Agricultural Journal 2 (2): 236-241, 2007

The Use of a Multicriteria Method in Irrigation Water Allocations

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Abstract: Demand for water is increasing all around the world, therefore a well-established process of water allocation needs to be developed to balance the demand with the supply. In this study, an attempt to improve water use efficiency by better water allocation decisions has been made. Water allocation has been considered as a multicriterion decision problem. ELECTRE I, a multicriterion decision aid, is used to determine preferences among five watercourses by considering socio-economic objectives. The use of ELECTRE I in this study is justified by the involvement of stakeholders, who assign weights to the criteria of their own choice. The results indicate that Watercourse 1 is the most efficient water user and priority should be given to this in water allocations. Watercourse 2, on other hand, is the most inefficient water user and should be least preferred in water allocations.

Key words: Multicriterion decision aid, socio-economic benefits, ELECTRE I, water allocation, multicritarion, stakeholders

INTRODUCTION

In several regions of the world, increasing water supply by constructing dams on rivers is not an environmentally feasible approach. In those regions, a balance between supply and demand can likely be established by changing water allocation rules from single criterion to multiple criteria. For that, direct (i.e., economic) and indirect (i.e., social) benefits obtained from the use of irrigation water should be measured. In present water allocation decisions, social benefits generated from the use of irrigation water are generally ignored. These benefits are now understood by many societies and are receiving more importance than previously. Therefore, it has been realized that indirect social benefits should be considered in water allocations along with direct economic benefits.

In Pakistan, irrigation water allocation to farmers is based on a single criterion, the area of land to be irrigated (Rinaudo, 2002). Other criteria, for example, social and economic, have not been considered in water allocation decisions. Increasing demands for water from urban population and industries have increased the realization that allocation rules for irrigation water in the agriculture sector should be revised, as this sector is inefficient in water use (Zardari and Cordery, 2006). In the agriculture sector, a multicriterion aid should be applied in making irrigation water allocation decisions.

The socio-economic benefits generated from the use of volumes of irrigation water proportional to land area vary from watercourse to watercourse and user to user. This study has been carried out to assess those variations and to put scarce resources to better use. ELECTRE I has been used to rank watercourses attaining the higher economic and social benefits generated from irrigation water use. Integration of social and economic benefits into a single objective makes water allocation a complex problem. This complexity can be resolved by applying ELECTRE I, as it provides a sensibly accurate ranking of alternatives where many decision makers are involved and several criteria are considered (Morais and Almeida, 2006).

MULTICRITERIA DECISION MAKING (MCDM)

The application of an MCDM technique to a particular problem generally depends on the type of the problem (Vincke, 1992). In this study, a ranking of five watercourses according to quantifiable and non-quantifiable criteria was desired. ELECTRE I has been used to develop a ranking of watercourses, as it is thought to be the most appropriate multicriteria aid to solve such types of problems. This methodology is based on the outranking relation concept introduced by Roy (1996). Outranking has the idea of determining which activity or entity is superior to, or outranks the others.

ELECTRE I

The main idea in ELECTRE I is to eliminate less desirable alternatives and select alternatives that are more preferable among the majority of criteria considered. For

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this, it assumes that one solution is preferred to another if there are sufficient advantages and insignificant disadvantages of that choice. ELECTRE I is a non-compensatory method and requires inter-criteria information (i.e., weights) (Roy and Vanderpooten, 1996). These weights reflect the relative importance of the criteria. Generally, these weights are obtained from the decision makers. Three concepts, concordance, discordance and thresholds, are developed in ELECTRE I (Raj, 1995). These are explained as follows:

Concordance index: The concordance index, c (i, j), is the weighted measure of the number of criteria for which alternative i is preferred to alternative j (Roy, 1991; Raj, 1995). Therefore, c (i, j) can be viewed as a measure of the satisfaction that the decision maker receives in choosing alternative i over alternative j. The concordance index is defined as:

$$c(i,j) = \frac{\text{sum of weights for criteria where } i > j}{\text{total sum of weights}} \quad (1)$$

Roy and Vanderpooten (1996) state that for each criterion a weight should be assigned, increasing with the importance of the criterion. Zardari *et al.* (2006) provide a thorough discussion of the computation process for criteria weights. The criteria weights used in this study are taken from their work.

