Application of the analytic hierarchy process to prioritise irrigation asset renewals: the case of the La Khe irrigation scheme, Vietnam

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Keywords

Assets management, Irrigation works, Analytical hierarchy process, Vietnam

Abstract

In recent years, many organisations responsible for economic infrastructure have developed asset management systems to improve the financial and service performance of their facilities. Asset management is an integrated approach to improving the ability of an irrigation system to deliver water at a defined level of service in the most cost-effective manner. This paper describes how the analytic hierarchy process (AHP) is applied to identify priorities for asset renewals in the La Khe irrigation scheme in North Vietnam. The AHP methodology was coupled with the expected maximum utility (EMU) to evaluate renewal priorities of assets grouped by types and by location within the hydraulic system.

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Introduction

Irrigation plays an important role in the development of countries where agriculture is an essential sector of the economy. It can also improve drainage and flood protection within a region. However, managers, planners and researchers have become increasingly concerned about the poor performance of many irrigation systems. In recent years, management systems have been developed to help improve the financial and service performance of existing irrigation schemes as an alternative to constructing new schemes.

In recent years, much attention has been paid to the operation of water distribution networks and irrigation schemes. A key element in the ability to deliver an adequate level of service is the ability of the physical infrastructure to meet the operational objectives of the system. Asset management embraces a new philosophy intended to improve the effectiveness and sustainability of irrigation and drainage infrastructure and improve the standard of service provision to irrigators.

Generally, financial resources have not been available or have not kept pace with the maintenance and replacement requirements of many assets. Lack of adequate funding for maintenance has created severe constraints on the sustainability of irrigation infrastructure. Furthermore, in addition to maintenance it is necessary to provide regular funds for asset – upgrading and replacement. The aim of the asset renewal strategy is to identify and choose the optimum asset for a particular service. This includes optimising both the technical and financial options suitable to improve the performance of assets. Options may include among others do-nothing, continue to maintain, rehabilitate or modernise. In making these choices, asset managers are often confronted with the problem of selecting a criteria that can assist them in making a rational decision while taking into account several judgement factors. While economic assessment by benefit/cost methods can be applied for this purpose, it is difficult to arrive at an objective assessment of benefits and costs from asset renewals and many assumptions must be made in the process of appraising the costs and benefits of particular asset renewal. Life cycle cost methods provide an objective approach to evaluate investment decisions, however they are many difficulties in quantifying the risk costs and other benefits associated with each particular type of hydraulic assets. More importantly, these methods do not allow for consideration of the operators' experience in identifying the main deficiencies associated with the existing hydraulic infrastructure.

To overcome these constraints, the analytic hierarchy process (AHP) based on sound engineering evaluation of asset performance factors is a more desirable way of assessing renewal priorities. The AHP method also provides additional flexibility for grouping assets according to various criteria such as location and hierarchy in the irrigation system and types of assets.

This paper describes how the AHP is applied to determine priorities for renewals of irrigation and drainage infrastructure assets for the La Khe irrigation system, Vietnam. The methodology is used to determine renewal priorities on the basis of multiple qualitative measures of asset attributes and performance. This analysis forms part of a wider strategy for developing a comprehensive strategy for maintenance and renewals of assets in selected irrigation and drainage systems in Vietnam aimed at improving the sustainability of hydraulic infrastructure assets.

The analytic hierarchy process

The analytic hierarchy process (AHP) is a robust and flexible methodology for multi-criteria decision analysis (Saaty, 1980). The aim of this method is to derive quantitative weights from qualitative statements on the relative importance of criteria obtained from a comparison of all pairs of criteria. The AHP has been applied in numerous and diverse areas such as business, conflict resolution, energy, health, education, transportation, economics, social and political sciences and technical design.

