MULTICRITERION DECISION ANALYSIS FOR EVALUATING WATER USE IN AGRICULTURE: A CASE STUDY FROM GREECE

J. GANOULIS, E. KOLOKYTHA, Y. MYLOPOULOS

Hydraulics Laboratory, Department of Civil Engineering,
Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
Tel. +30-2310-99.56.82 Fax +30-2310-99.56.81 e-mail iganouli@civil.auth.gr

ABSTRACT

The paper presents a suitable methodology for evaluating the more sustainable use of water for irrigation purposes by considering economic, technical, environmental and social aspects of water resources management. Alternative policies based on different criteria are evaluated by using Multicriterion Decision Analysis (MCDA). A Greek case study of irrigation system development is presented. Different policies are formulated by combining data such as water pricing, the type of irrigation scheme used, crop distribution, and the use of fertilizers. The criteria used to evaluate the best possible solution include economic factors, namely the initial cost of the irrigation system, maintenance costs and crop profitability, environmental factors, which comprise water volume used, water pollution during and after irrigation and efficiency of water use, and social factors, including the employment of rural labour. The methodology of Compromise Programming (CP) is employed to rank alternative strategies. Results indicate that the most preferable strategy would be to adopt a drip irrigation system together with a moderate change in the water pricing policy, and to use green fertilizers.

KEY WORDS:

Water pricing, irrigation water, multicriterion decision analysis, compromise programming, Greece

INTRODUCTION

The use of water for agricultural purposes is a fundamental issue for debate, since on a global basis the agricultural sector is the highest consumer of water. Although the extension of irrigated areas has augmented agricultural production and food supply, a series of shortcomings has contributed to negative impacts on both water quantity and quality.

Whilst the agricultural sector is the most important in economical terms in all Mediterranean countries, it has also become the largest consumer of water. In Greece, the average amount of water used for agricultural purposes ranges from 80 to 85% of the total use of water, as compared to an average of 70% on a global scale (source: Greek Ministry of Agriculture). At the same time, the use of water in agriculture has become very inefficient, with an efficiency rate of only about 35%. Large quantities of fresh water are misused because farmers lack knowledge about appropriate irrigation practices, have inadequate irrigation systems, plant non-adapted types of crops and do not plant on a timely basis.

On the agronomic front, the principal means used to augment land productivity have been the wide use of advanced fertilizers and the high consumption of manure. This has resulted in the very extensive and uncontrollable pollution of soil and groundwater. In many cases, inadequate drainage has produced extensive salinization of irrigation land.

The intensive use of pesticides has increased the threat to public health from long-term chemical and toxic pollution.Effective preventive measures need to be taken immediately, as temporary improvements are not enough to control environmental deterioration on a long term basis, nor to avoid serious socio-economic consequences. Clearly, water resources development projects must be planned, designed and operated in an environmentally sound way. (Biswas 1997).

This paper suggests a suitable strategy for the more sustainable use of water in agriculture taking into account economic, technical, environmental and social aspects of water resources management. The study is divided into problem description and formulation of the payoff matrix, short description and application of Compromise Programming (CP) to rank alternative strategies (Goicoechea et al., 1982) followed by sensitivity analysis and finally conclusions and suggestions.

METHODOLOGICAL APPROACH

MULTICRITERION DECISION ANALYSIS (MCDA)

MCDA techniques are gaining importance as potential tools for solving complex real world problems, because of their inherent ability to consider different alternative scenarios, the best of which may then be analysed in depth before being finally implemented. (Goicoechea et al., 1982; Szidarovszky et al., 1986; Pomerol and Romero, 2000). In order to apply MCDA techniques, it is important to specify the following:

- **The objectives**, which indicate the directions of state change of the system under examination and need to be maximized, minimized or maintained in the same position.
- **The attributes**, which refer to the characteristics, factors and indices of the alternative management scenarios. An attribute should provide the means for evaluating the attainment level of an objective.
- **The constraints,** which are restrictions on attributes and decision variables that can or cannot be expressed mathematically.

In MCDA the aim is not to obtain an optimal solution, as would be the case with only one objective, but a "non-inferior" or "non-dominated" solution. This is a solution that improves all objective functions. Other solutions cannot improve a single objective without causing a degradation of at least one other objective.

