriculture, can be successfully involved in the development and introduction of improved irrigation and water management practices. Also here the link between adaptive research and irrigation extension is clearly established, as efficient water use is directly linked to better production and higher profits.

3. Main Elements of Irrigation Technology Transfer

The technology process proves a crucial element in each irrigation development programme. No standard solutions can be provided as each case proves to be specific to the typical institutional, technical and agro-ecological conditions of a given country. The development of appropriate procedures for technology transfer adapted to the local conditions therefore forms an essential element in the success of any technical assistance programme.

FAO is actively involved in a range of countries worldwide in the introduction of new irrigation technologies and techniques (Stratford *et al.* 1993). To review the various elements which need to be taken into account in the development of a successful technology transfer programme, the example is taken of the On-farm Water Management Programme (OFWM) in Indonesia.

The FAO On-farm Water Management Programme in Indonesia. For more than 10 years FAO has been involved in Indonesia in the development and introduction of improved water management at farm level (Smith 1993). Technical assistance has been provided since 1983 to the Directorate for Land Rehabilitation and Development of the Ministry of Agriculture in seven provinces in Indonesia. Main objective of the programme is the introduction of improved on-farm water practices through direct support to the Water Users' Associations. Through a process of training and testing various development procedures, a successful programme has been developed which has now been adopted on a national scale and is being introduced in several regional irrigation development programmes.

Although solutions may be country-specific, the experiences in the development of the programme may provide a good example of the various aspects which have proved to be important in the technology transfer process of irrigation to the farmers' field.

3.1. INSTITUTIONAL FRAMEWORK

The staff and agencies involved in the introduction of improved water management are essential elements in the process of technology transfer. In the OFWM Programme this proved even more crucial than originally anticipated.

The task of introducing improved water management in the farmers' fields was originally assigned to the water management officer at district level. This officer is a field technician with a higher agricultural education and is responsible for the development and implementation of land and water development activities of the Ministry in the concerned district. Monitoring and guidance are provided by senior technical staff in each province, which supervise 20 to 30 district officers.

The formulation of the tasks of the water management officer in the on-farm programme was the basis on which a specific curriculum and training programme was prepared which included training in water management concepts and technical procedures for the introduction of water management improvements based on a diagnostic field analysis of the farm irrigation system.

The training was successful in so far as the officer was able to prepare and implement a water management improvement plan with reasonable success. However, the communications with the farmers in the preparations of the plan remained weak and, once the construction works were completed, little follow-up was given in strengthening the water users' association and in introducing better operation and maintenance practices. The sustainability of the improvements therefore remained in many cases restricted to the physical improvement of the scheme.

In order to ensure better communication with farmers over a sustained period and also to integrate water management with improved agricultural practices, the field extension worker and subject matter specialist of the agricultural extension service were engaged in the programme. This proved very successful as in particular the field extension worker has easy access to the farmers and an excellent knowledge of local conditions. His or her inputs combined with the technical support from the water management officer and the extension specialist proved a successful combination in the implementation of the support programme with the WUA.

The various staff involved in the programme required a good coordination and proper instructions on their specific activities and workplan. Additional training courses were required for each staff category to prepare them for their specific tasks and to provide the necessary background knowledge in water management.

Adequate attention was also given to the involvement of officials and coordination with other line departments and ministries involved in irrigation development and local government. In particular, the cooperation with the Ministry of Public Works, responsible for the design and operation of the irrigation system, proved important but not without constraints due to inter-ministerial competition.

3.2. STAFF TRAINING

The training of the different staff categories involved in on-farm water management proved a heavy burden but in many ways the key to results. Without an adequate preparation of the staff for their new tasks, no effective programme can be implemented.

3.2.1. *Curriculum Development*

For each staff category a skill analysis and training need assessment was carried out which formed the basis of the training programme design. Training was aimed both to give staff the necessary technical knowledge and background on the subject and to familiarize them with the procedures in their new tasks in on-farm water management. In particular this preparation for future tasks proved very important.

3.2.2. *Training Methodology*

The OFWM programme successfully introduced a three-phase training procedure to prepare staff for future tasks. A first 2 - 4 week training was conducted in the training centre and was followed by a practical period at the duty station. Here the trainee carried out a pilot study using the newly-acquired knowledge and skills and prepared a report on the case study results. The report was presented and discussed during a second training session in the training centre. This 3-phase training concept proved highly beneficial: the quality of the classroom training improved considerable as the topics focused on the tasks to be carried out in the field; the trainee had a chance to apply the procedure first, to overcome any initial resistance to a new task and to discuss the constraints and difficulties encountered.

The methodology was well appreciated in view of its obvious impact and was later also adopted in other technical training programmes of the Ministry of Agriculture.

3.2.3. *Training Materials*

Development of the training methodology and preparation of the training material with relevant practical exercises required a major effort and considerable OFWM programme resources were devoted to these activities. It proved however essential to secure quality and uniformity of the training.

3.2.4. *Training of Trainers*

Training of trainers, selection of good resource persons, evaluation and monitoring of the training courses were all additional elements to be given due attention in the development of the programme.

A constraint experienced in the development and implementation of the training programmes was the low prestige and casualness with which training was often regarded. When requested to provide a training session, experts and technicians take the usual handbooks and manuals from the shelves and routinely present the standard subjects and the topics in their own sphere of interest, often with little or no relevance to the future tasks of the trainees. Training of trainers is very much is a topic to be taken seriously if the impact of training is considered important.

3.3. FARMERS' TRAINING

The farmers' training evolved very much as the central part of the development process, the importance and extent of which only was fully realized in the later phase of the OFWM programme.

Although farmers are the immediate beneficiaries, no specific farmers' involvement or farmers' training was originally included in the OFWM programme. As is common in many irrigation development and rehabilitation projects, it was assumed that the irrigation technicians consult with farmers on the improvements and that the solutions constructed by the technicians be appreciated and properly used by farmers. This assumption proved largely incorrect: in order to indeed achieve the full involvement of farmers as a guarantee for sustainability, procedures for a systematic farmers' involvement and a sustained support to farmers over an extended period need to be developed and put in place. In the OFWM programme this was achieved by conducting a range of training sessions for farmers over a period of 2 years.

The approach and methodologies applied in the training were developed in a process of careful testing, close monitoring and continuous evaluation and adjustment. The following elements proved essential in the farmers' training process :

3.3.1. *Key Farmers*

The large number of farmers made it effectively impossible to train everybody. For that reason only a selection of representative farmers participated in the farmers' training sessions. Care was taken, however, that through informal contacts and local meetings all farmers were informed and involved in the programme. The selection of the key farmers was done in consultation with community leaders and village officals and was based on a division of the irrigation areas into 5 to 6 sub-blocks. From each sub-block 4 farmer representatives, including at least one woman, were elected to participate in the course. The block division proved a very workable unit, representing a homogeneous area and a group with a common interest in water allocation, which formed one of the key elements for water management improvements.

3.3.2. *Women's Representatives*

The representation of women in the course become very rewarding, as the number of women-managed farms represents a sizable portion, and fee contributions and conflict management are favourably influenced by the presence of women. Although at first somewhat uneasy, as women normally do not take part in technical training activities, their participation was quickly accepted and much appreciated.

3.3.3. *Training Schedule*

The training of farmers was organized in a range of well-defined training courses spread over a period of 2 years, each with its own programme and objectives.

A continuous training course was not considered suitable for farmers and the training sessions are therefore organized on a weekly basis on a fixed day of the week, assuring an opportunity for reflection and discussion with other farmers during the remainder of the week.

The first 5-weeks training course was aimed to introduce farmers the concepts and benefits of improved water management and to prepare a water management action plan to be implemented subsequently by the farmers. The second training course was conducted after 3 months over a period of 3 weeks, where results of the implementation of the water management action plan were evaluated and an improved cropping plan was prepared, covering water allocation, cropping pattern and appropriate agricultural practices. Subsequently every 3-4 months additional short training courses were organized over at least a one-year period to follow-up on the activities of the farmers' group, to identify shortcomings and constraints encountered and to promote and adjust the development plans.

The importance of a strict training schedule over a sustained periode of time may be compared with the procedures of the Training & Visit extension system introduced in many countries (Hayward 1990).

3.3.4. *Training Methodologies*

The training was built around group and field activities with a minimum of class room presentations. In particular the group activities, organized on a block basis, were much appreciated by farmers and provided lively opportunities for discussions. They formed the basis for a workable set-up in the water users' association based on irrigation blocks.

3.3.5. *Trainers of farmers*

The training of the farmers was implemented by a team of field technicians and included the water management technician, the subject matter specialist and the field extension worker. In particular the latter played an important role in the animation of the farmers' training sessions. The role of the trainer is that of a facilitator and resource person, rather than a lecturer. A continuous constraint proved the habit of many technicians to present too complicated lectures to farmers.

3.4. THE WATER USERS' ASSOCIATION

One of the main objectives of the on-farm water management programme was the establishment and strengthening of the water users' group into a viable and sustainable farmers' organization able to assume responsibility for the operation and maintenance of the irrigation system.

The WUA was therefore taken as the immediate target group of the farmers' training and adequate attention was given to the organizational and institutional aspects of the association and its financial management. The subdivision into irrigation blocks became the basis of the organizational framework of the WUA.

Once established as a functioning unit, the water users group, forms an attractive unit to undertake additional initiatives and can be easily involved in other training and extension activities of the Ministry of Agriculture.

Examples of such were the involvement of the water users groups of the OFWM programme in a joint programme with the Integrated Pest Management Programme of FAO in Indonesia.

As experience elsewhere has also proved, the formation of viable water management groups remains a tedious process with many pitfalls. Despite the obvious number of benefits, farmers must have compelling reasons to participate actively in the water users' association. Unless some basic conditions are met, water users' groups will not spontaneously form, function and remain operational. Some of the basic conditions are that the benefits for a majority of the individual farmers should be clear and obvious, while a certain harmony and homogeneity in the composition in the group should exist as strong social differences will lead to insurmountable opposition on the part of the farmers.

Strong local leadership and support from influential members of the community will be another important factor, along with adequate government recognition and regulations to support the activities of the water users' association.

The major factor for sustainability of the association is the confidence and trust in its board members. Too often the associations are used to better the interests of certain individuals. It is clear that once this becomes clear to the other farmers, the association is doomed.

Only rarely are all conditions met in a favourable way and a sustained support over some length of time is therefore almost always necessary to overcome at least part of the problems. Certain communities with too strongly opposed interest groups, will never be able to form viable units.

3.5. WATER MANAGEMENT IMPROVEMENTS

The types of water management techniques and technologies which may be successfully introduced will differ from one location to the other and depend largely on the specific conditions and constraints as determined by the existing infrastructure and the ecological and socio-economic environment.

It became clear that farmers and technicians often have different views on the best technical solutions. Technicians inclined to propose too complicated or unpractical solutions, while farmers will favour an indiscriminate increase in water supply. There is a clear tendency to emphasize the physical improvements of the system (canal lining, higher derivation dams) as it proves much more difficult to introduce successful management procedures (better water disribution, accurate field waterings) although here potentially the greatest benefits can be obtained.

Substantial improvements in the arrangements for water distribution can be achieved if more and earlier water can be made available to the downstream parts of the system. Better maintenance procedures, including farmers' contributions in cash and kind, will improve water availability, as will the introduction of appropriate procedures for field irrigation methods and the adoption of crop irrigation schedules. Drainage provisions and land conservation measures will prevent waterlogging and land deterioration.

The introduction of successful water management requires the adaption of the techniques and procedures to the agro-economic conditions of the farming system in order to be successfully adopted by farmers. This is not easy as a complex of technical, agricultural and management aspects needs to be taken into account. Any new technique should be profitable to be successfully adopted by farmers, requiring a close and extended cooperation between the technician and the farmer and farmer group, to find suitable solutions and overcome occurring problems.

The process of regular returning to the farmers through a range of scheduled training courses proved very important in the OFWM programme in order to provide an opportunity to discuss the problems experienced in introducing the new techniques and procedures and to adapt solutions. Both technicians and farmers benefitted. The technicians became more motivated and self-confident as with their greater exposure to the problems in the field greater and more valuable experience was built up and contributions became more relevant and appreciated.

3.6. DIAGNOSTIC ANALYSIS

The introduction of improved water management is very site-specific and, as no standard solutions can be provided, a process of problem identification and solution finding has been adopted, referred to as diagnostic analysis.

In the original OFWM programme approach the water management officers were entrusted with the task of diagnostic analysis, based on which the improvement plan was developed. This was changed in a later phase into a procedure included in the farmers' training course, where farmers systematically identify the water management problems, discuss solutions and propose an action plan for the implementation of the solutions.

This proved very successful as farmers are familiar with their own conditions, and, once shown the basics of water management problems, are well able to carry out the diagnostic analysis. The improvement plan proposed on this basis is also a guarantee for acceptance by the farmers. The agricultural staff and technical specialists should function exclusively as facilitators and technical resource persons, and should refrain from imposing their solutions.

3.7. INTEGRATION WITH AGRICULTURAL IMPROVEMENTS

Irrigation water management is not an aim in itself, but a means to increase optimal crop production in an effective, efficient and sustainable way. The additional income from increased agricultural crop production should indeed justify the additional expenses in irrigation water management.

In order to ensure that irrigated crop production indeed increased thanks to the irrigation facilities and improved water management conditions, adequate attention was given to an intensification and diversification of the cropping plan and the introduction of appropriate agricultural practices. This included improved seeds, integrated pest management, land cultivation practices and marketing conditions. The involvement of the agricultural extension staff proved very useful in this.

The agricultural improvements were, similar to the water management programme, introduced through a process of diagnostic analysis, carried out by farmers, who identified constraints and discussed and proposed solutions for improvements of the agricultural production system based on improved water management conditions.

3.8. COST SHARING

The financial assistance for the maintenance of public support services to the irrigation sector has become a growing concern and any assistance programme should have an economic justification in providing support services and subsidizing investments in the irrigation infrastructure. The specific aim of strengthening of the water users' groups is to transfer at least part of the responsibilities and costs of the operation and maintenance of the irrigation system to the beneficiaries.

In order to create from the beginning a commitment to responsibility and participation in the project activities, strict conditions were set for the provision of programme support in the form of construction materials. The contributions from farmers were a condition sine-qua-non and formed at least half of the total cost to be given in kind, in cash or in labour. The financial contributions provided by the OFWM programme were supplemental and one-time only.

In particular, the strategy also proved helpful in selecting the really viable schemes as only those farmers' groups where selected which indeed showed a strong motivation. Their willingness to invest a substantial contribution was a guarantee that improvement work were indeed technically and financially viable.

