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# Computer Software Applications for Salinity Management: A Review

Pakorn Ditthakit

[1]Division of Civil Engineering, School of Engineering and Resources Management, Walailak University, Nakhon Si Thammarat 80161, Thailand

**Abstract:** Soil salinity adversely affects crop production for inland and coastal agricultural areas. To comprehend the behaviors of salt transport processes in soils leading to preparedness of such problem-solving measure, numerous simulation models have been developed as decision making tools. The advantage of computer software is that it can be used to fill data gaps in measurements in terms of spatial and temporal resolution and to analyze different leaching and management scenarios. However, the capabilities and limitations of each model are different and carry their own characteristic features. To suitably select a model for a specific application, analyst could understand in details of soil water and salt flow processes as well as capabilities of computer simulation models. The objective of this paper is to summarize water and salt transport models in soils. The features of salinity management software are discussed and compared. The examples of computer software applications for salinity management are also presented. The review will provide technical knowledge to aid analyst in appropriately applying and selecting computer simulation software for managing salinity problems.

**Key words:** simulation model, soil water flow models, salinity and solute transport models, salinity management.

## INTRODUCTION

Agricultural productions are necessary as providing the food and fiber needs of human beings. These needs increase as the population increases (Rhoades *et al*., 1992). Severally environmental changes on the earth affect all significant growing factors. One of the major problems impeding agricultural development is saline soil and water in irrigated lands. Many millions of agricultural lands have gone out of yield poorly because of salt and alkali accumulations (Fireman and Kraus, 1965).

The total area of saline soils is 397 million ha and of sodic soils 434 million ha at global level. Of the current 230 million ha of irrigated land, 45 million ha are salt-affected soils (19.5 percent) and of the almost 1500 million ha of dryland agriculture, 32 million are salt-affected soils (2.1 percent) to varying degrees by human-induced processes (FAO/AGL, 2000). The problems of soil salinity are most widespread in the arid and semi-arid regions but salt affected soils also occur extensively in sub-humid and humid climates, particularly in the coastal regions where the ingress of sea water through estuaries and rivers and through groundwater causes large-scale salinization (Abrol *et al*., 1988).

The main cause leading to saline soil and water is natural processes or human-induced processes. For example, accumulation of salts may be the result of a gradual accumulation of products of weathering or one-time submerged of soils under sea water, or the result of the salt stored in soil profile and groundwater being mobilized by extra water is provided by human activities (Ghassemi, F. *et al*., 1995). There are three main reasons why soil water salinity is often a concern in agriculture: 1) specific toxicity to plants, 2) detrimental to soil structure (permeability), and 3) increase the solute (osmotic) potential, decreasing available water (Hargreaves and Merkley, 1998). In Thailand, the areas facing with the soil salinity problem is in northeastern part and coastal area zone in central part such as Samut Prakan province, Samut Sakorn province as well as east and west coast of southern part. The northeast part of Thailand is the source of saline soil due to evaporation and salt transport.

To amend saline soil and water problems, various methods have been performed, such as physical management, chemical practices, biological practices, and human aspects. With the rapid advance in computer technology at present, numerous simulation models have been developed as decision making tools for aiding salinity management. The advantage of using simulation model is that it can be used to fill data gaps in measurements in terms of spatial and temporal resolution and to analyze different leaching and management scenarios (Droogers, P. *et al*., 2001a).

**Corresponding Author:** Pakorn Ditthakit, Division of Civil Engineering, School of Engineering and Resources Management, Walailak University, Nakhon Si Thammarat 80161, Thailand
E-mail: pakorn@wu.ac.th)

Passioura (1996) classified the models into two groups, including scientific and engineering models. Scientific models are concerned to test theories and hypothesis; conversely, engineering models are applied to achieve particular practical outcome. Additionally, models can be divided depending on scope of application, that is, basin-scale models and field-scale models (Torabi *et. al*, 2004).