The AHP has been successfully applied in a number of construction projects. It has been used in decision support systems to assist in the selection of the most appropriate contractor for construction contracts. It helped construction clients in Hong Kong identify contractors with the best potential to deliver satisfactory outcomes in a final contractor selection process that was not based simply based on the lowest bid (Fong and Choi, 2000). Recently the AHP was used to develop a contractor screening process that was categorised into a number of predefined contractor criteria, including experience, financial stability and past performance (Mahdi *et al.*, 2002). The AHP has also been used in planning pipeline construction projects to undertake risk analysis (Dey *et al.*, 1996).

The basic elements of the method has been described in detail in various publications (Janssen, 1992; Nijkamp *et al.*, 1990). These are briefly described in the Appendix for the interested reader and cross referenced to the computational steps used in the case study.

When making choices for renewal of assets, it is essential to establish weightings or priorities for the evaluation factors, criteria and alternatives that are considered. The AHP can be used to structure decision problems into hierarchy of factors and criteria. This approach to decision making is designed to deal with both rationality and intuition when alternatives are assessed using several factors and criteria. The most important step is to formulate the decision problem into a hierarchical structure.

Determining the structure of the hierarchy involves identifying the appropriate factors and criteria used to evaluate alternatives. Relative weightings are estimated from preference information provided using pair-wise comparisons. A nine point numerical scale is used to represent the strength of preferences. A value of 1 is used if a pair of factors or criteria are considered equally important. Higher values express stronger importance. A matrix is typically formed containing the preference coefficients (Eq. A.1). These coefficients can also be checked for consistency. The relative importance weightings are estimated using the normalized eigenvectors of the preference coefficients matrix.

The factors and criteria weightings are then combined to produce a set of composite weightings that can be used to rank the alternatives. Generally the weighted summation method is used to determine these aggregate weightings (Eq. A.4). The following analysis will deal with the application of this method to the prioritisation of asset renewals in the main distribution system of the La Khe irrigation scheme in Vietnam.

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Application of the analytic hierarchy process: the La Khe irrigation scheme

The AHP method is applied to analyse and systematically determine a system of prioritising – asset renewals in the La Khe irrigation system, Vietnam. The La Khe system provides irrigation service to 9,600ha and drainage service to 13,000ha. The scheme is representative of some 30 schemes in the Red River Delta of Vietnam that share several common features that limit their productivity and performance, namely:

Dilapidated infrastructure resulting from insufficient maintenance:

- high reliance on pumping for irrigation and drainage; and
- poor water management practices.

In most of these systems, the general condition of the hydraulic infrastructure is poor. This combined with shortcomings in the design criteria limits the ability to implement and attain improved operational objectives. Further complications arise from poorly defined operational rules and specifications to guide the day-to-day operation of the water supply system (Malano *et al.*, 1999).

The AHP methodology is applied here to the infrastructure assets located on the main water supply canal of the La Khe System (Tran, 1999). This is consistent with the fact that current irrigation reforms efforts are aimed to transfer responsibility for operation of the secondary and tertiary canal system to farmers, leaving the La Khe Irrigation Company with the responsibility of operating the main system assets. The set of assets that form the main water supply systems are:

- 16 canal reaches from CR1 to CR16;
- four cross gate regulators from RN1 to RN4;
- 60 offtakes; and
- one pump station with six pump units.

One key aim of future investment in the irrigation sector in Vietnam is to ensure the sustainability of rehabilitated or modernised irrigation and drainage infrastructure. This can be achieved by ensuring that the pricing of water supply and drainage services are commensurate with the actual cost of delivering these services. An important component of service cost is the consideration of an adequate maintenance and renewals program to ensure the provision of service in perpetuity. In this context, the present analysis focuses on the methodology adopted to prioritise future renewals of irrigation and drainage assets.