Discordance index: The discordance index, d (i, j), represents the maximum discomfort that the decision maker experiences when dealing with criteria for which alternative j>alternative I (j is preferred to i) (Goicoechea *et al.*, 1982). To define the discordance index, interval scales are first assigned to the criteria. The interval scale compares the discomfort levels of any criteria. The choice of the number of points to assign to each criterion depends on the level of importance the decision maker wishes to attach to the range between the 'best' and 'worst' levels of each criterion. Interval scales used in this study are proportional to the criteria weights. The discordance index is defined as:

$$d(i,j) = \frac{\text{max. interval where } j \text{ is preferred to } i}{\text{largest interval scale in alternatives where } j > i} \quad (2)$$

Threshold values: To indicate decision maker preferences, the next step is to define a (relatively large) concordance threshold, p and a (relatively low) discordance threshold, q. Alternative i outranks (is preferred to) alternative *j* if its concordance index, c (i, j), lies above the chosen threshold value (p) and its discordance index, d (i, j), lies below the threshold value (q). The choice of threshold values (p, q) is entirely subjective and depends on the type of the data and the decision maker's preferences. The higher the value of p and the lower the value of q the greater the level of confidence one can ascribe to the clarity of the decision in question. For the chosen threshold values, the condition shown in Eq. 3 will produce an outranking relationship (a preference ordering of alternatives) among the alternatives from concordance and discordance matrices (these matrices are developed from Eq. 1, 2, respectively).

$$c(i,j) > p \ \text{ and } \ d(i,j) < q \quad (3)$$

MULTICRITERION PROBLEM FORMULATION

In multicriteria decision-making, the problem formulation depends on the definition of alternatives, objectives, decision makers and the criteria. However, in a water allocation problem, the alternative options are known at the start, therefore only the objective and the criteria are needed to be defined.

Establishing the criteria: Establishing of water allocation criteria for this study was initiated with the assistance of a group of decision makers and was completed with the development of a ranking system among those criteria. The criteria for selection of suitable decision makers for this study are adopted from Zardari *et al.* (2006). Based on those selection criteria, 20 decision makers belonging to the surveyed watercourses were chosen and were asked to rank the chosen water allocation criteria. Their opinions were gathered and analyzed. The aspects that the decision makers considered important for the evaluation of the watercourses can be classified as follows:

- Maximizing economic benefits
- Maximizing social benefits

The above factors were subdivided into six water allocation criteria. These were:

Maximizing economic benefits

- Higher value of a unit volume of water (C1)
- Higher livestock income (C2)
- More revenue recovery by the Irrigation Agency (C3)

Maximizing social benefits

- Water allocation that benefits more population (C4)
- Higher dependency on agriculture income (C5)
- Respecting senior water rights (C6)

Measuring the criteria: The following study describes how the value of each criterion was measured.

Higher value of a unit volume of water: In the agriculture sector, total farm benefits divided by the amount of water delivered produces the value of a unit volume of water. The higher the value of a unit volume of water the more efficient the water user.

Higher livestock income: In some areas, farmers are relatively more dependent on livestock income and the bulk of the farm area was used to produce fodder. Their income from selling livestock was comparatively high. Therefore, we assume that water allocated to those areas would produce more benefits than areas where the farmers are comparatively more dependent on crop income. Thus, the areas with a large number of livestock get more weightage in water allocations.

Revenue recovery by the Provincial Irrigation Department (PID): To keep water projects serviceable, it is important that at least operation and maintenance (O and M) costs should be recovered from the actual beneficiaries. Thus, watercourses where there are higher water charges should get priority in water allocations. Indirectly, this criterion encourages water use efficiency.

Water allocation that may benefit more population: If the aim of water allocations is to minimize the impacts of water scarcity then heavily populated areas would get more weightage than thinly populated areas. Inclusion of this criterion may assist in reducing mass migration problems.

Higher dependency on agriculture income: If the farm income is the only source of income of the majority of farmers in a particular region then that region should get priority in water allocations.

Respecting senior water rights: To respect senior water rights, the old irrigation regions would get priority in water allocation over newly developed regions. This criterion may conflict with ideas of 'efficient water use'. The field data was collected from 70 farms situated on fivec watercourses (Lundo Distributary, Lower Indus River Basin). The field data is shown in Table 1.

Weights allocation to the criteria: To establish relative importance between the criteria, weights are assigned tothe criteria. In a broad sense, weights are forms of representation of the preferences of the decision makers (Choo *et al*., 1999). In this study, the importance of each criterion was estimated by the decision makers in the form of weights that were established using a questionnaire. The decision makers were asked to evaluate the importance of each criterion on a scale of 1 to 6. After that, the median of the weights for a certain criterion was chosen to be its final weight. The practical reason for using this kind of simple version for obtaining weights was that the decision makers were not prepared to give themselves enough time to make use of more sophisticated methods. The weights obtained from the decision makers are shown in Table 1.

