Multicriteria Decision Making (Compromise Programming) for Integrated Water Resources Management in an Irrigation Scheme

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ABSTRACT

The performance objectives of an irrigation scheme are productivity, equity, adequacy, reliability, surety index and frequency index. These objectives conflict with each other so multiple objectives need to be considered when making decisions.

An approach based on multi criteria decision making (MCDM) technique of compromise programming is presented in this paper. It consists of identifying different performance objectives (POs) (for example, productivity, equity etc.) that contribute to "overall performance index" (OPI) of irrigation management. Weights are assigned to each PO that reflects its relative importance. The values of the indicators are obtained from simulation-optimization modeling and weights are obtained by analytical hierarchical process (AHP). OPIs are obtained for different alternatives and the preferred alternative is the one that is nearest to the ideal point.

The applicability of the developed approach is demonstrated with the help of case study from Maharashtra State, India, using the "AWAM" model to estimate the values of POs for different irrigation strategies or alternatives and comparison of POs obtained from the survey of head, middle and tail reach farmers. The results indicated that MCDM generated the same irrigation strategy for head and middle reach farmers; but a different strategy for tail reach farmers, based on their expressed PO weights.

INTRODUCTION

The major objectives of irrigation schemes in developing countries are to optimize different performance objectives (POs) such as productivity, equity, surety index, adequacy, reliability of water supply, frequency index and sustainability in the process of water allocation to different users (farmers). Gorantiwar and Smout (2005) reviewed different POs used for water management of irrigation scheme and proposed the detailed framework of performance assessment of irrigation water management of irrigation schemes. Traditionally the approach has been to manage the water resources in irrigation scheme by optimizing only one PO. However when the water supply is limited, these objectives conflict and compete with each other and are not commensurable. Conflicts resulting from these objectives may endanger the economic and social order within an irrigation scheme. The attainment of the optimal value of each objective is not possible. Hence the tradeoff between them is necessary to identify the suitable optimal policy and avoid conflicts amongst farmers.

This indicates that "How can the irrigation plans and schedules be obtained and adapted to handle multiple objectives?" is the main unsolved question in the management of irrigation scheme. However there are a number of fundamental problems when there are multiple objectives. For instance, in irrigation water management of irrigation schemes, there are a number of decision makers (farmers, irrigation managers, and policy makers), each with a preference ordering over a number of POs; and number of alternatives for irrigation water management (irrigation strategies), and each with different values of POs. Our goal is to choose the "fair" alternative that aggregates the preferences of all the decision makers. Therefore there is a need to consider multiple objectives when making decisions. The technique used for this purpose is multi criteria decision making (MCDM) that provides powerful tools for engineers who are faced with increasingly complex decisions and conflicting objectives.

MCDM based on compromise programming is proposed in this paper. The compromise programming is suitable for this MCDM in irrigation water management because POs conflict with each other. This method identifies alternatives or solutions that are closest to the ideal solution as determined by some measure of distance.

The applicability of the developed approach is demonstrated with the help of a semi-hypothetical case study on Nazare Medium Irrigation Scheme, Maharashtra State, India. The "AWAM" model developed by the authors was used to estimate the values of POs for different alternatives or irrigation strategies.

METHOD

This section describes the method used for compromise programming and Analytic Hierarchy Process (AHP) for estimation of weights.

Compromise Programming

An approach based on MCDM technique of compromise programming (Zeleny, 1973) is proposed in this paper. It is used to identify solutions that are closest to the ideal solution as determined by some measure of distance. It consists of identifying the different attributes or indicators or performance objectives (POs) (for example, productivity, equity etc.) that contribute to "overall performance index" (OPI) of irrigation management in an irrigation scheme. The weights are assigned to each PO that reflects the relative importance of that PO compared to other POs. The values of the POs are obtained from the simulation-optimization modeling. The weights are obtained by analytical hierarchical process (AHP). OPI is then obtained by calculating the distance that determines the closeness to the ideal solution with the help of ideal and worst values for each of the POs and weights. OPIs are obtained for different alternatives or irrigation strategies and the preferred alternative would be the one that is nearest to the ideal point in terms of the distance.