Let us consider, for example, the problem of maximizing two conflicting objectives Y_1 and Y_2 subject to a set of constraints

$$g_j(x_1, x_2,..., x_n) \leq = \geq 0 \qquad j = 1, 2, .., m$$

Each couple of values Y_1 and Y_2 that satisfy the constraints lies within the *feasible region or feasible space* (Fig. 1). This is the set of "*non-inferior*" *or "non-dominated*" solutions. This region is limited by a curve ABCD called a *feasibility frontier*. This curve is defined by the fact that there can be no increase in one objective along it without a decrease in the value of the other objective. Every decision vector on this curve takes a maximum value of the objective Y_2 given a particular value of objective Y_1.

The selection of one particular solution from a set of non-inferior solutions depends on the preferences of the decision maker. This may be indicated by a family of *iso-preference* or *indifference curves* (Fig. 1). The *efficient solution* is defined by the point B on the feasibility frontier that has the maximum level of preference.

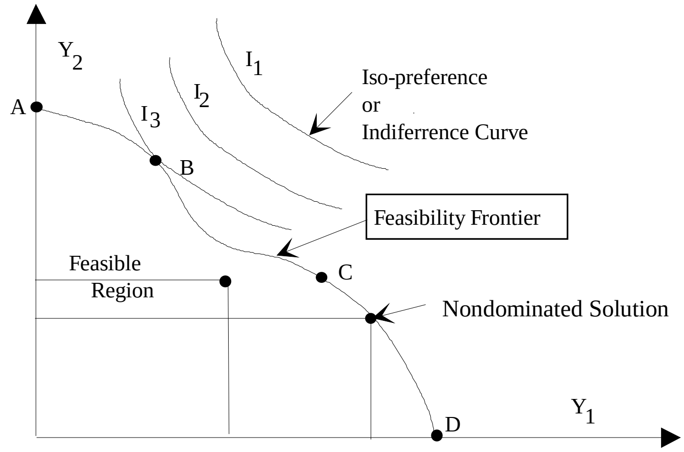

Fig. 1 Non-dominated solutions for a two-objective problem.

Trade-offs between objectives may be done at different levels to obtain some composite economic or ecological indicators. When data are imprecise or missing, fuzzy set theory is very useful. Then different strategies or options may be ranked using different techniques, such as the one based on the minimum composite distance from the ideal solution (Fig. 2).

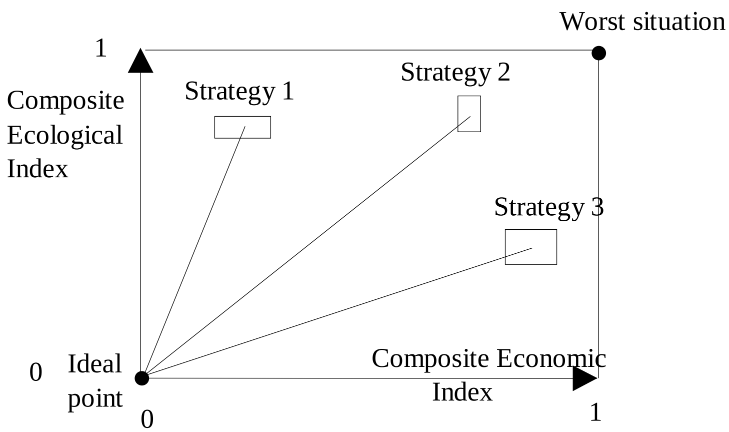

Fig. 2: Ranking between different options expressed in terms of economic and ecological indexes.