Structuring the problem into a hierarchy

The overall aim of this analysis is to prioritise the renewal of assets in the La Khe irrigation which form part of the main water distribution system in the La Khe irrigation System, Vietnam. Figure 1 depicts the three levels of the hierarchy employed in this study and Table I describes in detail the set of criteria used to assess the asset performance factors. The first level comprises the type of asset. In this study, assets were of four different types, canals, structures, offtakes and pumps. The next level comprises the three major factors that affect the performance of assets: hydraulic performance (HP), condition (0) and importance (I). The lowest level are the criteria associated with each factor for each particular type of asset.

Each asset within an irrigation system has its own role and performs a certain function. Performance assessment is a process that determines how well assets perform in the system to achieve the function for which they were designed. Hydraulic performance (HP), condition (C) and importance (I) of assets are three essential factors that affect the overall performance whereas Importance measures the impact of potential asset failure on the operational performance of the system.

The hydraulic performance of assets is defined as the ability to accomplish their particular function in the irrigation or drainage system. For example, to evaluate the hydraulic function of a canal reach, factors such as the actual discharge, flow depth, bed width are compared with the initial design or the actual capacity requirement to meet operational objectives related to the level of services to be provided by the irrigation organisation.

The condition of an asset is primarily a function of age and operating condition. This is generally assessed by the hydraulic effectiveness, structural integrity of the asset and the operability of the various components, e.g. gates and lifting devices in gated cross regulators.

Asset importance is a key factor in determining the consequences of asset failure and takes into consideration the

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Figure 1 The AHP hierarchy levels for asset renewals