The example of computer software package used for salinity management in basin-scale models is hydrosalinity model (Walker, 1970; Tanji, 1977; Tedeschi *et al.*, 2001) and WSBM model (Droogers, P. *et al*., 2001a). The field-scale models based on water flow and solute transport equation or mass balance equation, such as LEACHC model (Wagenet and Hutson, 1987), SWAP model (Feddes *et al*., 1978; van Dam *et al*., 1997), SOWACH model (Dudley and Hanks, 1991), HYDRUS model (Šimunek *et al*., 1998), UNSATCHEM model (Šimunek *et al*., 1996).

The objective of this paper is to summarize water and salt transport models in soils and to discuss and compare features of salinity management software packages, especially for field-scale models.

***Principles of Water Flow and Salt Flow Processes:***

To understand salt transport processes in soils, it should consider both the water flow and the salt flow. Such considerations is beneficial to know the concentration and location of dissolved constitute in the soil profile, the removal of undesirable constituents, the reactions of the constituents with each other, and the soil matrix during the displacement (Biggar and Nielsen, 1962).

***Water Flow Models:***

The basic soil-water flow equation can be derived conservation of mass or continuity principle. The three dimension form of continuity equation is given by (Or *et al*. 2004):

$$\frac{\partial\theta}{\partial t} = \nabla J_w = \left(\frac{\partial J_{wz}}{\partial z} + \frac{\partial J_{wy}}{\partial y} + \frac{\partial J_{wx}}{\partial x}\right) \qquad (1)$$

where q is water content; t is time; Ñ is the del operator or gradient of J; and $J_{wz}$, $J_{wy,}$ $J_{wx}$ are the flux in the z, y, and x directions, respectively. Combining Buckingham-Darcy's law for the flux ($J_w$) with the continuity equation yields a Richard equation. The Richard equation for three-dimensional flow in a Cartesian coordinate system is:

$$\frac{\partial\theta}{\partial t} = \nabla\left[K(h)\nabla H\right] = \frac{\partial}{\partial x}\left(K(h)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K(h)\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right) + \frac{\partial K(h)}{\partial z} \qquad (2)$$

where K(h) is hydraulic conductivity; z is depth; and h is matric potential. The assumptions of the above equation are based on isothermal conditions, of flow through a rigid soil matrix. The water flow for non-steady vertical one dimensional flow is:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] + A(z,t) \qquad (3)$$

where H is soil hydraulic head; and A(z,t) is the root-extraction term (sink term) representing water lost per unit time by transpiration. The above equation without sink term is called the Richards equation. Equation 3 can be written in term of water content form or pressure form as follows:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z} + K(\theta)\right] + A(z,t) \qquad (4)$$

where D(q) is the soil water diffusivity.

$$\frac{\partial h}{\partial t}C(\theta) = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] + A(z,t) \qquad (5)$$

where h is the pressure head and C(q) is the water capacity equal to $\partial\theta/\partial h$ .

Both analytical solution and numerical solution have been used to solve partial differential equation for water flow. For example, Brutsaert (1968a, 1968 b) used analytic solution for determining soil moisture content at different soil depth.

Garder *et al*. (1970) solved the Richard equation analytically for water redistribution with or without considering gravity terms. Parlange (1971a, 1971b) solved infiltration equation by analytical technique based on assumption of homogeneous and isotropic throughout the profile. Due to complexities of flow system, it is often difficult to apply analytical solution for solving water flow equation. Then, the numerical techniques, finite difference and finite element methods, has been used instead of analytic solution (Philip,1957; Hank and Bowers,1962; Whisler and Klute, 1965; Staple,1969; Nimah and Hanks, 1973a&1973b) For example, Kabala and Milly (1990) solved Richards equation using a finite element method to simulate the movement of water in unsaturated heterogeneous soils and made sensitivity analyses of the model.