The integration of water management improvements with agricultural improvements allowed closer monitoring of the increase in agricultural production caused by improved water management, which should be in relation to the expenditures on physical improvements, staff training costs and the support services provided to farmers.

Evaluation studies on the impact of the OFWM programme showed typically an increase of 20 to 30% in agricultural production , mainly through a higher cropping intensity as areas previously not, too late or insufficiently irrigated, could grow a double or triple crop with better yields. Estimated benefits were in the order of $US 200 per hectare per year.

Costs for the programme amounted to approximately $US 50 per ha, of which 70% was destined for farmers, including the farmers' training and a subsidy for construction materials, while 30% was required for the training, travel and allowances of staff.

4. Conclusions

In summarizing the experiences related to the transfer of technologies in the field of irrigation and water management, a number of aspects may be listed for consideration in any irrigation or water management development programme:

4.1. INTEGRATION OF TECHNOLOGY DEVELOPMENT AND TECHNOLOGY TRANSFER

Technology transfer is an integral part of development. Any development programme should include as inherent part of its programme a mechanism to test, adapt, demonstrate and introduce new techniques and methodologies in the farmers' fields.

A greater involvement of research institutes in irrigation extension is a condition for sustainability of water resources development

4.2. ADAPTION TO LOCAL CONDITIONS

The introduction of new technologies and irrigation development should take into account the specific local conditions and the various technical, agricultural, institutional and socio-economic aspects.

- Diagnostic analysis or performance assessment has proved to be a useful procedure to introduce improved water management practices.
- The farming system approach will be helpful in assessing suitability and feasibility of new techniques in a given socio-economic environment.
- With increasing complexity of the techniques an individual approach in the adaptation process is required. The need for adequately trained irrigation technicians both for government services and for private organizations will

greatly increase, in particular in developing countries.

4.3. PROCESS OF TECHNOLOGY TRANSFER TO THE FARM

The process of introduction of new technologies into the farmers' fields requires careful analysis and the preparation of a detailed programme to ensure a successful and sustainable transfer. The support services to be provided by which institutes and agencies are to be determined, while approach and methodologies for farmers' involvement need to be determined and may include: mass communication, group activities and individual approach.

An individual approach seems most appropriate in developed countries, while in developing countries a participatory group approach is preferable in view of the number of farmers and the social coherence of the group.

Various techniques such as specially-designed training and extension programmes and mass information campaigns may be designed to ensure an effective support for transfer.

Appropriate and adequate government resources and policies should be available to ensure and sustain support services for the transfer programme.

4.4. INSTITUTIONAL FRAMEWORK FOR SUPPORT SERVICEs

The agencies and institutes entrusted with the tasks of technology transfer play an important role in providing the appropriate support services to farmers.

Traditionally the agricultural extension service has been the competent agency given the responsibility of technology transfer at farm level. Its lack of specific technical knowledge in irrigation and water management has proved a major constraint in the introduction of irrigation technologies. The irrigation agencies on the other hand have little experience and interest in providing effective support to farmers.

Establishment of a separate irrigation extension agency may prove to great a burden for an already overcharged public administration service. The role of semi-public and private organizations in providing paid or partly paid support services to farmers may provide an attractive alternative.

Each country will require its own solutions in finding the optimal institutional framework for technology transfer in irrigation.

4.5. STAFF TRAINING

The training of staff involved in irrigation development and technology transfer will be in many ways the key to the introduction of new technologies in irrigation, especially in water management.

Specialized training is required to prepare different staff categories for providing an effective support in technology transfer in irrigation development programmes.

Both in the public and private support services more technical manpower is required to assist in the process of technology transfer as well as adaptive research activities.

The design and implementation of training and educational programmes in water management will require, however, a major effort in many countries, as few staff are adequately skilled to implement the transfer programmes effectively .

4.6. PROCEDURES AND PROGRAMME FORMULATION

To be successful any technology transfer programme requires careful design and planning. Close monitoring and continuous evaluation of the transfer progress are required to indeed come to a successful strategy.

Appropriate and adequate government policies and strategies should be established to ensure the necessary resources and legislation to support the technology transfer programmes.

4.7. COST EFFECTIVENESS

Whatever programme is defined, its feasibility and sustainability will be determined by its cost effectiveness. Any public expenditures either for government staff providing support services or subsidies for improvement works should have a relevance on the expected benefits.

Any programme should promote the principle of self-reliance of farmers in operation and maintenance of irrigation facilities.

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PART VIII

REGIONAL PERSPECTIVES

SUSTAINABILITY CONCERNS IN ASIAN IRRIGATION

K. MOHTADULLAH, GAYLORD V. SKOGERBOE,
C. M. WIJAYARATNA
International Irrigation Management Institute
P O Box 2075
Colombo
Sri Lanka

1. Introduction

The term "sustainability" is now firmly entrenched in development rhetoric. Both international and national agricultural research institutes are under mounting pressure to develop technologies or formulate resource management strategies that are not only economically attractive to farmers but also minimize the depletion of the natural resource base and damages to the environment. Yet, the notion of sustainability has been subjected to such widely disparate interpretations and in a variety of contexts, which creates a potential for misunderstanding. Unless it is properly defined "sustainability" will merely become a rhetorical term which will lose its luster with time, rather than become an useful operational concept for policymakers, researchers and others attempting to formulate policies and strategies to foster economic development.

This paper provides a broad review of the more common definitions of sustainability. An attempt is made to arrive at a working definition for sustainability in relation to irrigation. This is followed by a discussion on the current concerns with sustainability of irrigation systems, with particular reference to Asian irrigation. The paper concludes with some proposals for developing a research agenda on sustainability issues in irrigation development.

2. The Concept of Sustainability

Sustainability is invariably used to describe a goal which is undoubtedly desirable. The word "sustain" is defined in the Oxford Dictionary as "keep from falling or sinking, especially for prolonged periods." In the context of resources and the environment, "sustain" would mean to maintain or prolong the productive use of resources and the integrity of the resource base.

Dixon and Fallon (1989) identify three distinct uses for the concept of sustainability.

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First, as a physical concept for a single resource; for example groundwater, fisheries, forestry and so on. Second, as a physical concept for a group or system of resources, such as agriculture; where the focus is not on a single component, but explicitly on a variety of outputs from the system of resources. Third, as a social-physical economic concept.

The expansion of the concept of sustainability from the context of physical resource base to broader goals of development, such as a sustained increase in the level of societal and individual welfare, may be attributed to the Brundtland Commission Report. This report defined sustainable development in terms of the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987). When it comes to agriculture, the Consultative Group on International Agricultural Research (CGIAR) in 1987 adopted the following definition: "A sustainable agriculture is one that, over the long term, enhances environmental quality and the resource base on which agriculture depends, provides for basic human food and fibre needs, is economically viable, and enhances the quality of life for farmers and society as a whole" (Crosson and Anderson 1993).

In relation to agriculture, the term sustainability could only be approached as an eco-system where a set of elements -- agricultural production units -- interact with their natural environment. Agricultural systems should be assessed in relation to four properties: (a) Productivity of the system, i.e. yield or income; (b) Stability of the system in terms of stable yields and income; (c) Minimum fluctuations of yield and incomes; and (d) Equity in terms of income distribution.

Sustainability of an agro eco-system may be one of the several socially desirable properties. For the incorporation of sustainability of agricultural production as a development objective, one needs to have an idea of the tradeoffs between those properties for maximizing social welfare. For example, maximizing yields in the past, especially during the era of the green revolution, occurred without paying attention to the stability of production increases or to the equal distribution of the benefits. In recent years, there has been increasing concerns for improving sustainability of agricultural production while maintaining productivity, stability and equity.

3. Irrigation Development in Asia

3.1. IRRIGATED AREA

There are many difficulties with statistical data for irrigated lands. However, the total estimated land under irrigation is approximately 242 million hectares (FAO 1992). Slightly more than 60 percent of this land lies in Asia, with China, India and Pakistan accounting for half of the world's irrigated cropland. During the time period 1960-90, the amount of irrigated land in Asia increased by 60 million ha.

Between 1950 and 1982 the World Bank loaned $10 billion for irrigation development, with 90 percent of these loans being made in the 1970s. These loans averaged around 40 percent of total project costs, so World Bank support represented a total investment of $25 billion. Donor investments have declined considerably since their peak in 1979 (Yudelman 1993).

In most countries, the potential for expanding the area under irrigation is diminishing rapidly mainly because of the escalating cost of tapping and developing new sources of water -- the easy and cheaper sources are already in use. Also, because of the decline in grain prices during the 1980s, the major donors have reduced the level of funding for irrigation development, especially for new construction.

The large irrigation investments in the 1970s resulted from a major shift in the supply of food, which occurred when the global production of food grains dropped due to unfavourable weather that prevailed in major grain producing areas. Consequently, grain prices (notably rice) rose sharply in the mid-1970s. Naturally, this signified a situation in which irrigated investments appeared to be "profitable." And in response to this trend, donors increased the level of lending for irrigation development. These investments were biased towards "hardware" elements of irrigation development; new constructions were initiated and more and more lands were brought under irrigation.

In the late 1970s, the reverse occurred. Food grain supplies increased and, consequently, a sharp drop in grain prices was experienced. Because of this, a notable reduction in irrigation investments by the donors has occurred. However, it may not be prudent to consider "price signals" as the major determinants of irrigation investment. Remarkable periodic fluctuations in prices itself disqualifies price as the sole determinant of investment. Moreover, the extent to which the conditions of perfect competition exists in food markets is questionable. For instance, thousands of consumers may not go at all to markets as they cannot afford the prices, whether it be "high" or "low." Similarly, a large number of subsistence farmers may be affected if investment in irrigated agriculture is diminished. However, future investment strategies in most of these countries need to be modified, with more emphasis on less costly management approaches, applied research, and modernization of agriculture while protecting basic food needs. The discussion will return to this subject at a later stage.

3.2. GROUNDWATER DEVELOPMENT

A very large proportion of surface irrigation projects in the developing countries are large-scale public-sector projects funded by government or state revenues and managed by public-sector officials. However, recent technological changes have brought an important private-sector component into the picture. The development and diffusion of inexpensive, internal combustion engines and pumps have made it possible for individual farmers, or groups of farmers, to use small wells to exploit shallow groundwater aquifers, and to use low lift pumps for drawing water from rivers and channels to irrigate rice in the "dry season." Expansion has been most pronounced in Asia (Yudelman 1993).

There has been a proliferation of wells owned by individuals in South Asia and by groups in China (Yudelman 1989). Private groundwater development has enabled large areas with good land and irrigation potential to be brought under production quickly, almost certainly more rapidly than would have been the case in state-controlled projects. In Thailand, there are more than 5 million small pumps used primarily to lift water from canals and rivers for use on rice paddies. The spread of private wells has been most notable in India where the number of wells increased from 459,000 units in 1968 to 3.3 million units in 1984/1985. Within India, in the state of Uttar Pradesh, privately owned tubewells increased more than tenfold from 120,000 to 1.6 million during this period. About 1.1 million of the 1.6 million tubewells are diesel-powered with the remainder using electric pump units. About half of the irrigated area is now said to be served by underground water. Much of this is in command areas, and complements the use of surface water (Yudelman 1989).

The spread of privately owned wells has increased dramatically during the past decade. Private groundwater development in places like central India and parts of Bangladesh appears to have been a great success. However, there is a significant lag in the institutional, legal and technical arrangements for managing this phenomenon in such a way as to safeguard the natural resource base, promote equity and optimize the use of water (Le Moigne *et al.* 1991). This is partly due to a lack of adequate information to make sound judgements about the extent to which the groundwater table is being depleted.

4. Food Demand

4.1. POPULATION GROWTH

Following World War II, the population of the globe more than doubled, increasing from 2.5 billion in 1950 to 5.3 billion in 1990. Most of this increase took place in the poorer countries of the world where the population grew from 1.6 billion in 1950 to 4 billion in 1990.

The largest population increases will be in Asia where the annual growth rate will be 56 million from 1990-2000. Then, the population rate will continue to decline. But, by the year 2050, it is expected that Asia's population will exceed the world population in 1990 (Yudelman 1993).

4.2. CEREALS

The most important foods in the developing world are cereals, which include rice, wheat, corn, millet, sorghum, rye and barley. About 52 percent of the global supply of cereals is grown in developing countries including 94 percent of the world's supply of rice, 50 percent of the global wheat supply, and 40 percent of coarse grains. Overall, cereals accounted for about 83 percent of the major food production in developing countries during 1980. Regionally, Asia is the largest producer and consumer of grain, accounting for 75 percent that is produced and consumed in developing countries. The consumption of cereals in the developing countries has risen from 170 kilograms (kg) per person per year in 1960 to 236 kg/person/year in 1990 (Yudelman 1993).

In the future, as Asian societies develop and grow, there will likely be a shift in food demand similar to what has occurred in Japan and Korea. Instead of a heavy reliance on rice, a more diversified diet consisting of a large increase in wheat products, meats, dairy products, vegetables and fruits will gradually take place.

4.3. INCREASING YIELDS

The possibility of increasing farmers' yield depends on the present level of yields and the technologically "potential" yield. Both of them depend on the quality of the crop production environment, especially the area irrigated and drained. The present yield level depends on the extent to which farmers are currently using fertilizer-responsive varieties. Fertilizer and modern variety adoption are, in turn, related to the extent and quality of irrigation, as well as other factors. The technologically potential yield can be enhanced with research, but there are physiological limits to the process that science has not yet overcome. In fact, plant breeders are rather skeptical about achieving the type of scientific breakthroughs that launch the green revolution. The present technologically potential yield, represented by yields in the South and Southeast Asian countries, leave an adequate exploitable gap. Only in East Asia are actual national yields approaching their potential level, and in China this may be a serious factor limiting future production growth.

In the late 1970s scientists believed that there was a significant amount of "un-tapped yield potential" in irrigated production systems, especially in Asia. Moreover, they observed that much of this could be captured by improvements in crop management in general and water management in particular. Surprisingly, by the end of 1980s, some researchers have observed a stagnating or declining trend in productivity of major food grains grown mainly under irrigation.

For rice, the major crop under irrigation in most of the Asian countries, recent studies indicate that the technological yield frontier has stagnated and shown signs of long-term decline. Farm level evidence indicates that farmer yields are catching up to the yield frontier in a few countries and that further exploitation of the yield gap is not economical. Incremental costs of achieving further yield gains exceed the incremental returns. Similar declining rice yield trends have been observed in other experimental stations in India, Thailand and Indonesia (Pingali 1990 quoting from Nambiar and Ghosh 1984, Gymantasiri *et al.* 1980, INSURF 1987).