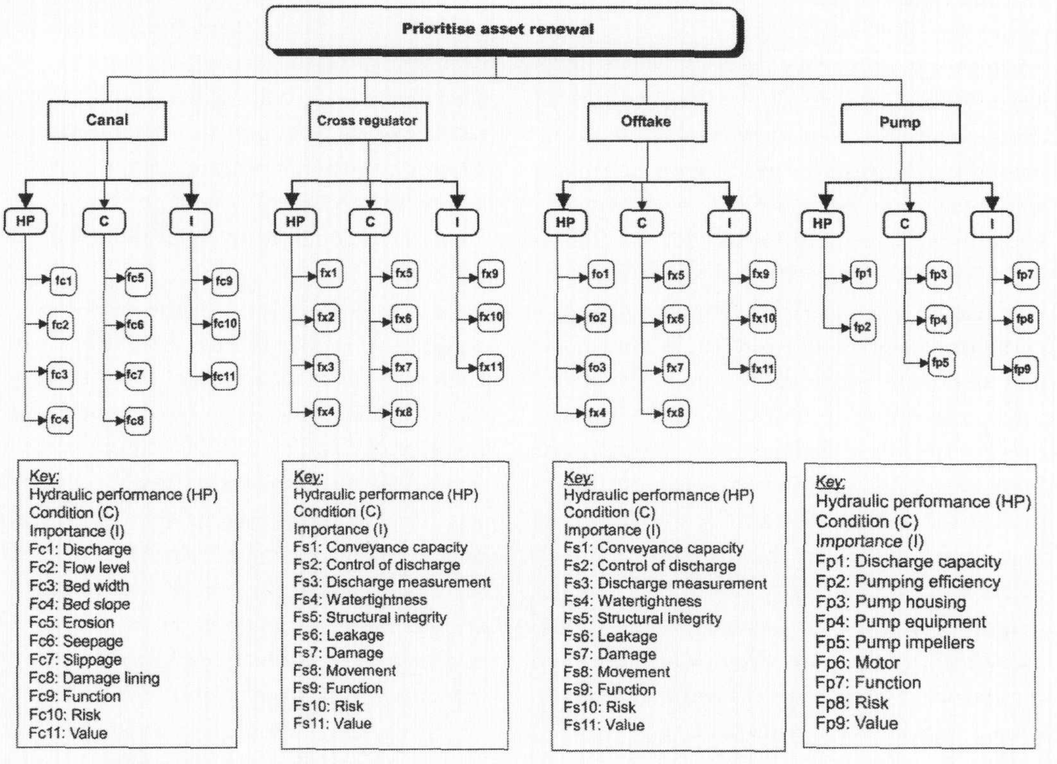

Table I Criteria related to asset types

Asset type	Hydraulic performance	Condition	Importance
Canals	Discharge	Erosion	Function
	Water level	Seepage	Risk
	Slope	Slippage	Value
	Width	Lining damage	
Cross regulators and offtakes	Conveyance capacity	Movement	Function
	Discharge control	Structural integrity	Risk
	Discharge measurement	Surface condition (damage)	Value
	Watertightness		
Pumps	Pumping capacity	Pump housing	Function
		Pump impellers	Risk
	Pumping efficiency	Pump motors	Value
		Pump equipment	

extent of damages (physical and economical) arising from the failure of the asset to perform its function. The importance of assets in this study is measure by three factors namely: Function, risk of failure and cost of asset renewals (Cornish and Skutsch, 1997).

Table II Judgement criteria for asset types

	Canals	Cross regulators	Offtakes	Pumps
Canals	1	2	5	3
Cross regulators	0.5	1	5	3
Offtakes	0.2	0.2	1	0.33
Pumps	0.33	0.33	3	1

Importance judgement

n order to determine the relative importance of the four assets types in the first level of the hierarchy, a 4×4 matrix was formed on the basis of Eq. A2 as shown in Table II. Whilst the relative preference was not established through a systematic survey of stakeholders (company staff, farmer representatives, government representatives), informal interviews were held with company operational staff and some farmers' representatives to seek their

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views on the level of importance of the various types of assets. This matrix represents the judgements of the relative importance of the four asset types within the irrigation system. In this matrix, canals are assessed as the most important (five on the preference scale) compared with control structures, pumps and flow measurement structures. The main reason for this is the essential role canals are judge to have because of their dual function irrigation-cum- drainage in this system. When canals and structures were compared, it was unclear whether to assess it as moderately more important (three on the preference scale) or equally important (one on the preference scale). Therefore, the choice of judgement is two on the preference scale. According to their function in this irrigation, pumps are considered moderately more important than offtakes and cross regulators moderately less important than canals and structures respectively.

Estimating relative weightings

Using the preference information contained in Table II, the relative importance of the assets types was computed as the components of the normalized eigenvectors of the matrix (Eqs A3 and A4). The relative weightings expressing the importance of canals, structures, pumps and offtakes are shown in Table III.

Judgements of the relative importance of the three performance factors for the intermediate level in the hierarchy are specified in Table IV. The results show that hydraulic performance is the most important factor in determining the overall performance of assets when compared with condition and importance factors. Assets in irrigation systems have specific hydraulic characteristics related to the function that they perform. Therefore, when assessing the performance of assets, the technical condition should be considered much more important than the physical condition.

For the lowest level in the hierarchy, weightings of the relative importance of each criteria within each performance factor were estimated separately depending on asset type (Tables V-VII). These were also derived from judgements made using pair-wise comparisons. Experience in operating and managing similar irrigation systems as well as results from previous research studies formed the basis of these judgements. In absence of other information, a useful approach to ascertain these weightings is to conduct a survey of expert opinions among system operators and managers associated with the system.

The assessment of relative importance is a subjective task that requires experience and expert knowledge. It is therefore important to ascertain the consistency of judgements as reflected in the proportionality of preferences. The consistency ratio (CR) is used for this purpose as described in Eqs A5 to A8. A consistency ratio of 10 per cent or less is considered to be acceptable. The evaluation of the consistency ratios for the relative weightings in Tables A3 to A7 shows that the level of consistency is acceptable in all cases.