Campbell (1991) developed a computer model to predict root water extraction and plant water status for a given soil-plant-atmosphere system. Hank *et al.* (1991) developed a numerical model called SOWATET (soil-water-crop atmosphere-irrigation management model) to simulate infiltration and redistribution of water in a uniform soil with a known initial water content profile and with different intensities of water added to the soil surface.

***Salt Flow Models:***

The solute movement through soil can take place by means of three processes: 1) convective transport of chemical can occur as a result of the movement of bulk phase in which the chemical is dissolved; 2) diffusive transport in the liquid phase in response to an aqueous concentration gradient; and 3) dispersive transport can occur due to differences in flow velocities at pore scale. The combination of such three mechanisms is described by the convection-dispersion equation (CDE) as shown in the following equation (Or *et al*. 2004).

$$J_S = -D_e \frac{\partial c}{\partial x} + J_w c \qquad (6)$$

where $J_S$ is the total mass of solute transport across a unit cross-section area of soil per unit time, $J_W$ is the water flux, $D_e$ is the combined diffusion-dispersion coefficient, and ¶c/¶x is the spatial solute gradient. The CDE in one dimension is:

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left[\theta D(\theta, q)\frac{\partial C}{\partial z} - qC\right] + S \qquad (7)$$

where q is the volumetric moisture content; t is time; z is soil depth; D(q,q) is the apparent diffusion that accounts for dispersion and diffusion which affect ion solute movement in the liquid phase; C is chemical concentration; q is water flux; and s is a sink term for chemical species. Salt flow models application depend on their degrees of complexity (Jury, 1982; Addiscot and Wagenet,1985). Aslam (1993) classified salt flow models into 3 types: 1) solute transport models without chemical reaction, cation exchange model, and chemical equilibrium models.

***Applying Simulation Models:***

As mentioned above, simulation models for water flow processes and solute transport processes are mostly based on numerical techniques for solving partial differential equations. The general main steps for applying simulation model (fig.1) are as follows (modified from Spitz and Moreno, 1996).

1) Compiling and interpreting field data: The simulation models actually develop into a site-specific model when real field data are assigned. The model users have to always recognize that the quality of the simulations depend on the validity of model physics and the quality of the input data, not the sophistication of numerical model.

2) Developing a conceptual model: To appropriately model natural system with simulation models, the model users are necessary to understand all site conditions. The development of a suitable concept model is the key to a successful modeling study.

3) Preparing the computer software: In this step, the model users have to select computer software suitable with their works. There is no existing model applicable to all functions. Then, input all required data, define boundary and initial conditions.

4) Calibrating and validating the model: calibration and validation are required to overcome the lack of input data, but they also accommodate the simplification of natural system in the model. The observed filed data and predicted data are compared with any statistical analysis, such as root mean square error (RMSE), modeling efficient (EF), and so forth. Like calibration process, validation process is comparison of observed data and predicted data, but use observed field data in different duration from used in calibration processes. Model validation is required to demonstrate that the model can be reliably used to make predictions.