APPLICATION OF ELECTRE I

Concordance index: As earlier discussed, the concordance index is the weighted measure of the number of criteria for which alternative i is preferred to alternative *j*. For that, weights are assigned to the criteria by the decision makers.

For illustration, the computation of the concordance index for WC-1 and WC-2 from Table 1 and Eq. 1 is described as follows:

$$c(1,2) = \frac{4+5}{20.5} = 0.44$$

(Shown in row 2 and column 3 of Table 2)
Similarly, the concordance indices (Table 2) for other pairs of watercourses were computed.

Discordance index: The discordance index, by definition, is the maximum discomfort that one experiences when dealing with criteria for which alternative j is preferred to alternative i. For that, interval scales to the criteria are assigned. For this study, interval scales shown in last column of Table 3 are assigned on the basis of the decision makers' judgments regarding the importance of each criterion.

Table 1: Criteria weights and field data

Criteria	Weights	WC-1	WC-2	WC-3	WC-4	WC-5
Value of a unit water (C1) (US$/$10^3$ m^3)	4	110	50	102	73	156
Livestock income (C2) (US$/season)	2	57.5	165	144	272	45
Revenue collected by PID (C3) (US$/yr)	1	11.3	11.5	9.6	4.5	12.5
Average number of people depending on income of each farm (C4)	5	9.55	12.65	13.30	9.87	6.65
Percent of farmers that have no other income source (C5)	5	75	50	62	73	71
Average farming experience (C6) (yrs)	3.5	18.75	20.7	16.9	15.3	33.2

Note: WC = Watercourse

By using Eq. 4, the numerical values (Table 3) are computed from Table 1 and interval scales.

$$NV_{i,j} = \frac{\text{criterion}\,(i, j)\ \text{data value} * \text{interval scale to criteria}\ i}{\text{max. data value for criterion}\ i}$$

Where, NV = Numerical Value; i = criteria no.; j = alternative no.

For illustration, the Numerical Value (NV) for C1 and WC-1 is computed as follows:

$$NV\,(C1, WC\text{-}1) = \frac{110 * 80}{156} = 56.4$$

This numerical value, 56.4, is shown in row 2 and column 3 of Table 3. In the same way, the numerical values for other combinations were computed. With the use of these numerical values along with the interval scales shown in Table 3, the discordance indices shown in Table 4 were determined. The procedure to compute discordance index from Eq. 2 is illustrated for WC-1 and WC-2 as follows:

The difference in numerical values where WC-2 was preferred to WC-1 was calculated and the maximum difference was taken, i.e., 23.3 (=95.1-71.8). This maximum difference was then divided by the largest interval scales where WC-2 was preferred to WC-1.

$$d(WC\text{-}1, WC\text{-}2) = \frac{95.1 - 71.8}{100} = 0.23$$

(This is shown in row 2 and column 3 of Table 4)
Similarly, the discordance indices for other pairs of watercourses were determined from Eq. 2.

Outranking relationship: After the construction of concordance and discordance matrices (Table 2 and 4, respectively), the next step was to develop three outranking relationships (average, strong, weak) between the alternatives by using three pairs of threshold values (p, q) and satisfying the condition shown in Eq. 3. In this paper, the average outranking relationship is developed from the use of mean concordance and discordance values. For the strong outranking relationship, the mean concordance value was increased by 20% and the mean discordance value was reduced by 20%. The weak outranking relationship, on the other hand, is developed by reducing the concordance and increasing the discordance values by 20%. All these three outranking relationships are shown in Table 5. It should be noted that the selection of threshold values (p, q) is entirely a subjective approach and depends on the decision maker's choice and the size of concordance and discordance indices.

Table 2: Concordance matrix

WC	WC-1	WC-2	WC-3	WC-4	WC-5
WC-1	-	0.44	0.66	0.66	0.59
WC-2	0.56	-	0.32	0.46	0.34
WC-3	0.34	0.68	-	0.66	0.34
WC-4	0.34	0.54	0.34	-	0.59
WC-5	0.41	0.66	0.66	0.41	-

Table 3: Numerical values for the criteria

		Calculated numerical values					
Criteria	Weights	WC-1	WC-2	WC-3	WC-4	WC-5	Scales
C1	4	56.4	25.6	52.3	37.4	80	80
C2	2	8.5	24.3	21.2	40	6.6	40
C3	1	18.1	18.4	15.4	7.2	20	20
C4	5	71.8	95.1	100	74.2	50	100
C5	5	100	66.7	82.7	97.3	94.7	100
C6	3.5	39.5	43.6	35.6	32.3	70	70