Table III Estimated importance weightings for asset types

Asset type	Importance weighting
Canals	0.46
Cross regulators	0.32
Offtakes	0.07
Pumps	0.15

Note: CR = 0.036

Table IV Relative weighting scores for performance factors

Performance factor	Relative weighting
Hydraulic performance	0.64
Condition	0.26
Importance	0.10

Note: CR = 0.028

Asset scoring

Weighted summation is a simple and commonly used evaluation method to assess the score for each alternative by taking into account the appropriate weighting and performance scores. This is expressed as:

$$U_{ij} = w_i^t \sum_{k=1}^{K} w_k^f \sum_{l=1}^{L(i,k)} w_{ikl}^c x_{ijkl} \qquad (1)$$

where:

U_{ij} = utility of asset number j of asset type i ($i = 1, \ldots, I$; $j = 1, \ldots, \mathcal{J}^i$); I = number of asset types; $\mathcal{J}^i$ = number of assets of type i;

Table V Estimated importance weightings scores for criteria used in assessing canals

Performance factor	Hydraulic performance				Condition			Importance		
Criteria	Discharge	Flow level	Bed width	Bed slope	Erosion	Seepage	Slippage	Function	Risk	Value
Relative weighting	0.45	0.13	0.29	0.14	0.13	0.07	0.52	0.58	0.28	0.14
		CR = 0.014				CR = 0.068			CR = 0.108	

Table VI Estimated importance weightings scores for criteria used in assessing cross regulators and offtakes

Performance factor	Hydraulic performance					Condition			Importance		
Criteria	CC	CD	DM	W-t	SI	Leakage	Damage	Movement	Function	Risk	Value
Relative weighting	0.52	0.28	0.10	0.10	0.15	0.46	0.33	0.07	0.58	0.28	0.14
			CR = 0.0				CR = 0.036			CR = 0.108	

Notes: CC = Conveyance capacity; CD = Control of discharge; DM = Discharge measurement; W-t = Water-tightness; SI = Structural integrity

Table VII Estimated importance weightings scores for criteria used in assessing pumps

Performance factor	Hydraulic performance		Condition				Importance		
Criteria	Discharge capacity	Pumping efficiency	Pump housing	Pump equipment	Pump impeller	Motor	Function	Risk	Value
Relative weighting	0.25	0.75	0.13	0.24	0.17	0.46	0.58	0.28	0.14
		CR = 0.0			CR = 0.077			CR = 0.108	

w_i^t = importance weighting of asset type i;
w_k^f = importance weighting of performance factor k ($k = 1, \ldots, K$); K = number of performance factors;
w_{ikl}^c = importance weighting of criteria l for performance factor k for asset type i ($l = 1, \ldots, L(i, k)$), $L(i, k)$ = number of criteria l for asset type i for performance factor k;
x_{ijkl} = score of asset type i, for asset number j, for performance factor k, for criteria l.

In this study a scoring system ranging between 1 and 4 was applied to rate all the hydraulic performance, condition and importance factors with the only exception of the value of assets for which the actual replacement cost of the asset was used. In all cases a score of 1 represents the best outcome and a score of 4 the worst outcome. In order to take into consideration the different rating scale applied for the valuation of assets the score were standardised using the Max criterion as follows:

$$x' = \frac{x_{ij}}{\max_j [x_{ij}]} \qquad (2)$$

Table VIII shows the details of the final scores obtained for canal reaches. Similar tables were generated for cross regulators offtakes and pumps.

Prioritising renewals

Renewal decisions are usually made by grouping assets to be renewed according to a range of different criteria. The broad types of criteria often used for irrigation and drainage facilities include among others:

- renewal of individual assets;
- renewal according to asset types, e.g. canals, control structures, pumps, etc.;
- renewal according to asset location, e.g. upper system, middle system and lower system; and
- renewal according to combined criteria including types, location or other attribute.

The criteria used to prioritise asset renewals is to a large extent influenced by the characteristics of the system and many management factors including the type of delivery service that the agency provide to its users. The following prioritisation analysis iillustrates the prioritisation of asset renewals for the La Khe system in terms of types and location. The AHP methodology however can be applied to prioritisation by groupings based on any other criteria.