Compromise programming uses following equation to rank alternatives according to their distance from an ideal solution. One compromise distance for each alternative is obtained (in this case different alternatives are irrigation strategies).

$$L_j = \left\{ \sum_{i=1}^{n} \left[w_i^p \left(\frac{f_i - f_i^w}{f_i^b - f_i^w} \right) \right] \right\}$$

where L_j is distance metric of alternative, w_i is weight of indicator *I*, f_i^b is best value for indicator *I*, f_i^w is worst value for indicator *I* and f_i is actual value for indicator *i*

Analytic Hierarchy Process (AHP) for estimation of weights

Prior to examining alternatives, the decision maker must assign weights to indicate their preferences to the relative importance of the various POs. Saaty (1980) proposed the use of the AHP to obtain the weights from the stakeholders. At the core of the AHP lies a method of converting subjective assessments of relative importance to a set of overall scores or weights. AHP is performed in following steps.

Step 1-Setting up the POs: Overall performance index is the function of several POs. The POs to be considered are set up in this step.

Step 2-Perform pair wise comparisons for POs: The stakeholders (e.g. farmer or irrigation manager in this case) compare two POs as a pair for all combinations of pair. The pair wise comparison is performed with a judgement scale presented in Table 1. Each pair wise comparison assigns a numerical value to the pair corresponding to the relative importance between the two POs.

Table 1. Scale for pair wise comparisons.

Comparative Importance	Definition	Explanation
1	Equally important	Two POs equally influence
3	Moderately more important	One PO is moderately more influential than the other
5	Strongly more important	One PO has stronger influence than the other
7	Very strongly more important	One PO has significantly more influence over the other
9	Extremely more important	The difference between influences of the two POs is extremely significant
2, 4, 6, 8	Intermediate judgment values	Judgment values between equally, moderately, strongly, very strongly, and extremely.

Step 3-Prepare a matrix (judgement matrix) for POs: A matrix with the POs listed at the top and on the left is prepared. Based on pair wise comparison (Step-2), the matrix is then filled in with numerical values denoting the importance of the PO on the left relative to the importance of the PO on the top. A high value means that the PO on the left is relatively more important than the PO at the top. When a PO is compared with itself the ratio of importance is obviously one, resulting in a diagonal line across the matrix. Resulting matrix (below) is known as the judgement matrix.

	PO_1	PO_2	PO_3	PO_4	....	PO_n
PO_1	1	a_{12}	a_{13}	a_{14}		a_{1n}
PO_2	$1/a_{12}$	1	a_{23}	a_{24}		a_{2n}
PO_3	$1/a_{13}$	$1/a_{23}$	1	a_{34}		a_{3n}
PO_4	$1/a_{14}$	$1/a_{24}$	$1/a_{34}$	1		a_{4n}
:						
:						
PO_n	$1/a_{1n}$	$1/a_{2n}$	$1/a_{3n}$	$1/a_{4n}$		1

Note that if 'a_{ij}' is the judgment value when i^{th} PO is compared to j^{th} PO, then '$1/a_{ij}$' is the judgment value when j^{th} PO is compared to i^{th} PO. In other words, $a_{ji}=1/a_{ij}$.

Step 4-Compute the priority vector for POs: The geometric mean of each row (i.e., the elements in each row are multiplied with each other and then the n^{th} root is taken, where n is the number of elements in the row) is calculated. This forms the vector of geometric mean. The elements of this vector are then normalized by dividing them with the sum of the elements of the vector. The resulting normalized vector is an approximated maximum eigenvector, herein named as priority vector.

Step 5-Assess consistency of pair wise judgments: One of the most practical issues in AHP is non-consistency in pair wise comparisons. If all the comparisons are perfectly consistent, then the following expression should hold true for any combination of comparisons of the judgement matrix.

$$a_{ij} = a_{ik} \times a_{kj}$$

where a_{ij} is relative importance factor (tabulated values in Table 1) of i to j.

However, perfect consistency rarely occurs in practice. Consistency ratio (CR) is commonly used to reflect the degree of consistency of judgment matrix. The CR is calculated by following equations (Saaty, 1980).