Yet, to meet projected food demands by the year 2025, rice yields in developing countries will have to exceed average yields presently being achieved in developed countries. For other cereals, present yields in developed countries must be achieved by developing countries in 2025.

4.4. INCREASING CROPPING INTENSITY

Expanding the "effective irrigated area" by increasing cropping intensity would be a more economical option, especially in areas where further expansion in the irrigated land frontier is constrained due to financial problems, limits in water sources or supply, etc. Cropping intensity (or cropping index) is usually defined in terms of number of harvests per year from the same area of land. In order to eliminate the problem of differential characterization of long-season and short-season crops, and to reflect the degree of utilization of sunlight (1988) suggest the use of hectare-days. This combines the area factor and the proportion of the year during which a particular crop could be in a stage of active crop growth. However, such climatic factors as temperature and sunlight may vary between seasons and at different latitudes. For example, a month of growing season early or late in the year at higher latitudes is not the same as a month in mid-summer where both sunlight and mean temperature are more favourable for optimal crop growth. Hence, a more appropriate index may be used by incorporating a profit factor -- profit per unit of water per year or profit per unit of land per year, etc.

Increases in cropping intensity can be done effectively in several ways: (a) Introducing early maturing crops, thereby increasing the effective area planted to those crops per unit of time; (b) Multiple and relay cropping; and (c) Cultivating 2-3 crops per year by adopting water-saving techniques.

Staggering of land preparation, planting and other cultivation methods is a common phenomenon in many irrigation systems. Even though staggering may not be completely avoided due to some constraints, (e.g. limitations in labour and farm power, water supply, etc.) "planned staggering" of cultivation may be helpful in saving scarce water resources (through a reduction in the period of irrigation) and increasing the number of crops grown annually.

4.5. SHIFTING TO HIGH-VALUE CROPS AND DIVERSIFICATION

A great deal of development outside the traditional mono-crop farming is necessary not only to optimize the financial and economic returns to investment made in the irrigation sector, but also to improve the living standards of the growing populations in many Asian countries. Recently, crop diversification has been assigned a prominent place among the avenues available for improving land and water productivity. This may be a "response" to the declining trend in the growth rate of "new areas irrigated" and the declining profitability of monocrop culture, approaching self-sufficiency in basic staple foods and growing demand for different types of food crops.

A limited water supply condition not adequate to meet the requirements of rice during the dry season is experienced in many schemes with favourable soil conditions. Related to this is the distinct uni-modal dry season rainfall pattern which makes it possible to have a well-aerated favourable environment for irrigated crop diversification. Hence, water productivity, in general, can be increased under a diversified cropping pattern. Moreover, limited water available in the soil is better utilized by a mix of crops. For example, shallow and deep rooted crops may be included in such a crop mix to tap water available at different depths of the soil. Economic viability of such systems, therefore, may be maintained by diversification.

The progress in a program of diversified cropping, however, depends on a variety of factors: (a) Compatibility of the selected crop mix and land, water, climate, etc.; (b) Expected fluctuations of profits due to price shifts; and (c) Problems associated with markets and marketing risks associated with a particular cropping pattern, farmers' resource endorsements, etc.

5. Urban Water Needs

By the turn of the century, half of the world's population will be living in urban areas. There will be 21 megacities (more than 10 million people), of which 18 are located in developing countries.

The water supply situation for many cities in the developing countries has become deplorable. Many neighbourhoods only receive water 1-4 hours per day. Asian homes usually have a water tank on the roof, but in many locations, a tank has been placed in the ground, with a household pump to lift the water into the roof tank, because of extremely low water pressures. Certainly, obtaining clean water is an increasing problem for many urban areas.

In many Asian countries, 80-90 percent of the available water resources are diverted for irrigated agriculture. With time, some portions of these water supplies will have to be diverted from agricultural uses to urban uses. It has been estimated that each million of additional urban dwellers will require a water supply comparable to 10,000 ha of irrigated land. Thus, if the urban population increases by 2.5 billion people from 1990-2025, then 25 million ha of land would have to go out of production unless much higher management practices can be implemented on existing irrigated croplands.

6. Trends in Sustainability

Presently, there are a number of indicators that imply that many of our irrigation systems located in developing countries are not sustainable. In other words, the agricultural productivity is stagnant and in some locations declining. Yet, there is an urgent need to increase the agricultural productivity of irrigated croplands.

One of the first obvious indicators of a lack of sustainability is declining agricultural productivity, particularly at the lower periphery of an irrigation system. Another visual indicator is soil salinity.

The strongest indicator that an irrigation system is not being sustained is a deteriorating infrastructure. The majority of the irrigation systems constructed from 1950-90 are not being properly maintained. Often, rehabilitation is viewed as the only mechanism for correcting deferred maintenance deficiencies, which is quite similar in cost to the original investment in constructing the irrigation system.

A deteriorating infrastructure results in a declining capability for properly operating the system in a predictable, reliable and equitable manner. This, in turn, limits the management options for farmers.

When groundwater levels continue to decline for more than one decade, then the indication is that the present levels of pumping are not sustainable. Also, if the salinity concentration in the pumped water continues to rise year-after-year, even gradually, the indication is the pumped discharge rates cannot be sustained.

When the domestic water supplies for cities are inadequate, both in terms of quantity and quality, with the situation worsening year-by-year, then the urban water system is not sustainable.

There are an alarming number of indicators that irrigated agriculture is facing a deteriorating situation. Many irrigation systems are not presently sustainable. This situation needs to be reversed so that Asian irrigated agriculture can partially satisfy urban water needs while increasing agricultural productivity on existing croplands. In a very practical sense, all of this has to be achieved in a context of sustainability.

7. Future Strategy

For irrigated agriculture, the question of sustainability is one of resource management. At the same time, irrigated agriculture is "site specific", so that resource management practices must be appropriate to the physical and institutional environment.

To increase crop yields and cropping intensities on existing irrigation systems requires continual improvements in water management practices to meet future food demands.

Maintaining the physical environment for a productive agricultural system also requires continual improvements in agronomic (including irrigation) practices.

To continue pumping groundwater on a sustainable basis requires the proper combination of groundwater and irrigation practices that will also have to be continually improved over time.

Irrigation water supplies can be partially diverted to urban areas, without decreasing agricultural productivity, only if water management practices are further improved. In fact, a highly productive and sustainable irrigation system should be capable of increasing crop production with reduced water supplies, provided the management practices are properly adjusted to the decreased water supply.

A major question being addressed in many countries is the turnover of operations and maintenance activities for irrigation projects from public agencies to water users organizations. Turnover processes are being experimentally implemented in a number of Asian countries, such as the Philippines, Sri Lanka and Nepal. Many recent studies by the International Irrigation Management Institute (IIMI) have investigated farmer-managed irrigation systems. Serious discussions are underway in Pakistan regarding privatization of the world's largest irrigation system, but of course, there is considerable resistance.

A number of organizations, including IIMI, have made important strides in developing improved procedures for computer operation of irrigation systems. The implementation of this technology is now gaining momentum. Research has clearly shown that perturbations of water levels and discharges in canals are magnified as these flows move into the lower secondary and tertiary channels.

Likewise, research on surface irrigation of croplands shows that fluctuating discharge rates applied to croplands results in low application efficiencies. This, in turn, limits crop yields and reduces crop quality, thereby lowering profits.

In many developing countries, agricultural policies benefit urban consumers at a significant cost to rural farm families. Often, these policies are a definite deterrent to increasing agricultural productivity.

For Asian irrigation, there is a formidable task ahead in the next 10-30 years. Rapidly increasing populations, the necessity for improved diets, the limited potential for expanding the amount of land that can be irrigated present a major challenge. But deteriorating physical infrastructure, increasing soil salinization, tremendous inequities in water distribution, stagnant crop yields, and declining sustainability in many locations are symptomatic of major obstacles that must be overcome in meeting the challenge. Certainly, improved technologies are needed, but the greatest impediments to achieving the required agricultural outputs in the context of sustainability are institutional. In fact, institutional measures must lead the way in continually sustaining an increasingly more productive agricultural system, with technology providing the necessary support that facilitates the success of such measures.

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SUSTAINING IRRIGATED AGRICULTURE IN CHINA

L. CAI, Y. QIAN and D. XU
Institute of Water Conservancy and Hydroelectric Power Research (IWHR)
P.O.Box 366, Beijing 100044, P.R.China

1. Introduction

Irrigation in China has been practised for millennia. The Chinese ancient civilization was built on its irrigated agriculture.

Since the past 40 years, China has made a concerted effort to develop its water resources and its irrigated area. As a result, the area under irrigation has increased three-fold from 16 million in 1949 to 49.7 million ha in 1993. Though constituting less than half of the country's total cultivated land, it provides two thirds of total grain output, enabling China to achieve its self-sufficiency in food.

This paper outlines land and water resources in China. The development of irrigated agriculture and the problems it faces today are reviewed. The measures for sustaining irrigated agriculture in near future are discussed.

2. Land and Water Resources in China

China has an area of 960 million ha, of which 70% are mountains, plateaus and hilly areas, the rest are basins and plains. The total cultivated lands are about 110 million ha, of which 50% are concentrated in the three main plains (the Northeast Plain, the North China Plain and the Middle and Lower reaches plain of the Yangtze River), the Pearl River Delta and some inland plains. The average amount of cultivated land per capita is less than 0.1 ha.

Most cultivated lands are affected by monsoon climate with erratic rainfall patterns. It is wet, with plenty of rain in summer, and dry with northwest wind prevailing in winter. The annual average precipitation over the whole country is 628 mm, of which 70% are poured down during four months, for June to September. In addition, the rainfall varies quite a lot from year to year. For example, in North China plain, although the annual average rainfall is around 600 mm, it is observed that the annual rainfall may fall down to 200-300 mm in very dry years or rise to 1300-1500 mm in extraordinarily wet years. The spatial distribution of rainfall is also uneven, the annual

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average rainfall decreases from 1000-2000 mm in the southeast to 100-200 mm in the northwest.

The great variation of rainfall distribution in both space and time is the principle cause of drought, waterlogging and flood. On the average a major flood or drought occurred nearly every year during the period from 206 B.C. to 1949, while 1092 heavy floods and 1056 severe droughts were recorded.

The total water resources over the whole country is estimated about 2700 billion m^3, of which river runoff is 2600 billion m^3 and renewable groundwater 100 billion m^3. On average, the amount of fresh water available per capita per year is 2400 m^3. However, this figure is very different between river basins (Table 1). If a level of 500 m^3 per person per year is considered to be extremely low and to be a threshold for sustainable development (Golubev 1993), there are, in China, three river basins (the Huai, Hai and Liao) with a population of 252 million (in 1983) facing this situation. The figures in Table 1 show how acute is the problem of water scarcity faced by China today.

3. Development of Irrigated Agriculture in China: Achievement and Problems

Agriculture in China highly depends on farmland water conservancy, namely, the irrigation and drainage. In the course of practice for a long time, irrigation projects were considered to be essential for enhancing agricultural production and consequently for promoting national social-economic progress. This type of thinking was highlighted by Mao Zedong, the first Chairman of PRC, who termed irrigation as "the lifeblood of agriculture."

TABLE 1. Water and Land Resources in Main River Basins in China(1)

River basin	Catchment area (10^3 km^2)	Annual average runoff(2) (10^9 m^3)	Population(3) (10^6 persons)	Annual runoff per capita (m^3)	Cultivated land (10^6 ha)	Irrigated land(4) (10^6 ha)
Yangte	1800	965.0	368	2622	24.0	15.1
Yellow	750	598.2	88	673	12.4	4.3
Songha	550	62.4	49	1273	12.0	7.3
Pearl	450	336.0	77	4363	4.7	2.6
Hai	300	27.5	105	262	11.4	6.4
Liao	230	14.8	32	463	4.4	1.3
Huai	270	61.1	131	466	12.2	7.3

(1) From Ministry of Water Resources and Electric Power, (1983)
(2) From 1956 to 1979
(3) In 1965
(4) From Cui and Lou (1987)

Since the past 40 years China has made a concerted effort to develop its water resources. By the year of 1991, a large number of water development projects were built, including 80000 dams with a total storage capacity of 460 billion m^3, 5600 irrigation districts with an irrigated area over 677 ha each, 5.6 million sets of pumps with a total power of 70 million kW, and 2.8 million tubewells. The water supply capacity increased to 540 billion cubic meters per year. The flood control systems safeguarded more than half of the national population, two thirds of gross national industrial and agricultural product, and 30% of total national farmland. 55 million hectares suffering from serious soil erosion were harnessed. 19 million hectares liable to waterlogging and 5 million hectares of farmland affected by salinity were improved and ameliorated. The irrigated area increased threefold from 16 million hectares in 1949 to 48.7 million hectares in 1991. During this period, the investment put in water development was estimated about RMB 240 billion (US$65 billion) in total, of which RMB 132 billion (US$35.7 billion) in irrigation and RMB 57.6 billion (US$15.6 billion) in flood control and drainage.

The rate of the expansion of irrigated areas in China was maintained high from 1950 to 1980. This made it possible to increase production to keep up with food demands caused by the population growth. By the early 1980s, China reached its food self-sufficiency. The expansion of irrigated land and increased grain production versus the population growth in China from 1950 to 1993 are summarized in Table 2.

TABLE 2. Expansion of Irrigated Land and Increased Grain Production Versus the Population Growth

Parameters	1950*	1983*	1993	Ratio 1983/1950	Ratio 1993/1983	Increase rate (%) 1950-1983	Increase rate (%) 1983-1993
Population (billion)							
PRC	0.55	1.02	1.16	1.85	1.14	1.89	1.3
World	2.51	4.66		1.86		1.89	
Irrigated area (Mha)							
PRC	16	46	49.7	2.88	1.08	3.25	0.8
World	96	213		2.22		2.44	
Grain yields (Mton)							
PRC	132	387	450	2.93	1.16	3.31	1.6
World	623	1447		2.32		2.59	
Grain/capita (kg)							
PRC	239	379	388	1.59	1.02	1.41	0.2
World	248	310		1.25		0.68	

From Lou and Xu (1986)

After 1980, the growth of irrigated area has been slowed down considerably. There are several reasons for this: shortage of suitable lands or water; high cost of new projects such as interbasin water transfer from Yangtze River; loss of irrigated area due to encroachment of urban and transportation development; ageing of many hydraulic structures and facilities.

Irrigated agriculture in China today has a total area of 49.7 million ha. Though constituting about 45% of the national total cultivated land it provides approximately two thirds of grain, three fifths of cash crops and four fifths of vegetable produce for the whole nation. However, there are several problems now faced by irrigated agriculture. These problems mainly deal with the water scarcity and low efficiency of present irrigated agriculture.