When considering ways to group and prioritise assets, a variety of mathematical and statistical techniques can be used to quantity in an objective way the relation between a discrete choice and a set of variables. Discrete choice analysis uses the principles of utility

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Table VIII Final scores for canal reaches

Criteria	Factors																	
	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8	CR 9	CR 10	CR 11	CR 12	CR 13	CR 14	CR 15	CR 16	CW	FW
Hydraulic performance																		
Discharge	0.25	0.75	0.75	0.5	0.5	0.5	0.25	0.25	0.5	0.25	1.0	1.0	1.0	0.75	0.5	0.25	0.45	0.64
Flow level	0.25	1.0	0.75	0.5	0.75	0.75	0.5	0.5	0.5	0.25	1.0	1.0	1.0	0.75	0.75	0.25	0.12	0.64
Bed width	0.5	1.0	0.75	0.5	0.5	0.5	0.5	0.5	0.5	0.25	1.0	1.0	1.0	0.75	0.75	0.25	0.29	0.64
Bed slope	0.5	1.0	0.75	0.5	0.5	0.5	0.5	0.5	0.5	0.25	1.0	1.0	1.0	0.75	0.75	1.0	0.14	0.64
Condition																		
Erosion	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.75	1.0	1.0	1.0	1.0	1.0	0.5	0.25	0.13	0.26
Seepage	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.75	1.0	1.0	1.0	1.0	1.0	0.5	0.25	0.06	0.26
Slippage	0.75	0.75	0.75	0.5	0.75	0.75	0.75	0.5	0.75	1.0	1.0	1.0	1.0	1.0	0.5	0.25	0.52	0.26
Lining damage	0.25	0.25	0.25	0.5	0.25	0.25	0.25	0.25	0.75	1.0	1.0	1.0	1.0	1.0	0.25	0.25	0.28	0.26
Importance																		
Function	0.33	0.33	0.33	0.67	0.67	0.67	0.67	0.67	0.67	0.33	0.67	0.67	1.0	1.0	0.67	1.0	0.58	0.1
Risk	0.25	0.5	0.25	0.25	0.25	0.25	0.25	0.25	0.5	0.25	1.0	1.0	1.0	1.0	0.75	0.25	0.28	0.1
Value	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.14	0.1
Final score	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P		

Note: CR = Canal reach; CW = Criteria weighting; FW = Factor weighting;
Final scores: A = 0.413; B = 0.759; C = 0.6644; D = 0.5086; E = 0.5434; F = 0.5434; G = 0.4522; H = 0.4184; I = 0.5799; J = 0.4575; K = 0.9783; L = 0.9783; M = 0.9974; N = 0.8374; O = 0.5924; P = 0.3706

maximisation, where utility is defined as an attribute that the decision-maker attempts to maximise (Ben-Akiva and Lerman, 1985). A requirement of the basic choice model is that the range of alternatives must be distinct and independent.

The expected maximum utility (EMU) is used in this analysis to arrive at the choice of maximum utility. The EMU of a choice set provides a representative statistic of utilities of a set of alternative Hensher and Johnson (1981). EMU is defined as the logarithm of the sum of the exponential of representative utility of each or every alternatives in a choice set, as follows:

$$EMU - \ln\left(\sum_{\forall i \in I} e^{\alpha U_i}\right) \qquad (3)$$

where e is the exponential function, U_i is the utility value of alternative I, I is the choice set and α is a sensitivity coefficient. A coefficient α greater than 1.0 gives greater weight to the better alternatives whereas a coefficient α less than 1.0 diminishes the influence of the better alternatives. Throughout this analysis a coefficient $\alpha = 0.5$ was used.

As a first step for establishing group priorities, the priorities for renewal of individual assets must be established. The EMU is then used to aggregate assets by groups and determine their priority ranking according to a specified grouping criteria.