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

$$CR = \frac{CI}{RCI}$$

where CI is consistency index, $\lambda_{\max}$ is maximum eigenvalue of judgment matrix, RCI is random consistency index (as determined by Saaty, 1980) and n is the number of factors

Maximum eigenvalue ($\lambda_{\max}$) is obtained by adding the columns in the judgment matrix and multiplying the resulting vector by the vector of priorities (i.e., the approximated eigenvector) obtained earlier.

Step 6-Compute the relative weights/ranks: If the CR of the judgement matrix is satisfactory (less than 10% in this study), the priority vector values will be assigned as relative weights of factors.

APPLICATION TO IRRIGATION MANAGEMENT

Bos (1997) and Gorantiwar and Smout (2005) reviewed different performance objectives used for water management of irrigation schemes and proposed detailed frameworks for performance assessment of irrigation water management of irrigation schemes. In this study the following important performance objectives are considered. Readers are advised to refer to Gorantiwar and Smout (2005) for working out the details of these POs.

Productivity: It is related to output from the system in response to the input added to the system and there are several indicators of productivity. The principle outputs of the scheme are the crop production (or its economic equivalence) and the area irrigated.

Equity: The distribution of input resources in the irrigation scheme (area and seasonal or intraseasonal water) or the resulting output (crop production or net benefits) among the users (farmers) in a fair manner which is prescribed in the objectives of the irrigation scheme in the form of social welfare. Inter quartile allocation ratio is used as the measure of equity.

Surety index: It is the product of equities in area allocation and water distribution and provides the farmers surety of allocating the water to their total area with equitable distribution of water. For example, surety index of 1 would indicate that all the farmers are provided irrigation to their total area with equitable distribution of water.

Adequacy: Adequacy deals with water supply to the crop relative to its demand and is the ratio of the water allocated or supply from all the sources (irrigation, effective rainfall, capillary water etc.) and the demand due to all the processes (consumptive use, losses, land preparation, leaching for draining accumulated chemicals or salts,

other special needs etc) over a specific time period for a specific crop grown in a specific area.
Frequency index: This index denotes the frequency of water supply to the farmers.

The weights are assigned to each PO that reflects the relative importance of that PO. The weights are obtained by analytical hierarchical process (AHP).

The AWAM model (Gorantiwar, 1995 and Smout & Gorantiwar, 2005) is used for obtaining the values of different POs for a specified alternative or irrigation strategy. AWAM model allocates the land area and available surface water to different crops cultivated in different parts of the irrigation scheme to maximize the net benefits from the irrigation. AWAM model was developed for the irrigation schemes which operate under rotational water supply and not for the schemes where in water is delivered on demand. AWAM model has the following four phases and is executed for each irrigation interval or a set of irrigation intervals over the irrigation season or year.

1. Generation of irrigation strategies
2. Preparation of irrigation programs
3. Selection of irrigation programs
4. Optimum allocation of resources

Readers are advised to refer Smout and Gorantiwar (2005) for details of the AWAM model.

The OPI is then obtained by calculating the distance that determines the closeness to the ideal solution with the help of ideal and worst values for each of the indicators and weights. OPIs are obtained for different alternatives and the preferred alternative would be the one that is nearest to the ideal point.

CASE STUDY IRRIGATION SCHEME

"Nazare Medium Irrigation Scheme" in a semi-arid region of Maharashtra State of India is selected as the case study irrigation scheme. This irrigation scheme is representative of storage reservoir irrigation schemes that operate under rotational water supply in south Asia.

The irrigation season of this scheme starts from the 15^{th} October and ends on 14^{th} October of the next year. There are three distinct crop seasons within the irrigation season. These are winter (*Rabi*) (15^{th} October to 14^{th} February), summer (15^{th} February to 14^{th} June) and rainy (*Kharif*) (15^{th} June to 14^{th} October). As little rainfall is received in the *Rabi* season, the crops grown in this season are supplied with irrigation water for their growth. In the summer season no rainfall is received but it is characterized with high evapotranspiration. The irrigations are given to a limited extent in the summer season. Most of the rainfall is received in the *Kharif* (monsoon) season. Therefore the irrigations during *Kharif* season are of little interest in this study as the reservoir fills during this season. Therefore in this study, the irrigation season was considered to spread over *Rabi* and summer crop seasons only.