COMPROMISE PROGRAMMING (CP)

CP, which is a distance-based technique, defines the 'best' solution as the one in the set of efficient solutions whose point is at the least distance from an ideal point (Zeleny, 1982). The aim is to obtain a solution that is as 'close' as possible to some ideal. The distance measure used in CP is the family of L_p - metrics and given as

$$L_p(a) = \left[\sum_{j=1}^{J} w_j^p \left| \frac{f_j^* - f(a)}{M_j - m_j} \right|^p \right]^{\frac{1}{p}} \tag{1}$$

$L_p(a)$ = L_p - metric for alternative a, $f(a)$ = Value of criterion j for alternative a, M_j = Maximum (ideal) value of criterion j in set A, m_j = Minimum (anti ideal) value of criterion j in set A, f_j* = Ideal value of criterion j , w_j = Weight of the criterion j, p = Parameter reflecting the attitude of the decision maker with respect to compensation between deviations. For p=1, all deviations from f_j* are taken into account in direct proportion to their magnitudes, meaning that there is full (weighted) compensation between deviations. For $2 \leq p \leq \infty$ the largest deviation has the greatest influence so that compensation is only partial (large deviations are penalized). For p=∞, the largest deviation is the only one taken into account (min-max criterion) corresponding to zero compensation between deviations (perfect equity).

THE GREEK CASE

Greece is an agricultural country with 85% of water being consumed by the agricultural sector. Agriculture in Greece is vital for the economy, employing 22% of the workforce (National Statistics 2000). The main crops in the area under study are cotton, fruit, maize, sugar beet, grass and rice. The most popular irrigation system in Greece is surface irrigation (75% of cases), although there has been a move towards drip irrigation in the last few years. Drip irrigation needs to be subsidized for wide usage.

The total cost of a crop is made up of the variable cost of seeds, fertilizers and pesticides, the selection of mechanical means and some other indicators that vary according to the particular crop in question. Labour costs, the cost of the irrigation system applied and also the subsidies received for growing the given crop should also all be taken into consideration.

The study area consists of the irrigated areas in Imathia and Larisa (Central Greece). Water for irrigation is taken mostly from surface water resources, namely the River Pinios in Larisa and the River Aliakmon in Imathia. Water also comes from artificial lakes and wells. The artificial lakes pump water from the River Pinios and irrigate approximately 14 km^2, but the discharge of the river cannot satisfy the irrigation needs of the areas The area of Larisa consists of 1.168,334 km^2, which count for 42.1% of the Thessalian valley.

The region has a Mediterranean climate with mild temperatures, wet winters and hot, dry summers. There is insufficient rainfall over the whole year to satisfy agricultural demands, and therefore irrigation is essential to agricultural production as water deficits are common.

However, irrigation efficiency is estimated to be only around 40% and water pollution is a major problem due to salinity and water logging effects. The main problems that contribute to the poor utilization of the surface water resources are the following:

- Growing water intensive crops (cotton, rice)
- Using unlined distributaries and uncontrolled outlets, which makes the irrigation system more inefficient.
- The traditional cropping pattern is not able to harness the full potentiality of the irrigation facilities.
- A lack of irrigation planning involving all disciplines
- The inadequate participation of concerned agencies for monitoring and evaluating the distributaries contributes to the sub-optimal performance of the irrigation system.
- The poor economic conditions of farmers prevent modern farming practices being adopted
- Existing water pricing policy and water charges do not act as incentives for water conservation.

In light of the above points and considering the socio-economic conditions of farmers a suitable irrigation strategy is to be formulated to minimize the above drawbacks using MCDA techniques. CP has been selected using the family of L_p - metrics.

IDENTIFICATION OF CRITERIA

The following three groups of criteria are identified and given below with notations (Munasinghe and Sheareer, 1995).

- Economic factors including initial cost often paid by the state (CR1), maintenance cost (CR2), and profitability of crops (CR3).
- Environmental (sustainability related) factors including irrigation water volume used (CR4), water pollution during and after irrigation (CR5), and efficiency of water use (CR6).
- Social factors including employment (CR7).

In the CP method weights are used to express the preferences of the following three groups of decision makers,:

- those who give priority to economic effects
- those who give priority to environmental (sustainability) effects
- those who give priority to social effects.