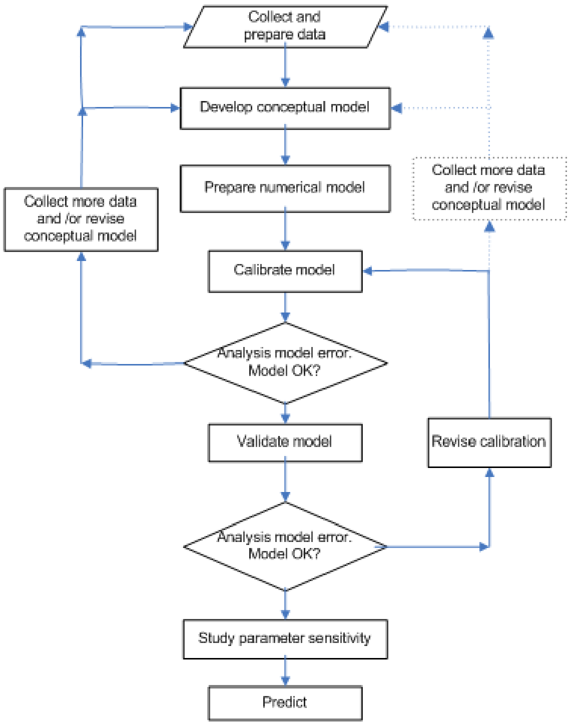


**Fig. 1:** The general main step for applying simulation model (Modified from Spitz and Moreno, 1996)

**Table1:** Technical feature comparison of different software packages.

| Features | UNSATCHEM 1D | UNSATCHEM 2D | LEACHC | HYDRUS 1D | HYDRUS 2D | SWAP | SOWACH |
|---|---|---|---|---|---|---|---|
| OS | | | | | | | |
| • Dos | | | √ | | | √ | √ |
| • Windows | √ | √ | √ | √ | √ | √ | √ |
| GUI | √ | √ | | √ | √ | √ | |
| CODE | | | | | | N/A | |
| • Fortran | √ | √ | √ | √ | √ | | |
| • C++ | √ | √ | | √ | √ | | |
| • QuickBasic | | | | | | | √ |
| • Delphi, Pascal | | | | | | √ | |
| Numerical solution | | | | | | | |
| • Finite difference | √ | √ | | √ | √ | | √ |
| • Finite element | √ | √ | | | | | |
| Cost | freeware | freeware | freeware | freeware | $1200 | freeware | freeware |
| Dimension | 1 D | 2D | 1D | 1 D | 2D | 1D | 1D |
| Direction | | | | | | | |
| • Horizontal | √ | √ | √ | √ | √ | | √ |
| • Vertical | √ | √ | √ | √ | √ | √ | √ |
| • Inclined | √ | √ | | √ | √ | | |
| Module | | | | | | | |
| • Water flow | √ | √ | √ | √ | √ | √ | √ |
| • Solute transport | √ | √ | √ | √ | √ | √ | √ |
| • Soil chemistry | √ | √ | √ | | | | √ |
| • Heat | √ | √ | √ | √ | √ | √ | |
| • Carbon dioxide | √ | √ | | | | | |
| • Crop yield | √ | √ | | √ | √ | √ | |
| • Atmosphere-plant | | | | | | | |
| • and soil interaction | | | | | | √ | |
| • Soil water-surface | | | | | | | |
| • water interaction | | | | | | √ | |
| • Soil water- | | | | | | | |
| groundwater interaction | | | | | | | √ |

5) Applying the model: The main objective of using simulation model is to predict the events at the future when applying alternative scenarios for solving problems. However, predictions into the far future are generally more uncertain. It is impossible for using calibrated and validated models with 2 years duration observed data in order to predict the event at 50 or 100 years at future. Additionally, model sensitivity analyses help to demonstrate the model responses to variation in uncertain input parameters, to guide additional field data collection, and to define parameters to be used in uncertain analysis.

***Computer Software Packages for Salinity Management:***

Five computer software packages widely used for salinity management are presented in this section, including UNSATCHEM model, LEACHC model HYDRUS model, SWAP model, and SOWACH model. Comparison of different software package features is given in Table1. The details of each model are as follows.

UNSATCHEM (Simunek, J. *et al*., 1996) is a software package for simulating water, heat, carbon dioxide and solute movement in one-dimensional variably saturated media, including horizontal, vertical, and generally inclined flow. It mainly consists of the *UNSCHEM* (version 2.0) computer program written by FORTRAN, and the UNSATCH interactive graphics-based user interface written by C++, running under the MS Windows 3.x, Windows 95, and Windows NT environments. The Richards' equation with sink term, water uptake by plant roots, for describing water flow processes and convection-dispersion type equations for describing heat, carbon dioxide and solute transport processes are solved by finite different and finite element method, respectively. It also has plant yield model based on water deficit effects. The software can account for equilibrium chemical reactions, such as complexation, cation exchange and precipitation-dissolution. The program may be applied to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The water flow part of the model can deal with prescribed head and flux boundaries, boundaries controlled by atmospheric conditions, as well as free drainage boundary conditions. Additionally, the family model, UNSATCHEM-2D, can be applied as such model, but for 2 dimensional flow (Simunek and Suarez, 1993).