The gross capacity and dead storage capacity of the reservoir are 22.31 and 5.68 Mm^3, respectively. One main canal originates from the headworks. The full supply discharge and the length of the main canal are 1.53 m^3/s and 3.05 km, respectively. One distributory canal with carrying capacity of 1.53 m^3/s emerges from the main canal, the length of which is 11.75 Km. The cultural command area (CCA) of the irrigation scheme is 3539 ha. There are 28 direct outlets (4 on the main canal and 24 on the distributory canal) and four minors (all on distributory canal) with 9 outlets. The details of the outlets on the minors could not be obtained and therefore CCA of all 28 outlets and 4 minors were considered as allocation units (AUs), resulting in 32 AUs. The data related to allocation units interms of different efficiencies; soil types etc were obtained from various sources. The climate over the entire command area was assumed as uniform. The command area is characterized with four different types of soils. In the present study as two crop seasons formed the irrigation season, gram, sorghum, onion, wheat (Rabi crops), groundnut and sunflower (summer crops) were considered in the analysis.

ALTERNATIVES-IRRIGATION STRATEGIES

Irrigation strategies were formulated as the combination of the following management strategies (irrigation amount and irrigation frequency), water distribution and cropping distribution.

Irrigation amount: The following options were considered**:**

1. Full irrigation (Fl-I): The irrigations were applied to bring the root zone soil moisture to the field capacity.
2. Fixed depth irrigation (Fx-I): The optimized fixed depth of irrigation, which was same for all crops, soils and climate and over the irrigation season, was applied.
3. Optimized deficit irrigation (ODI): The irrigations were applied in different optimum combinations of the depths between full irrigation and no irrigation.

Irrigation frequency: The following sets of irrigation interval (II) were chosen.

1. 14 days 2. 21 days 3. 28 days 4. 35 days
5. 21 days in winter season and 14 days in summer season (21-14 days)
6. 28 days in winter season and 21 days in summer season (28-21 days)
7. 35 days in winter season and 28 days in summer season (35-28 days)

Water distribution: The following options were considered:

1. Free water distribution (FWD)
2. Equitable distribution of seasonal water allocation based on CCA of AU (EDSW)
   - i. -by considering conveyance and distribution efficiencies
   - ii. -by considering conveyance efficiency
   - iii. -without considering any efficiencies
3. Equitable distribution of intraseasonal water based on CCA of AU (EDIW)
   - i. -by considering conveyance and distribution efficiencies
   - ii. -by considering conveyance efficiency
   - iii. -without considering any efficiencies

Cropping distribution: The following two options were considered.

1. Free cropping distribution (Fr-CD): No restrictions are put on the allocation of area or water or output to be obtained from the different crops. The model is therefore free to select any crops depending on which crops produce maximum total net benefits from the irrigation scheme.
2. Fixed cropping distribution (Fx-CD): Restricting the area under different crops according to particular requirement is referred to as the fixed cropping distribution. Based on the previous trend in this irrigation scheme, the fixed cropping distribution of (gram-25%, sorghum-20%, onion-10% and wheat-15 % in Rabi and Sunflower –10 % and groundnut-20% in summer season) was assumed.

RESULTS AND DISCUSSION

The different stakeholders that are involved in the irrigation management of irrigation schemes are farmers, irrigation managers and policy makers. These stakeholders have different perspective towards the POs. For example, the policy makers may be interested in increasing the productivity of the irrigation scheme; farmers are often interested to increase their production and irrigation mangers may be interested in increasing the irrigation efficiency or minimising the conflicts. Location also influences stakeholders' interests in different POs. For example, the farmers in the head reaches of the scheme are interested attaining the higher yield per unit area whereas the farmers at tail reaches might be interested in equitable distribution of water. In this particular study, only one type of stakeholder i.e. farmers is considered.