Water resources shortage has become a major limiting factor for China's development. There are 300 cities in China suffering from water shortage to varying degrees, which results in substantial economic loss.

A substantial increase in groundwater exploitation for irrigated agriculture has resulted in some adversely environmental impacts, including a dangerous drop in groundwater table in many parts of north and northwest China and some sea water intrusion in the coastal region. In North China Plains, for example, there are 1.8 million ha of cultivated land. The output of cereal crops and cotton amounted to 19% and 57% of the country's total in 1987, respectively. The irrigated land accounts for 57% of total cultivated, of which 47% are irrigated by surface waters and the rest by groundwaters. However, in Hai River Basin, north of the Yellow River, most of the irrigated land (82%) is supplied with groundwater and only 18% with surface water. The development of irrigated agriculture and intensive use of water resources have some effects on the local environment, including a considerable reduce in runoff into the sea (Table 3), salt accumulation in farmland (Table 4), and water table draw down. There are 40 watertable depression cones, covering an area of 12910 km^2, or 20% of the area of alluvial plain in Hebei Province.

TABLE 3. Amount of Water Flowing into the Sea* (10^9 m^3/yr)

River System	1956-59	1960-69	1970-79	1980-84	1956-84
Luan River	7.63	4.27	4.47	0.53	4.16
Northern part of Hai River	5.48	2.43	2.67	0.28	2.56
Southern part of Hai River	10.90	7.84	3.32	0.26	5.40
Tuhai and Majia rivers	0.17	1.65	1.18	0.39	1.07
Total	24.18	16.19	11.64	1.46	13.19

* From Xu (1992)

As a result from the increase of population in China and the improvement of the standard of living, the demand for water increase much (Table 5). Today's modest water scarcity will surely become more acute. The efficiency of irrigated agriculture must, therefore, increase.

Efficiency of irrigated agriculture is often evaluated by crop yield per unit irrigated land. Crop yields in main irrigation projects in China are nowadays still low. The surface irrigation efficiency over the country may be 0.3-0.4 and canal efficiency about 0.4-0.5. In 1993, the average volume of water applied per unit area is 12000 m^3/ha (including paddy rice, in southern part of China), and 6000-7500 m^3/ha in northern part of China. In 1989, in Hebei province, the measured data shown that the average amount of water applied per unit area was 5930 m^3/ha and the corresponding canal efficiency was 0.54. However, in many regions of north China, particularly in northern part of North China Plain where groundwater is over exploited, the irrigation or canal efficiency alone cannot be used to estimated either true losses or savings of water (Jensen *et al.* 1990).

TABLE 4. The balance of salts in the Hai River Plain*

Areas	Years	Input (10^3t)	Output (10^3t)	Balance (10^3t)	Accumulation in fields (kg/ha)
Lower reaches of Luan	1956-67	1388	1533	-145	326
	1968-79	1229	1245	-16	-36
	1980-84	559	149	411	924
Area North of Hai	1956-67	1751	1818	-67	-64
	1968-79	1505	1273	232	220
	1980-84	982	143	839	796
Area South of Hai	1956-67	4856	5247	-391	-89
	1968-79	3277	1711	1566	355
	1980-84	2025	140	1885	428
Area near Tuhai and Majia	1956-67	1902	1321	581	239
	1968-79	2914	1080	1834	755
	1980-84	3153	493	2660	1095
Total	1956-67	9897	9919	-22	-3
	1968-79	8925	5309	3616	434
	1980-84	6719	924	5795	695

* From Xu (1992)

The causes for low efficiency of irrigated agriculture are many and complex. The main problems directly in relation to water development are as follows:

- the protection from flooding and waterlogging disasters is still low; many irrigation areas are still threatened by extraordinary flood of the main rivers;
- the performance of large irrigation projects is declining due to structures ageing and improper maintenance, operation and management, which results in improper water supply to crops;
- in many irrigation areas, waterlogging and salinity are still reducing agricultural production.

4. Prospects for Irrigation Agriculture in China

During the last ten years, although irrigated land expanded slowly, the grain output increased much more (Table 2). This indicates that irrigated agriculture in China is changing from horizontal (expansion of area) to vertical (increasing yields per unit area) development, and that emphasis is moving from construction of new projects to management of existing projects. Agriculture has also entered a new stage of its development, changing from single purpose-high yield to multiple purposes: high yields, good quality and high benefits.

By the end of this century, total grain output and irrigated area are planned to reach 500 million tons and 53 million ha, respectively.

Table 5 Estimating demands for water in China by 2000*

Sector	1980 (billion m^3)	2000 (billion m^3)	Increase(%)
Agriculture	391.2	510	30.37
Industry	45.7	120	162.58
Municipal	6.8	20	194.11
Total	443.7	650	

* From Xue (1993)

China has been paying more attention on rehabilitation and modernization of existing irrigation projects. It is estimated that 60% of existing projects, covering an irrigated area over 19.2 million ha are in need of rehabilitation. The potential of both increasing yields and saving water is very large. Through rehabilitation and modernization as well as improved management, the reliability of available water supply and the flexibility of irrigation water distribution should be increased. The irrigation schedule should be adjusted to fit to the change of cropping pattern and intensity. Meanwhile, 27 million ha of low-yielding farmland influenced by waterlogging and salinity will be improved by construction of new drainage works or repair of existing drainage systems.

Advanced irrigation techniques are effective in water saving. Chinese government has adopted a policy to encourage farmers to use these techniques (Xue 1993). Recently, low pressure pipe lines for water supply have expanded quickly in tube-well irrigation areas, covering an area of about 2.5 million ha. The annual expansion rate is about 300,000 to 400,000 ha.

One of the primary factor affecting production levels and sustainability on existing irrigated agriculture is water and land management. Major efforts should address this aspect if the full potential of agricultural production is to be achieved. Therefore, new programs are needed to develop improved technology and management practices. Increased and coordinated research, coupled with information dissemination and training programs, are needed to transfer technologies from the world. The project "Improved water and soil management for sustainable agriculture in the Huang-Huai-Hai Plain (Northern China)", under contract with EC (Contract No. TS3*-CT93-0250), can been considered as an example.

China will also make major efforts to enhance harnessing main rivers and large lakes and to build a number of large and medium flood control, water storage and water transfer projects, in order to develop capacities against natural disasters and expanding irrigated areas. Particularly, The East Route and Mid Route of Yangtze River Water Transfer Northward are under construction, that their objectives are to supply water to cities, such as Beijing, Tianjin, and Jinan and to supplement irrigation water to the North China Plain. When they will be put into operation, the water shortage in North China will be reduced to some degree.

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SUSTAINABILITY CONCERNS IN AFRICAN IRRIGATION

F.N. GICHUKI
University of Nairobi
P.O. Box 30197
Nairobi, Kenya

1. Introduction

Irrigation has and will continue to play an important role in enhancing food security and improving the standards of living for many inhabitants of rural Africa. However, irrigation is beset with increasing problems such as water scarcity, soil degradation, water pollution, organisational and management problems, high implementation costs, low productivity and rate of returns, operation and maintenance deficiencies and associated environmental health problems. Sustainability of irrigated agriculture predicates on alleviation of these problems in a cost-effective manner. This paper presents the status of irrigation in Africa, highlights the main sustainability concerns and suggests how some of the constraints can be alleviated.

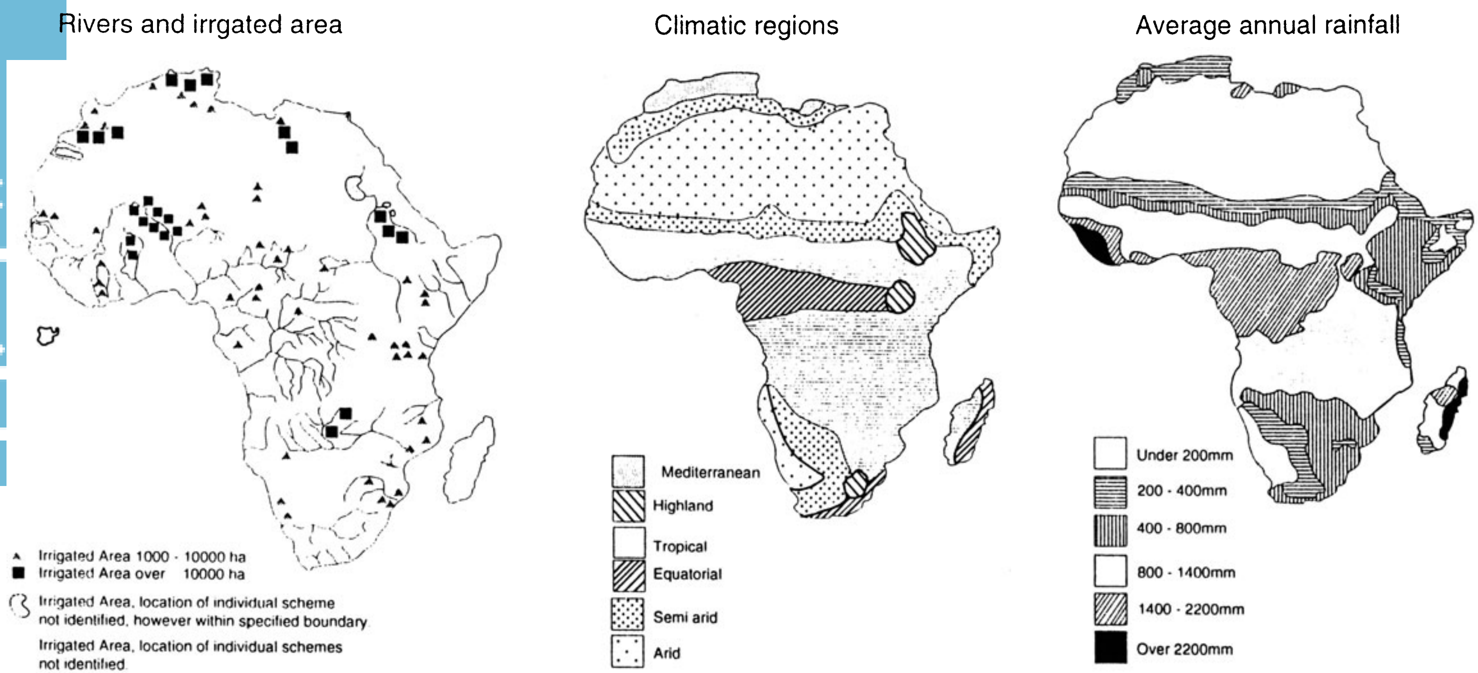
2. Status of Irrigation

2.1. EXTENT AND DISTRIBUTION OF IRRIGATION

The extent and distribution of irrigation in Africa is influenced by climate, water resources availability, suitable soils, availability of finances and financial viability, social viability and relative importance of irrigation (see Figure 1). By 1987, the irrigated area was estimated as 9.5 million hectares, covering 0.34% of the total land area (FAO 1987b). This represents 3.5% of the cropped area.

Approximately 61% of the irrigated area is found in Egypt, Sudan and Morocco. Ten countries account for 91% while the remaining countries account for 9% (see Table 1). Formal irrigation accounts for 67% of the total irrigation in Africa. Egypt, Sudan and Morocco accounts for 45%, 28% and 7% of formal irrigation in Africa respectively. Madagascar, Nigeria and Morocco accounts for 27%, 28% and 13% of traditional irrigation in Africa respectively.

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 589–599.



Source: Thompson (1965)

Figure 1. Climatic condition, water resources and irrigated area in Africa

2.2. CONTRIBUTION OF IRRIGATION TO AGRICULTURE

At the continent level approximately 30% of the area is climatically suited for rainfed production of main staple food grains and 45% is too dry for rainfed crop production (see Figure 1). However, some countries have over 80% of their land area unsuitable for rainfed crop production. An analysis of agricultural production in 43 countries, during the 1979-80 production year, indicated that irrigated agriculture accounted for 6.5% of the land and produced 20% of the agricultural production value. An irrigated hectare produced 3.5 times that of a rainfed hectare (FAO 1987b). The difference is even higher where the climatic risk of rainfed crop production constraints investment in rainfed agriculture (see Table 2).

Irrigated agriculture has made a significant contribution in rural development through increased volume of trade in rural trading centres; development of irrigation supportive infrastructure such as roads, telephone, electricity, schools, hospitals; increased employment opportunity (an irrigated hectare has 5 times the labour demand of rainfed hectare); improved water availability for domestic and livestock use; increased income and stabilising crop production in areas with erratic weather conditions.

TABLE 1. Distribution of irrigation in Africa

Country	Irrigated area ('000 ha)	[1]Relative importance of irrigation %	% of total irrigated area in Africa
Egypt	2,800	98.6	29
Sudan	1,848	14.8	19
Morocco	1,240	14.8	13
Nigeria	846		9
Madagascar	826	27.4	9
Algeria	298		3
Tunisia	241		3
Ethiopia	162	9.1	2
Somalia	160	15.0	2
Others	846		11

Source: FAO, (1987b). [1]Relative importance of irrigation: irrigated area as a percentage of cropped area.

TABLE 2. Contribution of irrigation to production

Crop	Irrigation production ('000 tons)	% of total production
Paddy rice	4,926	58
Cereals	7,493	14
Sugar cane	32,353	77
Root crops	2,517	3
Oil crops	925	9

Source: FAO (1987a)

2.3. DEVELOPED AND REMAINING IRRIGATION POTENTIAL

According to FAO (1986), potential irrigable area is estimated as 33,641,000 hectares, out of which only 14.6% of the potential is tapped (see Table 3). Although the values presented are based on 1986 estimates, it is unlikely that current values are significantly different due to:

- a decline in irrigated area as a result of salinization, institutional and financial problems;
- a decline in the annual rate of growth as a result of disappointing performance, lack of ideal sites and reduced donor support; and
- low level of cropping intensity (80% of cropping intensity in areas with a potential of 300% cropping intensity).

3. Sustainability Concerns

Although irrigation technology has the potential for increasing crop production, most Sub-Saharan Africa countries depend on food import and food aid, and experience widespread famine with devastating consequences. The current food crisis and environmental degradation has created awareness on the need for sustainable irrigation development. The main sustainability concerns fall into environmental, economic and social categories.

3.1. ENVIRONMENTAL CONCERNS

3.1.1. *Water Scarcity*

Most irrigation projects in Africa are located in areas with high evapotranspiration rates and low rainfall. This creates a high demand for irrigation water in areas where water is limited due to lack of suitable water storage site, siltation of reservoirs, low stream flows (particularly for seasonal rivers), low groundwater yield and recharge rate. These problems lead to sustainability concerns such as competition for water among users and among uses, high water lifting energy requirement and cost, mining of groundwater resources, draining of swamps and siltation of reservoirs.