*LEACHC* is the salinity version in LEACHM (Leaching Estimation And solute transport CHemistry Model) developed by Wagenet and Hutson (1987). The main modules of LEACHC include water flow module, solute transport module, and soil chemistry module. LEACHC model is written by FORTRAN and run under DOS, Windows 3.1 and Windows 95, and Digital Visual Fortran v.5 for computers running under Windows 95, Windows 98 or Windows NT. LEACHC model cannot simulate crop growth or crop yields, describe surface runoff and erosion, and account for the effects of regional, surface and groundwater flows (Hutson, 2003). Modeling water flow in soils, one-dimensional transient soil moisture movement in the vertical direction, is described using the Richard's equation with root-extraction term. Such equation is solved by a finite difference numerical technique. The top boundary can simulate, coinciding with surface conditions: ponded infiltration or non-ponded infiltration, evaporation or zero flux condition. The bottom boundary can simulate both case of having water table and of a freely drainage profile. The convection-diffusion equation (CDE) solved by a second order finite difference solution is applied for describing the one-dimensional salt transport process. Similarly, the model user can determine top boundary and bottom such cases mentioned earlier. The solute transport model is used to transport a chemical ion in solution as a non-reactive species. After independent movement of Ca, Mg, Na, K, Cl, and $SO_4$ ions as individual species, the chemistry model, CHEM, and cation exchange model, XCHANG, are used to bring the solution species into chemical equilibrium with lime and gypsum, and to adjust the exchange equilibria (Aslam,1993). The schematic diagram of LEACHC model is shown in figure 2.

*HYDRUS* (Simunek, J. *et al*., 1998) is software package for simulating water, heat, and solute movement in one-dimensional variably saturated media, including horizontal, vertical, and generally inclined flow. The main module of this model (version 2.0) consists of the HYDRUS (version 7.0) computer program written by FORTRAN, and the HYDRUS1D interactive graphics-based user interface written by C++. New version of HYDRUS model operates on windows operation system. The variably-saturated water flow, and heat and solute transport are described by Richards' equation with sink term to account for water uptake by plant and convection-dispersion equations, respectively. The governing flow and transport equations are solved numerically using Galerkin type linear finite element schemes. The heat transport equation considers conduction as well as convection with flowing water. The solute transport equations consider advective-dispersive transport in the liquid phase, and diffusion in the gaseous phase. The transport equations also include provisions for nonlinear and/or nonequilibrium reactions between the solid and liquid phases, linear equilibrium reactions between the liquid and gaseous phases, zero-order production, and two first-order degradation reactions. However, HYDRUS does not concern the chemical processes that occur in the soil solution, i.e.

precipitation/dissolution and exchange between the soil solution and the exchange complex of clay particles. The program may be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The water flow part of the model can deal with prescribed head and flux boundaries, boundaries controlled by atmospheric conditions, as well as free drainage boundary conditions. For solute transport the code supports both (constant and varying) prescribed concentration and concentration flux conditions. The unsaturated soil hydraulic properties are described using van Genuchten, (1980), Brooks and Correy, (1964) and modified van Genuchten type analytical functions. The model also concerns hysteresis phenomena, root growth simulated by means of a logistic growth function, and water and salinity stress. Additionally, the family model, HYDRUS-2D, can be applied as such model, but for 2 dimensional flow (Simunek, *et al*., 1999).