These opinions are reflected by three sets of criterion weights. Emphasis is given to the definition of a framework where conflicting criteria reflect the attitude of the different parties involved (farmers/water authorities). These weights have been allocated in order to reflect the relative importance of the above-mentioned criteria**.**

Set 1 is represented by weights (0.10, 0.10, 0.30), (0.10, 0.06, 0.09) and 0.25 for CR1 to CR7 stressing the economic criteria. Set 2 is represented by weights (0.09, 0.06, 0.10), (0.15, 0.15, 0.20) and 0.25 giving emphasis to environmental criteria, whereas (0.09, 0.06, 0.10), (0.10, 0.06, 0.09) and 0.50, are the weights for set 3, highlighting the impact of social factors.

FORMULATION OF ALTERNATIVE STRATEGIES

Alternative strategies (policies) that could change the planning scenario of the irrigation system were formed taking into account the following:

- Various irrigation schemes (A1: Surface, A2: Sprinkler, A3: Drip)
- Price of water in the district chosen (B1: Moderate, B2: High, B3: Very high).
- Distribution of crops over the area studied (C1: Existing cropping pattern; C2: Modified cropping pattern with decreased cultivation of cotton and increased growing of fruit/vegetables)
- The kind of fertilizer used, with different consequences for the environment (D1: Chemical fertilizers, D2: Green fertilizers).

APPLICATION OF CP

In the present study CP was applied to the planning problem. A qualitative evaluation of criteria was made based on the following data:

- The applied irrigation systems
- Existing water pricing policy
- The types of crops
- Crop distribution
- Use of fertilizers

This data was supplied by the water authorities of the areas under study. The convention of the qualitative approach into numerical (ideal and anti-ideal values) is presented in Table 1. Table 2 presents a decision matrix (DM) (actions versus direct consequences on different criteria), which is then formed. Combinations of the subdivisions of the four groups of data (irrigation scheme, water pricing, crop distribution and fertilizers) provide the alternative policies. The ten factors in Table 2, divided into four major sectors, yield 36 different alternative policies (3x3x2x2).

Table 3 presents a payoff matrix obtained by the above procedure.

Table 4 presents the ranking pattern for CP. Table 5 presents L_p metric values and the corresponding ranking pattern for the top five alternative policies for three values of $p=1,2,\infty$ for weight set 1. The alternative with the minimum L_p metric distance is selected as the compromise solution.

For p=1,2 it is concluded that alternative 26 (combination of drip irrigation system with moderate change in the existing water pricing with existing cropping pattern and growing crop with green fertilizers) is ranked as best (due to low L_p metric values of 0.17000 and 0.09294 p=1 and for p=2) whereas for $p=\infty$ the best solutions are 28 and 26. Based on the results in Table 5 it can be seen that when there is either full compensation between alternatives (p=1) or when there is a weighted deviation in proportion to the magnitude (p=2), alternative 26 is ranked best.

Table 1. Conversion of qualitative ranking into numerical

Notation	**Numerical value**	
Very high performance/Very cheap cost	1	A
High performance/High profitability/Cheap cost	0.8	B
Average	0.6	C
Low performance/Low profitability/High cost	0.4	D
Very low performance/Very high cost	0.2	E
No significant effect on the planning problem	0	F

Table 2. Decision Matrix (DM)

Alternative Strategies / Criteria	A1	A2	A3	B1	B2	B3	C1	C2	D1	D2
Initial Cost	1.0	0.6	0.6	0.0	0.0	0.0	0.4	0.6	0.4	0.8
Maintenance Cost	0.4	0.4	0.6	0.8	0.8	0.4	0.8	0.6	0.0	0.0
Profitability	0.6	0.8	1.0	0.8	0.6	0.4	0.8	0.6	0.6	0.8
Water Volume Used	0.4	0.6	0.8	0.6	0.6	0.8	0.6	0.4	0.0	0.0
Effect of Pollution	0.4	0.6	0.8	0.0	0.0	0.0	0.6	0.6	0.4	0.8
Water use Efficiency	0.4	0.6	0.8	0.6	0.6	0.8	0.8	0.6	0.0	0.0
Social Impact	0.6	0.4	0.4	1.0	0.4	0.2	0.8	1.0	0.4	0.8