3.1.2. *Fragile Soils*

Most soils in arid and semi-arid areas tend to be leached and deficient in major nutrients and are low in organic matter. Soil erosion, salinization and alkalinization problems have been reported in most schemes.

3.1.3. *Environmental Impacts of Irrigation Development*

Irrigation development is associated with numerous adverse environmental impacts. The main sustainability concerns are human health hazards (see Table 4), water pollution by sediment and chemical, water over-abstraction resulting in drying of downstream wetlands, salinization and disruption of migratory route of wild-life.

Table 3. Irrigation potential in Africa.

TABLE 3. Irrigation potential in Africa

Country	Irrigation potential ('000 ha)	Developed area as % of potential
Angola	6,700	< 1
Benin	86	26
Botswana	100	12
Burkina Faso	350	8
Cameroon	52	100
Central African Republic	240	8
Chad	1,900	4
Congo	340	2
Ethiopia	670	13
Gambia	72	36
Ghana	120	8
Guinea	150	30
Ivory Coast	130	40
Kenya	350	14
Lesotho	8	13
Madagascar	1,200	80
Malawi	290	7
Mali	340	47
Mauritania	39	59
Mozambique	2,400	3
Niger	100	30
Nigeria	2,000	43
Rwanda	44	34
Senegal	180	56
Sierra Leone	100	55
Somalia	87	92
Sudan	3,300	53
Tanzania	2,300	6
Togo	86	15
Uganda	410	3
Zaire	4,000	1
Zambia	3,500	< 1
Zimbabwe	280	46

Source: FAO (1986)

TABLE 4. Prevalence of Schistosomiasis

	Incidence %	
Project	Pre-project	Post-project
Aswan Dam, Egypt	6	60 in 3 yrs
Gezira Irrigation, Sudan	0	30-60 in 15 yrs
Arusha Chini Irrigation, Tanzania	Low	53-86 in 30 yrs

Source: Rosenfield and Bower (1978), quoted in FAO (1987a).

3.2. ECONOMIC CONCERNS

3.2.1. *High Cost of Irrigation Development*

Migot-Adholla (1988) reported on the high cost of modern large-scale irrigation projects (see Table 5). The main causes of high investment costs are: over-valuation of the local currency which inflates all costs in dollar terms; difficult access to remote project sites which increases transportation cost; shortage of skilled local people and use of foreign consultancy firms; high irrigation water requirements; and delays in project implementation.

TABLE 5. Estimated cost of irrigation development

Project	Year of preparation	Irrigated area (ha)	Investment cost US$/ha
Bhola Irrigation, Bangladesh[1]	1982	30,000	200
Gorgol Irrigation, Mauritania[1]	1980	3,600	1,600
Senary II, Cameroon[1]	1982	7,000	9,778
Morondora, Madagascar[1]	1983	2,500	30,000
Bura irrigation, Kenya[2]	1985	3,820	14,838

Source:[1] FAO (1987a); [2] Migot-Adholla (1988).

3.2.2. *Low Level of Crop Production*

Before irrigation development has taken place, water is identified as the major constraint to crop production. However, after irrigation water is supplied, other constraints manifest themselves leading to low crop yields and cropping intensities (see Tables 6 and 7). Low levels of crop production are attributed to poor crop husbandry and water management. The level of crop production inputs (fertiliser, pesticides, weeding, etc.) and the timeliness of operations such as planting and crop protection, are mainly due to lack of capital and knowledge and skills in irrigated agriculture.

TABLE 6. Crop yield levels

Crop	Condition	Yield
Rice	Partial water control	0.9 t/ha/yr
	Full water control	2.3-10 t/ha/yr
Sugar cane	Modern irrigation under industrial-style management	120-125 t/ha/yr
	State farms in Somalia	60 t/ha/yr
Cotton	Rainfed cotton	0.3 t/ha
	Irrigated cotton	1.5 t/ha

Source: FAO (1986)

TABLE 7. Farm level crop yield and cropping intensities

Project	Irrigated area per farm (ha)	Main crop	Crop yield (tons/ha)	Cropping intensity (%)
Toula, Niger	0.45	Rice	4.0	200
Nianga, Senegal	1.05	Rice	4.5	109
PISO, Senegal	0.31	Rice	6.0	60
Logone et Cham, Cameroon	0.25	Rice	5.1	150
Imbo, Burundi	0.75	Rice	4.0	100
Bas-Mangoky, Madagascar	0.5	Cotton	1.1	50

Source: van Steekeleburg (1988)

3.2.3. *Cost Recovery and Financing*

Although it has been demonstrated that with proper management there is a high return on irrigation investment, the rate of return for communal and centrally managed irrigation projects are generally low. This, coupled with the general objective of irrigation development for promoting food security and a belief that cost-recovery may impose a heavy burden on farmers, leads to a low level of cost recovery. In some cases no effort is made to charge for water, but instead the project aims at recovering operation and maintenance cost only.

Government and community-based irrigation projects are generally expensive and neither the government nor the community are able or willing to finance the project with their own resources. The main sources of external capital funding are the World Bank, African Development Bank, EEC, IFAD, bilateral donor agencies' loans and grants, UNDP/FAO and NGOs. Over-reliance on donor funding is a major sustainability concern.

3.3. SOCIAL CONCERNS

3.3.1. *Conflicts Among Water Users*

As the benefits of irrigation become more evident, more people become involved in irrigation development. In the Ewaso Ng'iro river basin of Kenya, pastoralists and wildlife are forced to move upstream as the river dries up due to over-abstraction for irrigation. This seasonal migration resulted in destruction of irrigation infrastructure and crops. This problem is exacerbated by the laxity in enforcing water laws.

3.3.2. *Resource Ownership*

The way people react to resource use and conservation depends on the ownership of the resource. Under individual irrigation project ownership, the owner takes maximum care of the resources, and sustainability of the project is one of his primary concerns. On the other hand where farmers are tenants, as in the case of National Irrigation Board projects in Kenya, the relationship between the Board and the farmers creates suspicion and results in very low farmers' participation in decision making.

3.3.3. *Gender Issues*

Approximately 46% of agricultural labour in Sub-Saharan Africa is provided by women (FAO 1987a). Women and men play separate but complementary roles and when irrigation is introduced in an area, it increases female labour more than male labour demand. Ironically, this is not matched with an increased level of access to production resources and support services.

Women continue to play minor roles in decision making at farm and scheme level, control of production resources, control of project outputs and participation in training and extension. Most women therefore feel over-burdened and unfairly rewarded. With increased awareness of women's rights, it is unlikely that they are going to continue to accept such poor terms of condition for their involvement in irrigated agriculture.

4. **Enhancing Sustainability: Kenya's Smallholder Experiences.**

4.1. BACKGROUND

Sustainability of irrigation has been of concern to many governments and donor agencies, communities, researchers, planners, implementers, and consumers of irrigated produce. Several workshops have addressed sustainability issues and made important recommendations which include:

- improvement of data and knowledge base;
- formation of sound irrigation policies;
- development of human resources to undertake project planning, implementation and management at all levels of irrigation projects; and
- improved research capacity and research-extension linkages. (FAO 1986, FAO 1987a, Thom 1988).

The approaches presented here have applied to Kenya's smallholder irrigation sector with satisfactory results.

4.2. IMPROVING FARMER'S PARTICIPATION

Modern irrigation development in Kenya has brought approximately 52,000 hectares (approximately 21% of the irrigation potential) under irrigation over a period of 30 years. Approximately 33,000 hectares are under the hands of private sectors operating large-scale schemes of high value crops such as coffee, flowers and vegetables. Public sector projects and smallholder irrigation projects account for 13,000 and 16,000 hectares respectively.

Most of the area under smallholder irrigation was developed as a part of Smallholder Irrigation Development Project (SIDP) of the Irrigation and Drainage Branch (IDB) started in 1977. Its intention was to operate in the realm of social good and assist smallholder by providing technical and financial assistance in the development of smallholder irrigation and drainage projects.

When the IDB of the Ministry of Agriculture was established, it emphased the development of irrigation projects in famine relief areas. Under such conditions, SIDP provided financial and technical assistance and hence the farmers did not feel a sense of ownership for the scheme. With time disagreements developed and many of the schemes fell into a state of disrepair.

Improved farmers' participation in the planning, design, implementation, operation and maintenance of the project was identified as a partial solution. Community development officers in the Ministry of Culture and Social Services and community mobilization NGOs were used to bridge the gap between engineers and the farmers.

Under a full grant funding strategy, the level of farmers' participation was low. This strategy soon created sustainability problems attributed to increasing demand for grant funds, low level of farmers' commitment to scheme operation and maintenance, and a drop in the level of production. To overcome this problem an element of cost-sharing was introduced. The level of farmers' contribution sought depended on the level of farmers' income, availability of labour, cost of the projects, donor policy and implementation duration. This has resulted in a significant improvement in the level of farmers participation.

4.3. IMPROVING THE QUALITY OF DESIGNS

When smallholder irrigation development project started, Kenya had a very low capacity for the design and implementation of smallholder irrigation projects. Over the last 30 years the number of irrigation specialists involved in smallholder irrigation development has risen from 0 to 196 (MALDM 1993). This has resulted in a significant improvement in the quality of design brought about by:

- increase in quality and quantity of irrigation specialists (14 officers with MSc degrees, 3 with post-graduate diplomas, 49 with BSc degrees and 129 with diplomas);
- establishment of a panel of experts to screen proposals for sustainability and cost-effectiveness, check quality of the design, and determine the optional allocation of scarce financial resources available through donor grants;
- use of standard culverts, division boxes and drop structures; and
- improving access to vital information data bases on climate, soil, river flows and abstractions, crop production and economic analysis data.

4.4. FUNDING IRRIGATION DEVELOPMENT

Past experiences of poor performance of irrigation projects, high cost of irrigation and reduced irrigation funding from major donors has constrained irrigation development. The immediate short-term solution to this problem was to seek a cost minimization approach and rank projects in term of their development priorities and suitability for grant or loan-funding. The long-term solution lay in reducing dependency on donor funding and in diversifying the financing by including domestic financial institutions. This led to the establishment of Smallholder Irrigation Scheme Development Organisation (SISDO) in 1991. Its goals are:-

- provision to farmers of irrigation infrastructure through loans;
- financing of farming inputs (seeds, fertilizers and pesticides) on a credit basis using a Grameen banking approach; and
- assisting farmers in organising themselves at group and scheme levels.

4.5. IMPROVING WATER DELIVERY AND COLLECTION OF WATER FEES

Establishment of smallholder farmer-owned and operated water undertaker organisation was found feasible under the following conditions:

- where a number of irrigation schemes can be served by a common intake and water conveyance system;
- where the government agencies are not willing or able to develop the water delivery infrastructure; and
- where the scheme committees and members are willing to work together to secure water.

In 1991, Smallholder Irrigation Support Organisation (SISO) was registered with the aim of ensuring sustainability of water delivery by creating an operational fund for South West Kano irrigation project. The fund is based on the payment of water fees (to be used for maintaining the major works) by farmers (MoA 1991). Phase I of South West Kano irrigation project consist of three clusters, each with 4-7 schemes of 20 to 90 hectares each. The total scheme area is 530 hectares. Group, scheme, cluster and project committees are set up to represent the farmers in dealing with SISO on water fee payment, assessment of maintenance requirements and evaluation of quotation and tender bids.

The main element in water fee repayment organisation is the group. The group has to pay its water fees for the season in full. If some members are unable or unwilling to pay, the group is forced to look for alternative ways of raising the money. This approach follows the loaning procedure used in the informal sector to groups, which secure each others loans. Non-payment of the group water fee is a breach of contract which leads to disconnection of the water supply for the next irrigation season. This project has been operational for one year and early indications are that the social structure built along clan lines will provide a strong cohesion required for sustaining the water delivery system.

4.6. REDUCING ADVERSE ENVIRONMENTAL IMPACTS

In 1991, the IDB incorporated environmental impact assessment into their irrigation and drainage project planning. The impact assessment is based on flooding and drainage hazards, water-borne diseases occurrence, pollution due to disposal of domestic wastes, encroachment into forests, swamps and desiccation of wetlands, loss of dry season grazing lands and overgrazing around the schemes, land use conflicts due to obstructing the movement of wildlife and pastoralist cattle, soil erosion due to bush clearing and land preparation, flooding and drainage hazards, disruptive effects on migrating fish, destruction of crops by livestock and wildlife, crop damage by pests and insufficient supply of wood-fuel.

The strategies used to reduce adverse environmental impacts include: improving soil and water management; instructions on proper handling of chemicals; and sound crop management to prevent build-up of soil-borne diseases and pests.

5. Conclusions and Recommendations

Irrigation in Africa, particularly, in Sub-Saharan Africa is relatively under-developed and its sustainability is at risk. This is evidenced by the low level of project performance, lack of clearly defined irrigation policies and implementation plans, and a decline in donor funding. Recommendations from research findings, irrigation workshops, etc. are rarely taken seriously. There is therefore a dire need to look for new and innovative ways to provide the much needed impetus for irrigation development.

In order to sustain irrigated agriculture in Sub-Saharan Africa a concerted effort is required to alleviate technological, managerial, environmental, institutional, economic and social constraints. Research is expected to play a key role and should address the following issues:

- developing additional water resources;
- improving water use efficiency;
- improving crop yields and cropping intensities;
- reducing soil resource degradation;
- reducing investment and operation and maintenance cost of irrigation projects;
- improving local contribution to irrigation development;
- policy support; and
- reducing conflicts among irrigation water users.