The POs that are stated in previous sections were considered for obtaining the OPI. In this study the productivity based on the economic equivalence of the crop production and the equity based on the seasonal distribution of water were considered. The lowest possible irrigation interval of 14 days was considered as ideal for calculating the frequency index.

It is necessary to obtain the weights for these POs from the farmers. The AHP method discussed above was used for obtaining the weights. The questionnaire was formulated for pair wise comparison of POs required for AHP. As the farmers at different reaches of the scheme may have different viewpoint about different POs, the farmers were divided in to three groups based on their relative location on the main canal: head reach, middle reach and tail reach. Five farmers were selected from each reach and were interviewed to obtain the pair wise comparison of POs.

The results of the pair wise comparison were analysed by using the method of AHP. However it was observed that CR of the judgement matrix was satisfactory for only one farmer from head reach, two farmers from the middle reach and one farmer from the tail reach. Therefore instead of going back to the farmers for resurvey, the weights that were consistent were considered for the analysis. In case of middle reach, out of two sets of weights that were consistent, the set for which the CR was the least was considered. The weights that were finally considered for obtaining OPI are presented in Table 2.

Table 2. Weights of different POs obtained for farmers from different reaches

Reach	Performance objectives				
	Productivity	Equity	Surety	Adequacy	Frequency
Head	0.39	0.05	0.25	0.22	0.10
Middle	0.25	0.12	0.34	0.18	0.11
Tail	0.04	0.44	0.15	0.17	0.20

The allocation plans and water delivery schedules were obtained for the different irrigation strategies resulted from different combinations management strategies, water and cropping distributions. The AWAM model was run for 231 times for this purpose. The POs (productivity, equity, surety index, adequacy and frequency index) were obtained from the output (allocation plan and water delivery schedules) for all these 231 combinations. The OPI was computed for head, middle and tail reach farmers using the weights obtained from AHP by compromise programming presented above. The Table 3 presents highest and lowest OPIs with corresponding irrigation strategy obtained from the perspective of head, middle and teal reach farmers.

Table 3. Highest and lowest OPIs with corresponding irrigation strategy

OPI and corresponding irrigation strategy	Reach		
	Head	Middle	Tail
Highest OPI			
Value	0.77	0.70	0.86
Irrigation strategy	ODI II= 21 days EDSW (w/o considering efficiencies) Fr-CD	ODI II= 21 days EDSW (w/o considering efficiencies) Fr-CD	Fl-I II= 14 days EDSW (considering efficiencies) Fr-CD
Lowest OPI			
Value	0.15	0.12	0.11
Irrigation strategy	Fl-I II= 28 days FWD Fx-CD	Fl-I II= 28 days FWD Fx-CD	Fl-I II= 28 days FWD Fx-CD

It is interesting to note that the PO weights of the head reach and middle reach farmers indicated the same preferred irrigation strategy based on OPI, out of 231 alternatives. It is also interesting to note that all the farmers irrespective of their relative location in the irrigation scheme were interested in equitable distribution of water. It is obvious that tail reach farmers would be interested in considering the efficiencies in distributing water proportionate to their area, as they are the ones who are allocated less water if efficiencies are not considered in distribution of water.

Table 3 shows that the head, middle and tail reach farmers provided the lowest OPI for the same irrigation strategy, though free water distribution would have been beneficial to head reach farmers as in free water distribution, they are provided with more water because of less losses of water in conveyance. Full irrigation with large irrigation interval of 28 days for fixed water distribution gives less value of productivity, adequacy and equity and hence ranked at the bottom of all the alternatives.

CONCLUSIONS

The paper has presented an approach based on multi criteria decision making (MCDM) technique of compromise programming for identifying alternative that is closest to the ideal alternative as determined by some measure of distance, in the scenario of conflicting objectives. The application of this approach to the case study irrigation scheme has identified the alternatives based on overall performance index for head, middle and tail reach farmers. The results indicated that the irrigation strategy differs for head and tail reach farmers. The approach can be further extended to include other stakeholders such as irrigation managers and policy makers. This approach will be useful for the decision makers to reduce the conflicts amongst different users, while optimising the use of irrigation water.

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