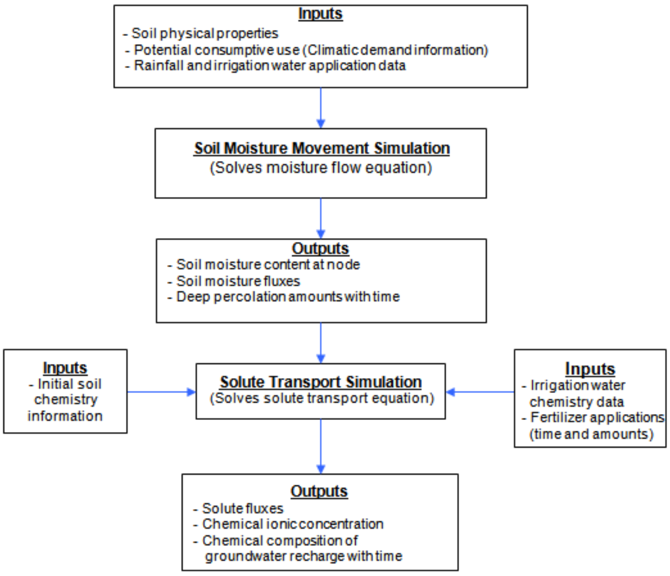


**Fig. 2:** Schematic Diagram of LEACHC Model.
Source: Aslam (1993)

*SWAP* (Soil, Water, Atmosphere and Plant) is software package used for simulating one dimensional vertical transport of water, solutes and heat in unsaturated/saturated soils, cultivated soils (Kroes and van Dam, 2003). The program has been developed by Alterra and Wageningen University, and is designed to simulate transport processes at field scale level and during whole growing seasons. The model also can predict crop yield due to water deficit effects and soil water salinity effects. However, SWAP model cannot deal with the chemical processes that occur in the soil solution, i.e. precipitation/dissolution and exchange between the soil solution and the exchange complex of clay particles (Kuper, 1997). The model can run under either DOS or Windows operation system, depending on its version, e.g. version 3.03 for DOS, version 207d having graphical user interface for Windows. The water flow and solute transport process are described by the Richard‘s equation and the convection-dispersion equation, respectively. The Van Genuchten and Mualem function are used to determine the relationships between the water content, the pressure head and the hydraulic conductivity. In addition, SWAP also concerns atmosphere-plant and soil interaction, soil water-surface water interaction, soil water-groundwater interaction, soil heterogeneity, crop growth, soil temperature. The schematic diagram of SWAP model is given in figure 3.

*SOWACH* (Soil-Plant-Atmosphere-Salinity Management Model) is a third generation salinity management model developed by Nimah and Hanks (1973a, b), Childs and Hanks (1975), and Robbins *et al*. (1980a, b). SOWACH is written by QuickBASIC and can run under DOS, and Windows operation system. The model can be used to simulate water flow processes, e.g. infiltration, redistribution, root uptake of water, soil evaporation or plant transpiration, water flow down to the ground water or a water table, as well as water flow up into the soil from a water table. In addition to its ability for predicting the transport of a non-interacting salt through the soil and, to and from a water table, it also simulate ion exchange, precipitation or dissolution of calcite and gypsum, and the formation of solution phase ion pairs and complexes. The Richard’s equation with the root extraction term is numerically approximated by finite different method. The convection-diffusion equation solved by a second order finite difference solution (CDE) is applied for describing the one-dimensional salt transport process. The boundary and initial conditions of both water flow model and solute transport model are prepared for different natural conditions like LEACHC model.