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ASSESSMENT OF IMPACTS OF IRRIGATED AGRICULTURE : A CASE STUDY

A. POULOVASSILIS, P. KERKIDES, S. AGGELIDES,
T. MIMIDES, M. PSYHOYOU, S. ALEXANDRIS,
G. KARGAS and A. SGOUMBOPOULOU
Agricultural University of Athens
Water Resources Management Sect.
75, Iera Odos , 118 55 , Athens Greece

1. Introduction

All terrestrial life ultimately depends on soil and water. So commonplace and seemingly abundant are these elements that we tend to treat them with contempt (Hillel 1991). Long before the advent of technology and toxic compounds , even before the advent of agriculture, humans began to affect their environment in far-reaching ways that destabilised natural ecosystems. Today the explosive growth of human population makes it necessary to increase productivity. According to FAO (1985) estimates, another 50 million hectares of land in the world could be developed for irrigated agriculture over the next 25 years and the area which could be rehabilitated is even larger (Feyen *et al.* 1992). Intensification of irrigated agriculture on the other hand cannot any longer be the solution. The ability of natural resources (soils and water) to produce food and fiber is limited. Any exploitation of land and water resources beyond certain limits will result in degradation and lowered productivity (FAO 1980). In 1987 the World Commission on Environment and Development published its report (Our Common Future) which outlines the dangers arising from attempts, both by developed and developing countries, to base progress on practices which are environmentally, socially and economically unsustainable . It lays out the prerequisites for " *sustainable development* " defined as forms of progress without compromising the ability of future generations to meet their needs. According to FAO (1992), in an attempt to translate sustainability into an operational reality, the following definition of sustainable development was adopted (Dudal 1992) "*the management and conservation of the natural resource base and the orientation of technological change to ensure the attainment and continued satisfaction of human needs - food, water, shelter, clothing and fuel - for present and future generations. Such sustainable development, including agriculture, forestry and fisheries conserves genetic resources, land and water resources, is environmentally non-degrading, is technically appropriate, is economically viable and socially acceptable.*"

L. S. Pereira et al. (eds.), Sustainability of Irrigated Agriculture, 601–613.

The problem of sustainable irrigated agriculture is a complicated one, since it involves in a complex manner a diversity of factors such as, climate, soils, crops, cultivation practices, water, energy and all these, coupled with human activities and attitudes whose visible aims are not always in accord with the concept of sustainability. The attainment of sustainable irrigated land - use requires increased people's involvement and participation. In this paper the case of Argolis, Peloponnese (Greece), is presented in an attempt to identify the factors which have resulted in present situation and try to promote remedial measures in the concept of sustainability, so that for this case, sustainability will not be just another fashionable word.

Argolis is a place lavishly endowed by nature. It embraces the sea, it is rich in springs and ground waters, it has fertile soils. It was not, therefore, accidental that it appeared to have been emerged as one of the most famous centres of the ancient Greek civilisations. Also it was not accidental its rapid economical development in modern times which has followed the intensification of its agriculture.

This intensification (which implied irrigation, application of fertilisers, use of improved plant varieties, mechanisation, establishment of agricultural industries, etc.), has started before World-War II to show, in particular, high expansion rates after 1950. It has gone ahead, without any plan or perspective for the future, by overexploiting the natural resources of the region, its only objective being the temporal economic benefits to the people of the area.

During the last thirty-five years ground waters have almost been exhausted, polluted and contaminated, the soils are in danger of degradation and even the quality of spring waters have been deteriorated. Argolis today is not just poorer than in the past, but it follows a degradation path which may ultimately lead it to desertification.

In order to illuminate all the above mentioned issues a comprehensive study has been undertaken for the case of Argolis. Data concerning the water potential of the area, its quality, quantity and time and space distribution were gathered processed and properly analysed. Data concerning the needs for irrigation water and the expansion of irrigated agriculture, which has taken place relatively recently were also collected and analysed. Moreover , data concerning the soils and the gradual accumulation of salts, as well as other pertinent information , which might be considered as raising the question on the sustainability of irrigated agriculture of the area, were collected and analysed with the aim of averting the danger of degradation of natural resources and with ultimate objective of setting the guidelines and measures of restoring the system soils - groundwater for a safe continuation of the practice of irrigated agriculture not only for the present but for the generations to come as well.

2. General Description of Argolis

2.1. THE WATERSHEDS OF ARGOLIS

The Argolis plain occupies the northern part of the geological depression situated between mountain Arachnaios and the Arcadic mountains. The southern part of this depression is occupied by the sea, thus forming the Argolis bay. The formation of the plain has been reached through segmental raising of land which took place in previous geological eras and transportation and deposition of sediments by the numerous streams which flow or used to flow into the Argolis bay. The thickness of the alluvial deposits is great, exceeding in some cases 600 m as it has been shown by an exploratory borehole drilled close to the village of Anifi.

The total area of the watersheds of Argolis (watersheds of Spiliotakis, Kalamakis,Kirimis, Xerias, Inachos, Dervenakiotis, Klesouras, Berbakas, Amorgianos, Ramantanis, Dafnopotamos, Kantia and Fichtia.) is 1070 km^2 approximately. This area is classified according to altitude and use as given by Tables 1 and 2 below.

TABLE 1. Distribution of land areas in Argolis according to their altitude

Physiography	Altitude (m)	Area (hectares)
mountainous areas	>500	38,600
semi-mountainous areas	200-500	26,500
flat areas	0-200	41,900
Total area		107,000

TABLE 2. Distribution of the flat areas in Argolis according to their use

Altitude (m)	Cultivated area (ha)	Pastures (ha)	Barren land (ha)	Urban area (ha)	Totals (ha)
0-100	25,300	750	1,050	2,000	29,100
100-200	4,000	7,100	700	1,000	12,800
Totals	29,300	7,850	1,750	3,000	41,900

With the exception of Xerias and Inachos winter streams which occasionally discharge their water directly into the sea, all other winter streams end at the outskirts of the plain where their waters are absorbed by the course sediments to recharge the underground water bearing formations.

2.2. CLIMATE

The climate of the region is of the Mediterranean type but showing a definite influence of the continental European climate. The mean monthly temperature is higher than 8 ^{o}C with a minimum (8-10 ^{o}C) during January and a maximum (28 ^{o}C) during August. However minimum temperatures can be as low as -5 ^{o}C and maximum ones as high as 45 ^{o}C. Continentality increases with distance from the sea and, as far as temperature is concerned, inner areas are colder than coastal areas by about 2 ^{o}C. The frost - risky period lasts 5 months (November-March) with only 5 days of partial frost, in areas close to the sea but nearly 25 frosty days in areas further distant from the sea.

The winter period is the most humid (around 75 % relative humidity) and the most rainy period, with the highest monthly mean precipitation (slightly less than 110 mm) in December. The least humid month (July), with relative humidity less than 55 % does not always coincide with the driest month (ranging from June to August), with average precipitation less than 10 mm. The yearly mean precipitation, slightly over 510 mm, is normally recorded within about 90 days (throughout the year).

Winds, from south and or north directions, blow with a mean velocity not exceeding 3.5m/s at the coastal area but are usually stronger further away from the sea.

2.3. GEOLOGY

The NE part of Peloponnese consists of geological formations that belong to two geotectonical zones namely Gavrovo-Tripolis and Olonos-Pindos. Also are encountered metalpine and neogene formations and tectonic sediments.

a) Gavrovo - Tripolis zone. It is composed of limestones, dolomites of Upper-Triassic and Lower-Eocene age and of flysch of Lower Eocene-Oligocene age.

The Proalpine basement of Tripolis consists from semi-metamorphic phyllites, clays with limestones and volcanic rocks in places.

b) Olonos-Pindos zone. It is found overthrusted on Tripolis zone and includes thin-platted limestones with clay-radiolarite intercalations. The age of this system is Triassic to Paleocene. The flysch of this zone is in conformity with the limestones and consists of clays and sandstones. In many cases between the two zones is encountered a tectonic - sedimentary melange which is part of the lower horizon of Olonos zone. Due to its plasticity this intermediate slided material assisted to the movement of the overburden masses during the last phase of Alpine orogenesis.

c) Meta-alpine sediments. These sediments are the Neogene formations from marls, sandstones, clays and conglomerates, as well as the Quarternary deposits from sands, pebbles and clays, where special emphasis will be given during the artificial recharge procedure.

3. The Soils of Argolis

According to the physical characteristics of the soil profiles, the soils of Argolis may be classified into seven soil series. Their main characteristics are given below :

- *First soil series*: It covers an area of 42.85 km^2 approximately and it is developing on the slopes of the limestone mountains and on the limestone hills of the plain. They are usually calcitic soils of small depth with a silty texture.
- *Second soil series*: It covers an area of 34.5 km^2 and is formed from the coarse sediment of the torrents. They contain a fair percentage of gravel (20 - 30 %) and their subsoil usually consists of cobbles, gravel and sand.
- *Third soil series*: It occupies an area of 35.85 km^2 and its soils may be characterised as colluvium with a high content of small limestone fragments. Their clay content is usually high and their depth rather small (30 - 50 cm).
- *Fourth soil series*: It covers an area of 8.5 km^2 approximately. These soils are formed on the sandy deposits of the streams and they contain gravels as well. They are deeper than two meters and their texture after removing the gravel is medium (L).
- *Fifth soil series*: It occupies an area of 25.6 km^2 approximately. These soils are deep with three distinctive layers. The first layer is of a sandy - loamy texture, of a depth of 25-30cm, and it lacks $CaCO_3$. The second layer is of a thickness 30-70 cm with a high clay content. Its $CaCO_3$ is very small. The third layer is usually encountered at a depth of 70 - 120 cm, it is of medium texture, and is rich of $CaCO_3$.
- *Sixth soil series*: It occupies an area of 54.9 km^2 approximately. Its soils are deep (>2m) and uniform and they may be characterised as marly clay loamy.
- *Seventh soil series*: It covers an area of 62.625 km^2. They are deep soils of a silty - clay texture. Some of them are uniform but others present layers in their profile. Their $CaCO_3$ lies between 20 and 40%.

The soils of Argolis may be separated into four irrigability categories as it is shown in the following Table 3 (areas in km^2)

TABLE 3. Distribution of soils in Argolis according to their irrigability

	Irrigability category				
Soil series	I	II	III	IV	Totals
1st	-	2.950	12.125	27.775	42.850
2nd	-	-	34.500	-	34.500
3rd	-	3.075	18.925	8.850	30.850
4th	-	8.500	-	-	8.500
5th	-	8.775	16.825	-	25.600
6th	26.375	26.900	-	1.625	54.900
7th	21.150	34.025	7.350	3.100	65.625
Totals	47.525	84.225	89.725	41.350	262.825
Percentages	18.1	32.1	34.1	15.7	100.00

4. Water Resources

4.1. UNDERGROUND AQUIFER FORMATIONS

Almost half of the rain water falling on the limestones of the area percolates through them and creates dynamic karstic aquifers. A part of this karstic water recharges the granular formations, while another emerges in the form of springs along the coasts or under the sea.

The granular aquifer formations are encountered into the low and semi-mountainous zone and according to their permeability are classified as follows:

- Aquifers with thin impermeable intercalations, sometimes of irregular or stratified form, exhibiting a variable permeability.
- Aquifuges or partially aquicludes. It concerns horizons from red clays with a fair proportion in sands and pebbles.

The whole region under interest is covered with clay silty sandy marly material from old and new alluvial deposits with appearances of conglomerates at the margins. The thickness of this material is usually smaller than 50 metres and forms the top layer confining the underlined aquifers. With the help of stratigraphic boreholes drilled, it may be assumed that three main aquifers of the plain developed within the depth of 100 metres from the surface. Figure 1 shows the variation of mean hydraulic heads of the three aquifers as they have been observed through the years, while Figure 2 shows their mean chloride content.

4.2. SPRING - WATER RESOURCES

4.2.1. *Discharge characteristics of the existing springs*

- *Kefalari Spring (Argos)*. It is an overflowing karstic spring emerging at an elevation of 24.30 m above sea level. Its discharge presents a strong variability directly related to the rainfall pattern. On the basis of the measurements conducted and their statistical treatment the discharge characteristics are shown in Table 4.

TABLE 4. Discharge characteristics of Kefalari spring (Argos)

Month	Number of measurement	Mean value (m^3/sec)	Standard deviation (m^3/sec)
January	16	3.169	2.547
February	12	3.987	2.560
March	17	4.719	1.856
April	17	4.074	1.871
May	17	2.905	1.543
June	20	2.281	1.531
July	17	1.552	1.900
August	18	0.764	0.401
September	16	0.547	0.354
October	15	0.301	0.324
November	13	0.719	0.897
December	15	2.173	2.324

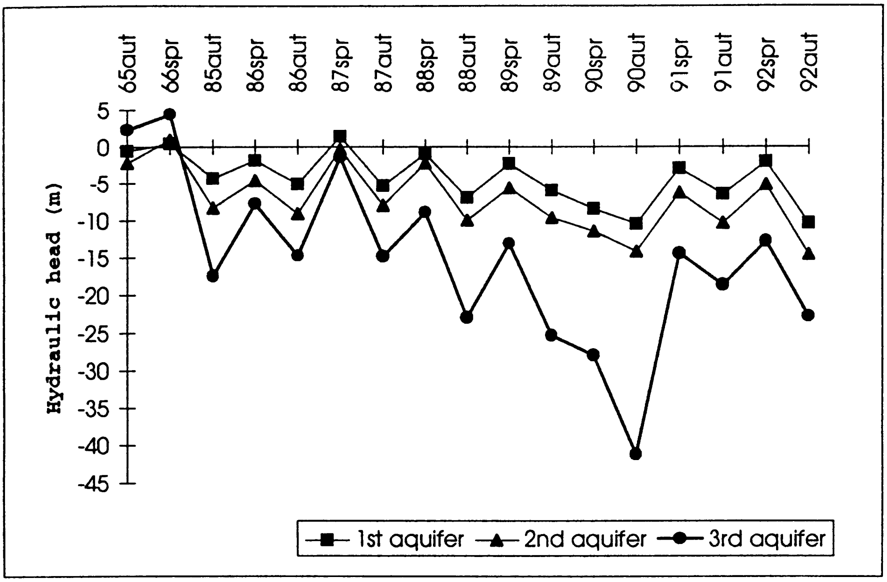

Figure 1 . Mean hydraulic heads (m) of the three aquifers of Argolis

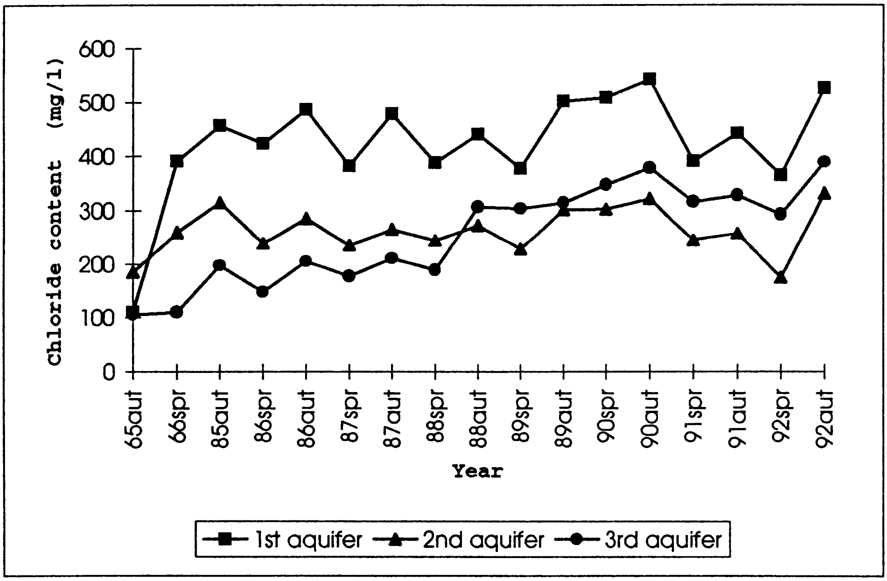

Figure 2 . Mean chloride contents (mg/l) of the three aquifers of Argolis

- *Lerni Spring (Myli).* It is a karstic spring emerging at an altitude of 0.60 m above sea level at a distance of 200 metres from the sea shore. Its discharge remains relatively constant throughout the year. The discharge characteristics are as shown in Table 5.