Table 4: Discordance matrix

WC	WC-1	WC-2	WC-3	WC-4	WC-5
WC-1	-	0.23	0.28	0.32	0.30
WC-2	0.33	-	0.27	0.31	0.54
WC-3	0.17	0.08	-	0.19	0.34
WC-4	0.19	0.21	0.26	-	0.43
WC-5	0.22	0.45	0.50	0.33	-

The three pairs of threshold values used to developed average, strong and weak outranking relationships in this study are (0.5, 0.3), (0.6, 0.24) and (0.4, 0.36) respectively. In each outranking relationship, the different dominance relationships (a relationship that compares only two alternatives and shows which alternative is better than another) between the watercourses were developed. For example, looking at Table 5, when stringent threshold values (0.6, 0.24) are used to produce strong outranking relationship, only two dominance relationships are determined, i.e., WC-3 is preferred to WC-2 (3P2) and WC-3 is preferred to WC-4 (3P4).

RESULTS AND DISCUSSION

When stringent thresholds were used, only two dominance relationships (3p2 and 3p4) occurred. No other dominance relationships occur and no preference order is observed between WC-2 and WC-4. Full interpretation of the results could only be made by considering all three outranking relationships shown in Table 5.

Table 5 shows that WC-5 outranks only a single watercourse, i.e., WC-4, only in the weak outranking relationship. No relationship is developed between WC-5 and WC-2 or WC-3. So, it cannot be predicted whether WC-5 outranks WC-2 and WC-3, or whether WC-2 and WC-3 outrank WC-5. However, relationships of WC-1

Table 5: Outranking results

Thresholds			WC-1	WC-2	WC-3	WC-4	WC-5
Stringent thresholds	WC-1	Preferred to					
p = 0.6	2	---do---					
q = 0.24	3	---do---		WC-2		WC-4	
	4	---do---					
	5	---do---					
Average thresholds	WC-1	Preferred to			WC-3		WC-5
p = 0.5	2	---do---					
q = 0.3	3	---do---		WC-2		WC-4	
	4	---do---		WC-2			
	5	---do---					
Relaxed thresholds	WC-1	Preferred to		WC-2	WC-3	WC-4	
p = 0.4	2	---do---					
q = 0.36	3	---do---		WC-2		WC-4	
	4	---do---		WC-2			
	5	---do---				WC-4	

with other watercourses are clearly demonstrated in Table 5. It shows that WC-1 outranks all watercourses including WC-5 in the three outranking relationships and it was not outranked by any watercourse. Therefore, it can be concluded that WC-1 is the most efficient water user and should get top priority in water allocations. On the other hand, WC-2 is the least preferable option, as it has not outranked any watercourses with any of the thresholds. Moreover, WC-1, WC-3 and WC-4 are preferred to WC-2 in one or more of the outranking relationships. Therefore, WC-2 is the least efficient water user and should receive least priority in water allocations. However, a complete ranking of watercourses can only be produced by applying ELECTRE II (which is beyond the scope of this study).

Sensitivity analyses: Looking at Table 5, when stringent threshold values (0.6, 0.24) were used in generating strong outranking relationship, only two dominance relationships, 3P2 and 3P4, were determined. However, when average threshold values (0.5, 0.3) were used, five different dominance relationships, 1P3, 1P5, 3P2, 3P4 and 4P2, were obtained. Finally, when relaxed threshold values (0.4, 0.36) were used in producing weak outranking relationship of watercourses, seven dominance relationships, 1P2, 1P3, 1P4, 3P2, 3P4, 4P2 and 5P4, were found. The trend of getting a larger number of dominance relationships by lowering threshold values evidently explains that the results are quite sensitive to the threshold values (p, q). The sensitivity analysis of ELECTRE I by changing threshold values through this study have confirmed the conclusions drawn by Olson (1996) and Zardari *et al.* (2006) regarding the sensitivity of threshold values in ELECTRE I.

CONCLUSION

It has been demonstrated that ELECTRE I can provide a solution for complex (not just economic) water allocation decision-making problems. Even though Watercourse 1 does not have the highest monetary return from water use, it was found to be the most efficient under socio-economic objectives. Therefore, priority should be given to this watercourse in water allocations. On the other hand, Watercourse 2 was determined as least efficient in water use. Finally, it was shown that the use of ELECTRE I assists in improving the quality of the water allocation decision by making it more explicit, rational and efficient.

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