Prioritising by location

Agencies in charge of operating irrigation and drainage facilities sometimes choose to carry out a staged renewal of assets according to their location in the systems. A simple approach often used to rehabilitate or maintain the infrastructure is to subdivide the system into sections commanded by the main canal. In this case, assets located along the main canal were grouped according to the four hydraulic pools defined by the position of the four cross regulators. Table IX shows the ranking of renewal priorities using the EMU assessment. The final ranking shows the sequence of priorities decreasing in the downstream direction demonstrated by a EMU = 3.84 for the first group and EMU = 3.33 for the bottom group. These results are heavily influenced by the increasing importance of assets located in the upstream reaches of the system as they command a larger area. Failure of assets in the top reaches of the system have a greater impact than assets located in the downstream

Table IX Final ranking of asset groups in terms of location

Group of assets	EMU	Final ranking
Group 1	3.84	1
Group 2	3.81	2
Group 3	3.53	3
Group 4	3.33	4

sections of the system, and as a result, greater economic consequences.

Prioritising by types

An alternative approach used in the renewal of irrigation and drainage infrastructure is to carry out the renewal in stages by structure types. The entire set of assets was grouped into four types in order to set priorities accordingly. These types are: Canal reaches, cross regulators, offtakes and pumps. Table X shows the outcome of applying the EMU assessment to each group of assets and the resulting priority ranking. The results show offtakes as having the highest order of priority for renewal followed by canals, pumps and cross regulators in decreasing order of priority.

Conclusions

A multi-criteria evaluation method utilizing the analytical hierarchy process (AHP) was used to develop a methodology for prioritising renewal of irrigation and drainage assets and to rank the alternative asset renewal options for the La Khe irrigation scheme in North Vietnam. Pair-wise judgements were used to estimate the relative importance weightings for asset types, performance factors and criteria. Although subjective, these weightings were estimated to reflect previous experience and research results. The consistency of the judgements were checked using the consistency ratio criteria and found to be acceptable.

Asset renewals were prioritised by location of assets and of assets types using the expected maximum utility method. Asset located in the upstream reaches of the system have a higher priority of renewal as a result of the greater impact in case of failure on the rest of the system.

A similar analysis carried out for assets grouped according to asset types shows that offtakes have the highest priority of renewal followed by cross regulators, offtakes and pumps.

Table X Final ranking of asset types

Group of assets	EMU	Final ranking
Group 1 (offtakes)	4.59	1
Group 2 (canals)	3.43	2
Group 3 (pumps)	2.78	3
Group 4 (cross regulators)	2.03	4

References

Ben-Akiva, M. and Lerman, S.R. (1985), *Discrete Choice Analysis: Theory and Application to Travel Demand*, MIT Press, Cambridge, MA, 390 pp.

Cornish, J. and Skutsch, J. (1997), *Hydraulics Research Wallingford*, Wallingford, p. 32.

Dey, P.K., Tabucanon, M.T. and Ogunlana, S.O. (1996), "Petroleum pipeline construction planning: a conceptual framework", *International Journal of Project Management*, Vol. 14 No. 4, pp. 231-40.

Fong, S.W. and Choi, S.K.Y. (2000), "Final contractor selection using the analytical hierarchy process", *Construction Management and Economics*, Vol. 18, pp. 547-57.

Hensher, D.A. and John, J.W. (1981), *Applied Discrete Choice Modelling*, Croom Helm, London, 468 pp.

Janssen, R. (1981), *Multiobjective Decision Support for Environmental Management*, Kluwer Academic Publishers, Dordrecht, 232 pp.

Mahdi, I.M., Riley, M.J., Fereig, S.M. and Alex, A.P. (2002), "A multi-criteria approach to contractor selection", *Engineering, Construction and Architectural Management*, Vol. 9 No. 1, pp. 29-37.