TABLE 5. Discharge characteristics of Lerni spring (Myli)

Month	Number of Measurements	Mean value (m^3/sec)	Standard deviation (m^3/sec)
January	19	1.764	0.385
February	14	1.784	0.717
March	21	1.900	0.443
April	17	1.919	0.571
May	21	1.740	0.381
June	22	1.665	0.416
July	21	1.368	0.185
August	19	1.334	0.185
September	20	1.445	0.435
October	18	1.451	0.553
November	16	1.439	0.221
December	17	1.602	0.303

- *Amymoni Spring (Myli).* Its discharge is of the order of 0.2 m^3/sec which remains relatively constant throughout the year.

- *Kiveri springs.* They form a group of karstic springs emerging at the sea shore at an altitude ranging between 0.25m and - 7.50 m. It is estimated that their total discharge is of the order of 10 - 12 m^3/sec remaining relatively constant throughout the year. However, few actual measurements have been conducted.

4.2.2. *Quality of spring waters*

With the exception of Kiveri springs the water of all other springs contain acceptable amounts of solutes, therefore it is considered as suitable for drinking. Their Cl^- content is small which shows that they do not come into contact with sea water. On the contrary chloride content of the water of Kiveri spring is rather high ranging between 6 to 15 meq/l with higher chloride content observed in the Autumn just before the rainy season (see Figure 3). Because of this its extensive use for irrigation may affect adversely the quality of both soils and ground water.

5. The Problem of Argolis.

From the data already presented it becomes evident that the problem of Argolis is not restricted in ensuring enough irrigation water for the maintenance and expansion of irrigated agriculture but it also involves the protection and rehabilitation of the natural resources of the region in order to avoid a further destruction of its ecosystem and restore its components. In the following it will be attempted to analyse the problem in order to present an integrated programme of interventions for pursuing the target set.

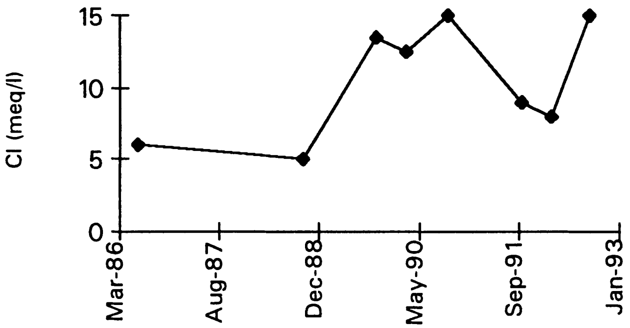

Figure 3. Chloride content of water of Kiveri springs

5.1. THE EXPANSION OF IRRIGATED AGRICULTURE

There is not accurate information concerning the development of irrigated agriculture in Argolis. And this holds not only for the years before the world war II, but also for the more recent periods. However the following Table 6 contains estimations of the irrigated areas and of the irrigation water used which must not differ much from the actual quantities involved.

TABLE 6. Expansion of irrigated agriculture(1945-1990)

Dates	1945	1965	1985	1990
Irrigated areas (ha)	5,500	12,500	17,000	19,500
Irrigation water applied (m^3x10^6/year)	45	100	135	145

Some information concerning the areas covered by various crops for the years 1965 and 1990 are given in the Tables 7 and 8 that follow.

TABLE 7. Area (in hectares) covered by various crops during 1965

Crops	Non-irrigated	Irrigated	Totals
Citrus trees	-	7,000	7,000
Vegetables	-	5,500	5,500
Cereals	4,500	-	4,500
Olive trees	6,500	-	6,500
Tobaccos	900	700	1,600
Vines	200	-	200
Fodder crops	3,000	-	3,000
Total	1,510	13,200	28,300

TABLE 8. Area (in hectares) covered by various crops during 1990

Crops	Non-Irrigated	Irrigated	Total
Citrus trees	-	11,200	11,200
Vegetables	-	2,250	2,250
Olive trees	6,760	230	6,990
Cereals	1,840	-	1,840
Tobaccos	-	2,120	2,120
Vines	-	80	80
Fodder crops	1,860	200	2,060
Other orchards	180	1,600	1,780
Total	10,640	17,680	28,320

The land which is already under cultivation in Argolis is close to the total cultivable one and out of that 26,500 ha can be considered as irrigable ones. Thus, there is in the region an area of about 7,000 ha which, taking into consideration the existing trend, will be put under irrigation when the water of Kiveri springs is massively transported in Argolis. It must be noted that the construction of the canal required for this transport is expected to be completed soon.

5.2. THE NEEDS FOR IRRIGATION WATER

If it is accepted that irrigated agriculture will expand to 26,500 ha in the near future and that the required mean specific discharge for the driest period of the year (June, July, August, September) will be in the order of 0.65 l/sec/ha, then the total discharge required for the whole area will be in the order of 17 m^3/sec. Further, if it is supposed that the required quantity of irrigation water per hectare and per year is about 7,000 m^3 , then the total quantity of irrigation water for the whole area will be close to $200 \times 10^6 m^3$/year.

The underground aquifers have been the main source of irrigation water through the years. Additional sources have been Kefalari and Lerni springs and lately the Kiveri springs. The following Table 9 shows the approximate contribution of each irrigation water source during the last 25 years.

TABLE 9. Contribution of various sources to irrigation water applied ($m^3 \times 10^6$/year)

Dates	Ground water	Kefalari and Lerni springs	Kiveri springs	Total water applied
1965	80	20	0	100
1985	100	20	15	135
1990	110	20	15	145

It is planned that, upon the completion of the Kiveri canal, the summer discharge of the Kiveri springs to be transported and used in Argolis plain for irrigation. Therefore Kiveri springs will be in the near future the main source for irrigation water. It has been maintained that the total discharge of Kiveri springs is around 12 m^3/sec having a chloride content close to 6 meq/l. However, during the last five years, it has been observed a rather serious increase of the chloride content which may be due to discharge decreases of the springs during relatively dry years. Thus, in order to cover the needs in irrigation water an additional water source with a specific discharge of about 6 m^3/sec will be needed even if the Kiveri spring discharge is actually maintained at 12 m^3/sec. Ground water can provide the additional quantity of water required after the aquifers have been recharged and the quantity of their water improved. Following the deterioration of the quality of ground water due to the percolation of agrochemicals, Lerni spring must become the main source of water for domestic use leaving about 0.80 m^3/sec for irrigation. It must also be noted that the summer discharges of Kefalari spring have to be ignored because of their strong variability.

5.3. THE DANGER OF DEGRADATION OF NATURAL RESOURCES

By supposing that about $150x10^6$ m^3 of water from Kiveri springs will be transported and used for irrigation in Argolis every year and that the mean $NaCl$ content of that water will be 10 meq/l then it may be concluded that about 90,000 metric tons of $NaCl$ will be deposited on its soils every year which corresponds to about 3500 kg/ha per year. The deposition would render the soils of Argolis unsuitable for agricultural use if the salts were to remain in the soil profile. The rain water would cause a partial leaching but it is doubtful if it would be able by itself to remove salts at a sufficient depth below the root zone. It is almost certain that for this, a leaching program must be applied.

However, the leaching of the salts implies their transportation to the ground water contained to the unconfined and semi - confined aquifers. The clayish layers separating the semi - confined aquifers (which are developed in the central part of the Argolis plain) may slow down the mixing of the leachates with their water but in the coarse sediments at the border of the plain where most of the natural recharging occurs there do not exist layers of low conductivity to avert them from reaching ground water. Actually it has been found that the nitrate content of ground water in the central part of the valley to be much smaller than at its outskirts. Thus, the use of Kiveri spring water for irrigation in areas with one uniform unconfined aquifer may result in a continuous deterioration of ground water quality to render it unsuitable for irrigation.

5.4. GUIDELINES FOR AVERTING DEGRADATION OF THE SYSTEM SOILS - GROUND WATER

They can be summarised in the following:

- The use of water from Kiveri springs must be restricted in the central part of Argolis plain where the underground aquifers are sandwiched between relatively impermeable clay layers. In this part a drainage system must be introduced in order to check the rise of the water table and to eject the leachates to the sea.
- The regions with coarse permeable sediments and with a common unconfined aquifer must be irrigated with ground water of good quality. Their area is about 8,000 ha and the water needed for their irrigation is estimated to be of the order

of $60x10^6$ m^3/year, quantity which is close to the rain water which naturally recharges ground water every year.

5.5. THE REHABILITATION OF THE UNDERGROUND AQUIFERS

It involves the improvement of the water quality of the aquifers and their replenishment. Both targets can be pursued by applying a program of artificial recharge through the existing boreholes. For this, the winter discharge of Kefalari spring is planned to be used which can reach by gravity the central part of the valley by means of the Kiveri canal. It is estimated that about $40x10^6$ m^3/year of Kefalari water may be secured for recharging the aquifers. Some winter discharge of Lerni spring can be also used for the same purpose.

6. Undergoing Research Projects

In order to solve rationally the problems of Argolis presented in the foregoing a number of research projects have been initiated, briefly described below:

- *Hydrology Project*:
  - collection and processing of all available meteorological data and particularly of the precipitation data ;
  - collection and processing of all surface run-off data in the watersheds of Argolis and execution of in situ measurements if necessary ;
  - setting up of the water balance for the whole region by determining the terms entering it.

- *Ground Water Project*:
  - additional stratigraphy work for locating the aquifers and their recharge region where common unconfined aquifer is present ;
  - measurements of the hydraulic characteristics of the aquifers, of their storage coefficient (S) and capacity ;
  - monitoring the piezometry and the quality of ground water ;
  - setting up a network of recharging boreholes and conducting artificial recharge on an experimental scale.

- *Spring Water Project*:
  - discharge measurements especially those of the Kiveri springs and correlating it with rainfall characteristics ;
  - chemical analysis of spring water and in particular monitoring the chloride content of Kiveri springs under intensive exploitation and correlating it with discharge characteristics .

- *Soil Protection Project*:
- determination of soil characteristics especially their salinity and alkalinity present status ;
- determination of the hydraulic characteristics of the soil profiles in various soil series ;
- monitoring water table heights and setting up salt balances of the soil profiles under various irrigation schemes.

7. Conclusions

The problem of Argolis depicts all adverse effects of irrigated agriculture when no plans or perspective for the future have been considered, the only motivation being the temporal economic benefits of the people of the area. As it has been presented, the irrational management of the irrigated agriculture and the overexploitation of the natural resources, may lead in just a few decades to such a degree of deterioration of these commodities, where no remedial measures can be enough to avert the real danger of desertification of the area.

Fortunately for the case of Argolis, there are hopes for the future, there are means by which sustainable irrigated agriculture can be exercised. These measures could face natural resources with respect and among other measures described above, an effective way of restoring and improving their quality is through the implementation of artificial recharge using the winter discharge of Kefalari spring (a source of good quality water).

The conveyance of this water to the sites where artificial recharge will be more effective, will be through the use of the Kiveri canal which has been constructed recently. Preliminary works show promise and people are encouraged to continue this practice.

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ANNEXES

Annex I: Format of the Workshop (Vimeiro, Portugal, 21-26 March 1994)

1st Day: Monday, 21 March	2nd Day: Tuesday, 22 March	3rd Day Wednesday, 23 March
Opening. ARW objectives.	Panel on Topic II.	Papers on Topic IV: **Irrigation water management and scheduling**
Papers on Topic I: **Sustainability of World Irrigation systems**	Introduction to discussion process.	
	Papers on Topic III: **Sustainability of indigenous soil and water conservation systems**	
Lunch	*Lunch*	*Lunch*
Panel on Topic I.	Panel on Topic III.	Excursion
Papers on Topic II: **Water management and water policies**	Group discussions.	
	Plenary discussion	
4th Day: Thursday, 24 March	**5th Day: Friday, 25 March**	**6th Day: Saturday, 26 March**
Papers on Topic VII: **Sustainability and environmental concerns**	Papers on Topic VI: **Irrigation scheme management**	Plenary discussion election of research priorities.
Group discussions.	Papers on Topic VII: **Sustainability and environmental concerns**	
		Closing/Recommendations for follow-up.
Lunch	*Lunch*	*Lunch*
Papers on Topic V: **On-farm irrigation systems**	Papers on Topic VIII: **Technology transfer**	
Group discussions.	Group discussions.	
Plenary discussion		

Annex II

LIST OF PAPERS PRESENTED TO THE WORKSHOP

I. SUSTAINABILITY OF WORLD IRRIGATION SYSTEMS

Irrigated agriculture at the cross-roads, Dr. M. JENSEN

Sustainability concerns of irrigated agriculture, Dr. L. SMEDEMA

Sustainability concerns in Asian irrigation, Mr. K. MOTHADULLAH

Sustainability concerns in Africa irrigation, Dr. F. GICHUKI

Sustaining irrigated agriculture in China, Mr. XU DI

II. WATER MANAGEMENT AND WATER POLICIES

Major issues in water resources for the 90's, Prof. E. VLACHOS

Droughts and mitigation of effects of droughts, Prof. A. Carmo VAZ

Irrigation management support using satellite remote sensing, GIS and simulation models,

Dr. M. MENENTI

Institutional questions and social challenges, Dr. H. HILL

III. SUSTAINABILITY OF INDIGENOUS WATER AND SOIL CONSERVATION SYSTEMS

Water and soil conservation techniques in Tunisia, Dr. H. MISSAOUI

Some reflections on the sustainability of soil and water conservation in Sub-Saharan Africa ,

Dr. C. REIJ

Water harvesting: past and future, Prof. D. PRINZ

IV. IRRIGATION WATER MANAGEMENT AND SCHEDULING

Measurement and estimation of evapotranspiration, Dr. B. ITIER

Water use efficiency, Dr. P. STEDUTO

Field scale modelling of water and solute transport for drainage design and irrigation management, Prof. R. FEDDES