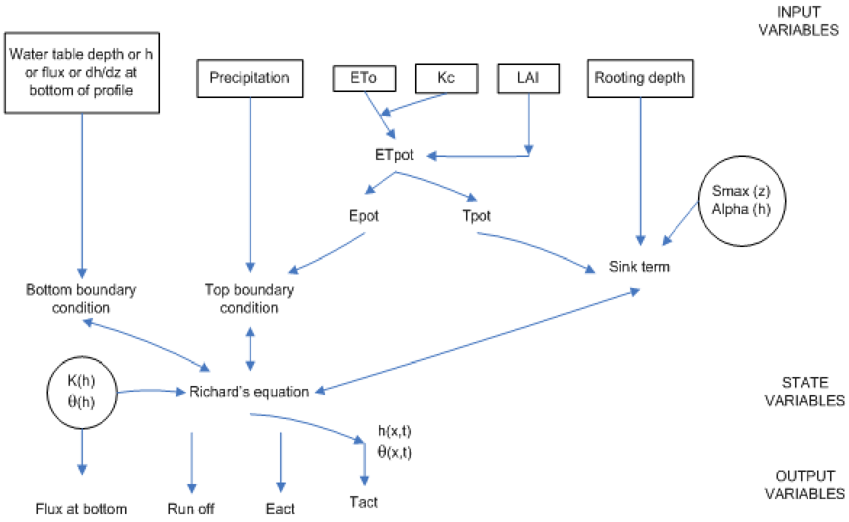


**Fig. 3:** Schematic Diagram of SWAP Model.
Source: Tedeschi and Menenti (2002)

***The Examples of Computer Software Application for Salinity Management:***

Ali *et al*. (2000a, 2000b) applied LEACHC model to investigate the effect of saline in shallow water tables. Model was validated using the lysimeter data and field data with the variation of different conditions, namely, water table depths, crops, surface condition, and irrigation delivery systems. There are agreement between concentrations of observed and predicted sodium and chloride quiet good as calcium concentrations were underpredicted. Ninety-nine treatments were investigated, including three water table depths, two water table salinity levels, four irrigation strategies, two soil types, and two crops. The study results indicated LEACHC model could simulate soil moisture movement and solute transport above shallow water tables satisfyingly and be used as a decision making tool for evaluating scenario to manage soil salinity problems due to saline in shallow water tables.

Droogers *et al*. (2001b) presented field-scale modeling to investigate salinity movement in irrigated lands. The SWAP model is applied to rapidly appraise the effect of changes in water quantity and water quality at the Rudasht irrigation project in Iran. The study results show that the current practice yields cotton satisfyingly. Changes in the amount of irrigation application with the current water quality level do not significantly affect crop yields for cotton. With the same annual irrigation application, however, improvement in the water quality levels can increase crop yields for cotton. In addition, improvement both water quality levels and water quantity levels is the best alternative for increasing cotton yields.

DL (2001) applied UNSATCHEM model to evaluate for its ability to predict field reclamation of a sodic saline soil. It found that model predictions of EC and SAR after reclamation gave a satisfactory fit to the measured values. The effectiveness of mixing gypsum to various depths was evaluated in terms of the predicted SAR profiles. Alternative management practices of green manuring in presence of calcite were simulated and appeared feasible. In this instance it appears likely that the field could have been reclaimed either with less water or without the addition of gypsum.

LV *et al.* (2002) used SOWACH model to test the effectiveness of increased rooting on yield when plants were irrigated with saline water but without leaching. The results point out that root production of the high-fibrous root type was stimulated more at low and medium salinity than that of the low-fibrous root type. Across salinity treatments, final root length density (cm root length per cm(3) soil volume) was 24% higher for the high-fibrous root type, and herbage yield of the high-fibrous root type was 14% higher than that of the low-fibrous root type. Differential rooting was greatest in the upper half of the root zone. High fibrous rooting in alfalfa is a trait with potential usefulness as a salinity stress avoidance mechanism.

***Conclusion:***

A comprehensive review of computer software package for salinity management is presented in this paper. The capabilities and limitations of such models are different and carry their own characteristic features. All models use Richards' equation and convection-dispersion for describing water flow and solute transport processes. All programs were continuously developed and most of programs have user-friendly interface and can operate on window operation system. The most important for use of program depends on not only model's capability but also the analyst's knowledge and understand in both water flow processes and solute transport processes; that is, simulation models should be used only by those with enough field experience to detect unreasonable results. In addition, the accuracy of field data is significant for simulating natural system with simulation models. The advantage of use of computer software is to analyze different leaching and management scenarios with less time consuming and expense.

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