Malano, H.M., Chien, N.V. and Turral, H.N. (1999), "Asset management in irrigation and drainage infrastructure – principles and case study", *Irrigation and Drainage Systems: An International Journal*, Vol. 13 No. 2, pp. 109-29.

Nijkamp, P., Rietveld, P. and Voogd, H. (1990), *Multicriteria Evaluation in Physical Planning*, North Holland, Amsterdam, 219 pp.

Saaty, T.L. (1980), *The Analytic Hierarchy Process*, McGraw-Hill, New York, NY, p. 21.

Tran, T.X.M. (1999), "Prioritisation for asset renewals case study: the La Khe irrigation system in Vietnam", research project, Department of Civil and Environmental Engineering, University of Melbourne, Melbourne, 68 pp.

Appendix. Description of the analytic hierarchy process (AHP)

Judgements are made about the relative importance of an attribute using a (nine point) numerical scale. Assume there are n attributes. Consider attributes i and j:

Assign:

1 if i and j are considered to be equally important

3 if i is considered to be weakly more important than j

5 if i is considered to be strongly more important than j

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Table AI

	n									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Average RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty, (1980, p. 21)

7 if i is considered to be very strongly more important than j
9 if i is considered to be absolutely more important than j
2,4,6 and 8 are intermediate values.

Comparison matrix

Form an $n \times n$ matrix, $\mathcal{A}$
where:
a_{ij} = importance of attribute i compared with attribute $j (i = 1, \ldots, n; j = 1, \ldots, n)$.

The properties of the matrix $\mathcal{A}$ are:
Main diagonal elements = 1, i.e.:

$$a_{ii} = 1 \quad \text{for } i = 1, \ldots, n \qquad \text{(A1)}$$

Reciprocals in the reverse element positions, i.e.:

$$a_{ij} = 1/a_{ji} (I = 1, \ldots, n; j = 1, \ldots, n) \qquad \text{(A2)}$$

Weightings vector

The vector of relative weightings for weighting i, i = 1,..., n is:

$$\mathcal{W} = (w_1, w_2, w_3, \ldots, w_n) \qquad \text{(A3)}$$

This is theoretically the normalised principal eigenvector. However, this is very difficult to estimate. A simple estimation method (Saaty, 1980) is the normalised principal vector which consists of multiplying the n elements in each row and then take the nth root as follows:

$$w_i = \frac{\left(\prod_j a_{ij}\right)^1 /n}{\sum_i \left(\prod_j a_{ij}\right)^1 /n} \qquad \text{(A4)}$$

Consistency estimates

λ_{max} – principal eigenvalue can be estimated as follows:

(1) Multiplying the comparisons matrix $\mathcal{A}(n \times n)$, by the transposed estimated weightings vector $\mathcal{W}(n \times 1)$, to obtain a new vector, $\mathcal{K}(1 \times n)$.
(2) Dividing each component of the vector $\mathcal{K}$, by corresponding elements in the transposed estimated weightings vector, $\mathcal{W}$. Call this vector $\mathcal{L}(1 \times n)$.
(3) Summing all the elements from vector $\mathcal{L}$ and dividing by the number of attributes, n.

Mathematically:

$$\mathcal{K} = \mathcal{A} \cdot \mathcal{W} \qquad \text{(A5)}$$

$\mathcal{L}$ is defined such that $l_i = k_i / w_i$

$$\lambda_{max} = \sum_i (l_i/n) \qquad \text{(A6)}$$

The closer λ_{max} is to n the more consistent the result.

The consistency index (CI) is defined as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \text{(A7)}$$

and the consistency ratio (CR) is defined as:

$$CR = CI \qquad \text{(A8)}$$

where RI is the consistency index of a randomly caused reciprocal matrix from a saclae of 1 to 9 (Saaty, 1980). A CR of 10 per cent or less is considered acceptable. The average values of random index (RI) for matrices of order 1 to 10 are given in Table AI.