Irrigation scheduling, Dr. D. HEERMANN

Irrigation scheduling in the agronomic practice, Dr. A. YAZAR

V. ON-FARM IRRIGATION SYSTEMS

Surface irrigation systems, Prof. L. S. PEREIRA

Sprinkler irrigation systems, Prof. J. R. GILLEY

Micro irrigation/fertigation systems, Dr. I. PAPADOPOULOS

Waste-water reuse, Prof. S. KYRITSIS

VI. IRRIGATION SCHEME MANAGEMENT

Performance parameters for a descentralized and participatory water administration, Dr. J. CHAMBOULEYRON

Regulation and control in irrigation systems, Mr. J. GOUSSARD

Operational tools to improve the management of irrigation delivery systems: data base, simulation models, automatic control, Mr. P. KOSSUTH

Sustainability concerns in the operation & management of irrigation systems, Mr. J. SAGARDOY

VII. SUSTAINABILITY AND ENVIRONMENTAL CONCERNS

Use and management of saline water for irrigation towards sustainable development, Dr. A. HAMDY

Salinity management in irrigated agriculture, Dr. N. K. TYAGI

Impacts of agrochemicals and water management systems on water quality, Prof. R. KANWAR

Vulnerability of soils under irrigation: Sustainability challenges, Prof. J. PORTA

Nitrate leaching under irrigated agriculture: contamination and control, Dr. F. MORENO

Drainage of irrigated land, Dr. B. LESAFFRE

Health impacts of agricultural development, Dr. I. HESPANHOL

The economic case for sustainable irrigation development, Prof. I. CARRUTHERS

Measurement of water and solutes movement in soils; application to management of nutrients in irrigated systems, Dr. G. VACHAUD

Sustainability of irrigated agriculture - the case of Argolis, Peloponese, Greece, Dr. P. KERKIDES

VIII. TECHNOLOGICAL TRANSFER

Cooperation with third countries and the international organizations. Relations with developing countries (DCs), Dr. M. CATIZZONE

Transfer of technology: implementation of sustainable irrigation in Brazil, Mr. F. A. RODRIGUEZ

Professional training requirements, Prof. J. FEYEN

Technology transfer for sustainable water resources development, Mr. M. SMITH

Role of consulting services, Mr. J. HENNESSY

Policies on science and technology, Ms. M. LOUREIRO

Quality control of equipment and servicing, Mr. D. BAUDEQUIN

POSTER PAPERS

Improvements in tillage and furrow opening for surface irrigation, Dr. R. JORGE

Simulation of demand in an irrigation system, with models ISAREG and IRRICEP, Dr. J. L. TEIXEIRA

Surface irrigation techniques and equipment, Dr. P. L. SOUSA

SWATCHP - A model for the continuous simulation of hydrologic processes in a vegetation-soil-aquifer-stream system, Dr. P. MATIAS

Water and nitrates under fertigation applied to level basins, Ms. M. R. CAMEIRA

Water balance of corn in the alluvial soils of the Sorraia Valley, Dr. R. M. FERNANDO

Annex III

LIST OF PARTICIPANTS

Directors of the ARW

Dr. Luis S. PEREIRA
Professor and Head, Department of Agricultural Engineering
Instituto Superior de Agronomia
Tapada da Ajuda
1399 Lisboa Codex, **PORTUGAL**

Dr. James R. GILLEY
Professor and Head, Agricultural Engineering Department
Texas A&M University
Scoates Hall
College Station, Texas 77845-2117, **U.S.A.**

Dr. Rainder A. FEDDES
Professor, Department of Water Resources
Wageningen Agricultural University
Nieuwe Kanaal 11
6709PA Wageningen, **THE NETHERLANDS**

Dr. Benoit LESAFFRE
Research Director
CEMAGREF
Parc de Tourvoie, B.P. 44
92163 Antony Cedex, **FRANCE**

Participants

Mrs. Ana S. AZEVEDO
Research Assistant, Department of Agricultural Engineering
Instituto Superior de Agronomia
Tapada da Ajuda
1399 Lisboa Codex, **PORTUGAL**

Mr. Eduardo B. AZEVEDO
Assistant, Departamento de Ciências Agrárias
Universidade dos Açores
Ilha Terceira - Terra Chã
9700 Angra do Heroísmo, **PORTUGAL**

Dr. Ruhí BASTUG
Associate Professor, Department of Agricultural Structures and Irrigation,
Akdeniz University
Antalya, **TURKEY**

Mr. Denis BAUDEQUIN
Irrigation Technology Program Leader
CEMAGREF
Groupement d'Aix -en-Provence
Le-Tholonet, B.P. 31
13612 Aix-en-Provence Cedex 1, **FRANCE**

Ms. Maria João CALEJO
Research Assistant, Department of Agricultural Engineering
Instituto Superior de Agronomia
Tapada da Ajuda
1399 Lisboa Codex, **PORTUGAL**

Ms. Maria R. CAMEIRA
Assistant, Department of Agricultural Engineering
Instituto Superior de Agronomia
Tapada da Ajuda
1399 Lisboa Codex, **PORTUGAL**

Dr. Ian CARRUTHERS
Professor, Department of Agricultural Economics
Wye College
University of London
Wye, Ashford
Kent - TN25 5 AH, **UNITED KINGDOM**

Dr. Mario CATIZZONE
Program Leader
STD Programme
CEC, DG XII - B - 4
Rue de la Loi 200
B - 1049 Brussels, **BELGIUM**

Dr. Jorge L. CHAMBOULEYRON
Head, Department of Irrigation and Drainage Engineering
Instituto Nacional de Ciencia y Tecnica Hídricas
Centro Regional Andino
Belgrano 210 Oeste-5500 Mendonza, **ARGENTINA**

Dr. Antonio DI GIULIO
Administrator, CHIEAM
11, Rue Newton
75116 Paris, **FRANCE**

Dr. Rui M. FERNANDO
Assistant Professor, Department of Agricultural Engineering
Instituto Superior de Agronomia
Tapada da Ajuda
1399 Lisboa Codex, **PORTUGAL**

Dr. Jan FEYEN
Professor and Director, Center for Irrigation Engineering
Katholieke Universiteit Leuven
Vital Decosterstraat 102
3000 Leuven, **BELGIUM**

Mr. José C. FONTES
Assistant, Departamento de Ciências Agrárias
Universidade dos Açores
Ilha Terceira - Terra Chã
9700 Angra do Heroísmo, **PORTUGAL**

Dr. Francis GICHUKI
Lecturer, Department of Agricultural Engineering
University of Nairobi - Kabete Campus
P.O. 30197, Nairobi, **KENYA**

Mr. Jean GOUSSARD
Consultant
28 Rue Gay-Lussac
38100 Grenoble, **FRANCE**

Dr. Atef HAMDY
Director of Research, Istituto Agronomico Mediterraneo - Bari
Via Ceglie 23
70010 Valenzano (BA), **ITALY**

Dr. Dale F. HEERMANN
Program Leader, USDA-ARS Northern Plains Area
AERC, Colorado State University
Fort Collins, CO 80523, **U.S.A.**

Mr. John HENNESSY
President Hon. of ICID
Director, Sir Alexander Gibb & Partners
Earley House, 427 London Road
Earley, Reading, Berks RG6 1BL, **UNITED KINGDOM**

Dr. Ivanildo HESPANHOL
Program Leader, Division of Environmental Health
World Health Organization
Community Water Supply & Sanitation Unit
CH - 1211 Geneva 27, **SWITZERLAND**

Dr. Harry M. HILL
Director General, Prairie Farm Rehabilitation Administration
Room 603, CIBC Tower
1800 Hamilton Street
Regina, Saskatchewan, S4P 4L2, **CANADA**

Dr. Bernard ITIER
Director, Department of Bioclimatology
INRA
F. 78850 Thiverval Grignon, **FRANCE**

Dr. Marvin E. JENSEN
President Hon. of the ICID
1207 Springwood Drive
Fort Collins, CO 80525-2850, **U.S.A.**

Dr. Ramesh S. KANWAR
Professor and Water Quality Project Leader, Department of Agricultural and Biosystems Engineering
Iowa State University
219B Davidson Hall
Ames, Iowa 50011, **U.S.A.**

Dr. Christos KARAVITIS
Research Associate, Department of Agricultural Engineering
University of Athens
Pontou 24, Drosia
Athens 14 563, **GREECE**

Dr. Petros KERKIDES
Associate Professor, Laboratory of Agricultural Hydraulics
Dept. of Land Reciclation and Agricultural Engineering
Agricultural University of Athens
75 Iera odos
GR - 118 55 Athens, **GREECE**

Dr. Pascal KOSUTH
Director, Irrigation Division
CEMAGREF
Groupement de Montpellier
361, Rue J-F Breton, B.P. 5095
34033 Montpellier Cedex 1, **FRANCE**

Dr. Spyros KYRITSIS
Professor, Agricultural Engineering Department
Agricultural University of Athens
75 Iera odos
GR - 118 55 Athens, **GREECE**

Dr. Cosimo LACERIGNOLA
Director, Istituto Agronomico Mediterraneo - Bari
Via Ceglie 23
70010 Valenzano (BA), **ITALY**

Dr. Manuela LOUREIRO
Research Administrator, Junta Nacional de Investigação Científica e Tecnológica (JNICT)
Av. D. Carlos I, 126
1200, Lisboa, **PORTUGAL**

Dr. Paulo MATIAS
Assistant Professor, Department of Agricultural Engineering
Instituto Superior de Agronomia
Tapada da Ajuda
1399 Lisboa Codex, **PORTUGAL**

Dr. Massimo MENENTI
Head, Dept. of Water Management for Arid Zones
The Winand Staring Center for Integrated Land, Soil and Water Research (SC-DLO)
Marijkeweg 11/12
P.O. Box 125
NL- 6700 AC Wageningen, **THE NETHERLANDS**

Dr. Habib MISSAOUI
Director, Soil and Water Conservation
Ministry of Agriculture
30, Rue Alain Savary
B.P. 51 Ariana
2080, Tunis, **TUNISIA**

Mr. Khalid MOHTADULLAH
Deputy Director General
International Irrigation Management Institute
P.O. Box 2075, Colombo, **SRI LANKA**

Dr. Félix MORENO
Senior Researcher, Institute of Natural Resources and Agro-Biology (CSIC)
Av. Reina Mercedes, s/n
Apartado 1052
41080 Sevilla, **SPAIN**

Dr. Ioannis PAPADOPOULOS
Senior Researcher, Agricultural Research Institute
Ministry of Agriculture and Natural Resources
P.O. Box 2016, Nicosia, **CYPRUS**

Mrs. Celestina G. PEDRAS
Assistant, Departamento de Ciências Agrárias
Universidade do Algarve
Campus de Gambelas
Gambelas, 8000 Faro, **PORTUGAL**

Dr. Jaime PORTA
Rector and Professor of Soil Science, Universidad de Lleida
Bisbe Messeguer
25006 Lleida, **SPAIN**

Dr. Dieter PRINZ
Professor and Head, Department of Rural Engineering
University of Karlshruhe
Kaiserstraβe 12
D-7500 Karlshruhe 1, **GERMANY**

Mrs. QIAN Yunbi
Head, Department of Irrigation and Drainage
Institute of Water Conservancy and Hydroelectric Power Research (IWHR)
20 West Chegongzhuand Rd.
P.O. Box 366, Beijing 100 044, **CHINA**

Dr. Christopher REIJ
Project Leader, Natural Resource Management Unit
Centre for Development and Cooperation Services
Free University of Amesterdam
De Boelelaan, 1115
1018 HV Amsterdam, **THE NETHERLANDS**

Mr. Fernando A. RODRIGUEZ
Director, Companhia de Desenvolvimento do Vale de S. Francisco
CODEVASF
SGAN, Q.601, Bloco I - Ed. Sede
CEP 70830-001 Brasília - DF, **BRAZIL**

Mr. Juan A. SAGARDOY
Senior Technical Officer, Land and Water Development Division
FAO
Via delle Terme de Caracalla
00 100 Rome, **ITALY**

Dr. Lambert SMEDEMA
Theme Manager, AGRN/IPTRID, Room N° 7017
The World Bank
1818 H. Street, N. W.
Washington D. C. 20433, **U. S. A.**

Dr. Martin SMITH
Senior Technical Officer, AGLW
FAO
Via delle Terme de Caracalla
00 100 Rome, **ITALY**

Dr. Pedro L. SOUSA
Assistant Professor, Department of Agricultural Engineering
Instituto Superior de Agronomia
Tapada da Ajuda
1399 Lisboa Codex, **PORTUGAL**

Mr. Vicente S. SOUSA
Assistant, Departamento de Fitotecnia e Engenharia Rural
Universidade de Trás-os-Montes e Alto Douro
Quinta dos Prados, Apartado 202
5001 Vila Real, **PORTUGAL**

Dr. Pasquale STEDUTO
Researcher, Istituto Agronomico Mediterraneo - Bari
Via Ceglie 23
70010 Valenzano (BA), **ITALY**

Dr. José L. TEIXEIRA
Associate Professor, Department of Agricultural Engineering
Instituto Superior de Agronomia
Tapada da Ajuda
1399 Lisboa Codex, **PORTUGAL**

Dr. Narendra K. TYAGÍ
Principal Scientist, Division of Drainage and Water Management
Central Soil Salinity Research Institute
Zarifa Farm, Kachswa Road
Karnal - 132001 (Haryana), **INDIA**

Dr. Georges VACHAUD
President of the European Geophysical Society
Laboratoire d'Études des Transferts en Hydrologie et Environnement, Institut de Mecanique de Grenoble (LTHE/IMG)
BP 53X
38041 Grenoble Cx, **FRANCE**

Dr. Alvaro C. VAZ
Associate Professor, Faculdade de Engenharia
Universidade Eduardo Mondlane
C.P. 257, Maputo, **MOZAMBIQUE**

Dr. Evan C. VLACHOS
Professor, Civil Engineering Department
International School for Water Resources and Associated Programmes
201 Weber Building
Colorado State University
Fort Collins, CO 80523, **U.S.A.**

Mr. XU Di
Engineer, Department of Irrigation and Drainage
Institute of Water Conservancy and Hydroelectric Power Research (IWHR)
20 West Chegongzhuand Rd.
P.O. Box 366
Beijing 100 044, **CHINA**

Mr. YE Sudong
Project Manager, Department of Irrigation and Drainage
Institute of Water Conservancy and Hydroelectric Power Research (IWHR)
20 West Chegongzhuand Rd.
P.O. Box 366
Beijing 100 044, **CHINA**