Table 3. Payoff Matrix

Alternative	CR1	CR2	CR3	CR4	CR5	CR6	CR7
1	1.80	2.00	2.80	1.60	1.40	1.80	2.80
2	2.20	2.00	3.00	1.60	1.80	1.80	3.20
3	2.00	1.80	2.60	1.40	1.40	1.60	3.00
4	2.40	1.80	2.80	1.40	1.80	1.60	3.40
5	1.80	2.00	2.60	1.60	1.40	1.80	2.20
6	2.20	2.00	2.80	1.60	1.80	1.80	2.60
7	2.00	1.80	2.40	1.40	1.40	1.60	2.40
8	2.40	1.80	2.60	1.40	1.80	1.60	2.80
9	1.80	1.60	2.40	1.80	1.40	2.00	2.00
10	2.20	1.60	2.60	1.80	1.80	2.00	2.40
11	2.00	1.40	2.20	1.60	1.40	1.80	2.20

Table 4. Ranking pattern obtained by CP techniques.

Rank	CP(p=1)	CP(p=2)	CP(p=∞)
1	26	26	28
2	28	28	26
3	14	14	14
4	30	2	2
5	2	16	16
6	25	25	17
7	16	27	25
8	32	30	32
9	34	32	13
10	4	13	1
11	27	18	15

Table 5. Lp distance from ideal solution for the top five alternatives, using Compromise Programming.

Rank	Lp metric value p=1	Alter-native	Lp metric value p=2	Alter-native	Lp metric value p=∞	Alter-native
1	.17000	26	.09294	26	.06247	28
2	.24125	28	.10113	28	.07054	26
3	.30750	14	.12402	14	.07609	14
4	.31375	30	.15193	2	.10672	2
5	.34875	2	.15963	16	.10729	16

CONCLUSIONS AND RECOMMENDATIONS

CP was applied to the case of a Greek irrigation system to facilitate sustainable water resources planning. By considering all the scenarios, along with extensive sensitivity analysis for different parameters, it is concluded that the best policy is one combining the adoption of a drip irrigation system, moderate changes in the existing water pricing policy, the maintenance of the current cropping pattern and the use of green fertilizers (alternative 26).

This policy is rather conservative, since it only promotes the use of more environmentally friendly fertilisers, giving priority to water quality, and does not make many changes to the current situation in general. As far as crop selection is concerned, the wide differences in crop values and their water requirements provide significant flexibility for irrigated agriculture to adjust to changes in water availability.

Water pricing reform alone cannot redirect the agricultural economy in Greece towards more sustainable use of water resources better geared suited to the available resources, which at the same time achieves high land productivity, ensures the social welfare of a large percentage of the working population and improves irrigation efficiency. The MCDA results show that the best solution involves a moderate change in the pricing policy and reinforces the option of an integrated approach.

The first step for this integrated approach is to form policies aimed at water and agricultural preservation, which give high priority to *economic efficiency, social equity and environmental protection.* These policies should be consolidated at governmental level in order to meet the expectations of different criteria. So that these policies may be successfully applied, both the performance of water suppliers and the levels of efficiency in the use of water by the different users need to be considered. Unless there is effective cooperation between the different parties (users, government etc) water resources are likely to be over-exploited and abused.

REFERENCES

Goicoechea, A., D. Hansen and L.Duckstein, 1982. “Introduction to multi-objective analysis with engineering and business applications”, John Wiley, New York.

Pomerol, J.Ch. and S.B. Romero, 2000.“Multicriterion decision in management: principles and practice”, Kluwer Academic Publishers, Netherlands.

Raju, K.S. and L.Duckstein, 2000. MULTICRIT: “Multicriterion decision support system”, Technical Report No. 4/2000, GRESE, ENGREF, Paris, France.

Szidarovszky, F., M. Gershon, and L.Duckstein, 1986. “Techniques for mutli-objective decision making in systems management”, Elsevier, Amsterdam.

Zeleny, M. 1982. “Multiple criteria decision making”, McGraw-Hill, New York.

Biswas A. 1997. “Water Resources. Environmental Planning Management and Development”, McGraw Hill.

Dinar A, A. and Subramarian 1997. “Water Pricing Experiences. An International Perspective”, World Bank , Washington D.C.

Munasinghe M. and W. Shearer 1995. “Defining and measuring sustainability. The Biophysical Foundations”, World Bank, Washington D.C.