

Multicriteria decision-making for efficient water and land resources allocation in irrigated agriculture

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Abstract The irrational use of water in agriculture is often responsible for several problems concerning the depletion and/or the pollution of water resources. In these cases specific policy measures should be taken to protect water resources from harmful agricultural activities, mitigating at the same time their potential impact on farmers' welfare. To this end, a multicriteria decision-making model is formulated that aims at allocating efficiently water and land resources in a rural area of Greece, by optimizing a set of important socio-economic and environmental objectives. According to the model's output, past and current decisions on irrigated agriculture turned out to be oriented towards meeting exclusively the socio-economic objectives. Yet, there are several other possible allocations schemes that could be applied in order to improve the performance of environmental indicators and to contribute to a more sustainable use of natural resources. Moreover, the decision-making model can be further employed to assess a number of additional policy measures in irrigated agriculture. In this framework, the outcome of imposing various water pricing policies was evaluated. The efficiency of these policies was found tightly connected to the elasticity of water demand. Namely, higher elasticity seems to enhance the flexibility in resource allocation and the movement towards environmental objectives.

Keywords Irrigation water pricing · Multicriteria decision-making · Multi-objective goal programming · Optimal resource allocation · Sustainable agriculture

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1 Introduction

Decision-making in irrigated agriculture is a process that quite often focuses on farmers' utility optimization. During the last few decades most decision-making studies were adjusted to the farm level by putting into practice either a conventional cost-benefit analysis or a multicriteria technique to satisfy economic, social and managerial criteria originated almost solely from the farmers' point of view. However, the pursuit of farmers' welfare maximization is often related to intensive agricultural activities that create significant environmental pressures on water availability (e.g., overexploitation due to irrigation) as well as on water resources quality (e.g., pollution due to fertilizers and pesticides). For this reason, contemporary policy-makers should recognize the environmental dimension of irrigated agriculture and incorporate some environmental criteria—along with the socio-economic ones—into a complex decision-making process. This process has also to be consistent with the concept of sustainability and particularly to safeguard that farming activities are environmentally non-degrading, economically viable and socially acceptable.

The main aim of this study is the formulation of a decision-making model that is capable to optimize a set of sustainability criteria by modifying resource allocation (water and land resources) in a representative irrigated area of Northern Greece. In the context of irrigated agriculture the following general categories of sustainability criteria can be outlined: (a) maintenance of the resource base, (b) low dependence on external inputs, (c) economic viability and (d) local farmers' acceptance (Tiwary 2000). The first two categories of criteria describe the environmental policy orientation, which is directly or indirectly connected to the protection of water resources (water quality and ecosystem integrity) as well as to the sufficiency and efficiency of water supply. On the other hand, economic viability and farmers' acceptance mark the socio-economic orientation of regional, agricultural and/or water policy. Some of the most frequently used criteria in this category tend to: (a) secure the income of farmers, (b) limit the unemployment rate and (c) safeguard the current water-agency revenues.

The sustainability criteria have not the same importance in all reference areas. Therefore, a weight should be attached to each one of them in order to signify its relative importance as perceived by the decision-maker. The most appropriate policy measures should then be identified and implemented according to these weights. To this end, a multicriteria decision-making model (MCDM) is a very appropriate tool to handle simultaneously several criteria of regional planning, to indicate the best resource allocation and, eventually, to assess the potential implications of various policy measures.

Recent literature on the subject comprises a number of studies that implement the multicriteria modeling of agricultural decision-making at a local or regional level of analysis (Ghosh et al. 1993; Manos and Gavezos 1995; Pal and Basu 1996; Gomez-Limon et al. 2002). However, only few of them (e.g. Tiwari et al. 1999) include environmental objectives related to water quality and availability. Besides, in most relevant studies, these attributes are treated only as negative impacts of different policy scenarios and not as decision criteria (objectives) in the MCDM model (Hayashi 2000). The present work takes a step forward the previous conceptual framework by defining sustainability criteria (in operational terms) and efficient solutions (regarding resource allocations) for a wide range of policy alternatives. According to this framework, the final outcome of different water pricing policies is also evaluated, using the results of MCDM from both regional and farm level analyses.

2 Conceptual framework

2.1 Overall description

The conceptual framework, regarding the methodological procedure followed in this paper, is displayed in Fig. 1. As shown in this figure, the whole procedure comprises two distinct stages: (a) the stage of model formulation, where all necessary inputs are introduced into the multicriteria model and (b) the stage of model application, where all solutions are obtained and then evaluated.

At the first stage of the proposed methodology the initial step is to define the sustainability criteria and to set the objective functions of the MCDM model. Special attention is paid in setting the objective functions in order to represent all key factors of irrigated agriculture that may optimize the utility of a decision-maker. The next step is to select the decision variables and the agricultural and environmental constraints of the MCDM model. All the above-mentioned elements are introduced into the model, which is based on the multi-objective goal programming (MOP) technique.

The MOP technique is applied in order to estimate all feasible solution points, concerning the best allocation of land and water resources, for a certain number of alternative scenarios (i.e., different weighting schemes of the decision-maker). Given the results of MOP, the set of efficient solution points is further estimated. The next step is the evaluation of the selected sustainability criteria (for all feasible solution points), by making use of a performance indicator. Moreover, the performance indicators are grouped into two composite indices, according to the policy orientation of each criterion (socio-economic or environmental). Hence, the resulting two-dimensional indicator (SE-ENV) can be used in order to compare all feasible solution points but also to evaluate the potential impact of several agricultural or water policy measures.

2.2 The multicriteria decision-making approach

As already mentioned, the methodology employed in this paper is based on MOP, which actually is a vector optimization technique. In general, MOP is applied in order to solve problems of simultaneous optimization of several objectives, subject to a set of linear constraints. It seeks to identify a set of efficient (or Pareto optimal) solutions in those cases, where optimal solutions cannot be defined due to the number of objectives (Rehman and Romero 1993).

In particular, the efficient set generating technique selected in this paper is the weighting method. According to this technique, feasible solutions are generated through the parametric variation of the weights (w_i) attributed to each criterion (objective). It is worth noting that these weights cannot be interpreted in a general way as measures of the relative importance given from the decision-maker to each of the objectives (Romero and Rehman 2003). For this reason an interactive approach between the decision-maker and the results generated from the MOP approach should be employed. However, the different weighting schemes, apart from generating the efficient set, may also reflect: (a) an alternative policy environment, as well as, (b) the various effects of criteria prioritization on the final resolution.

In MOP, each criterion should be mathematically expressed as an objective function, $f_i(x)$, that is a function of the decision variables (x_j), which is going to be optimized:

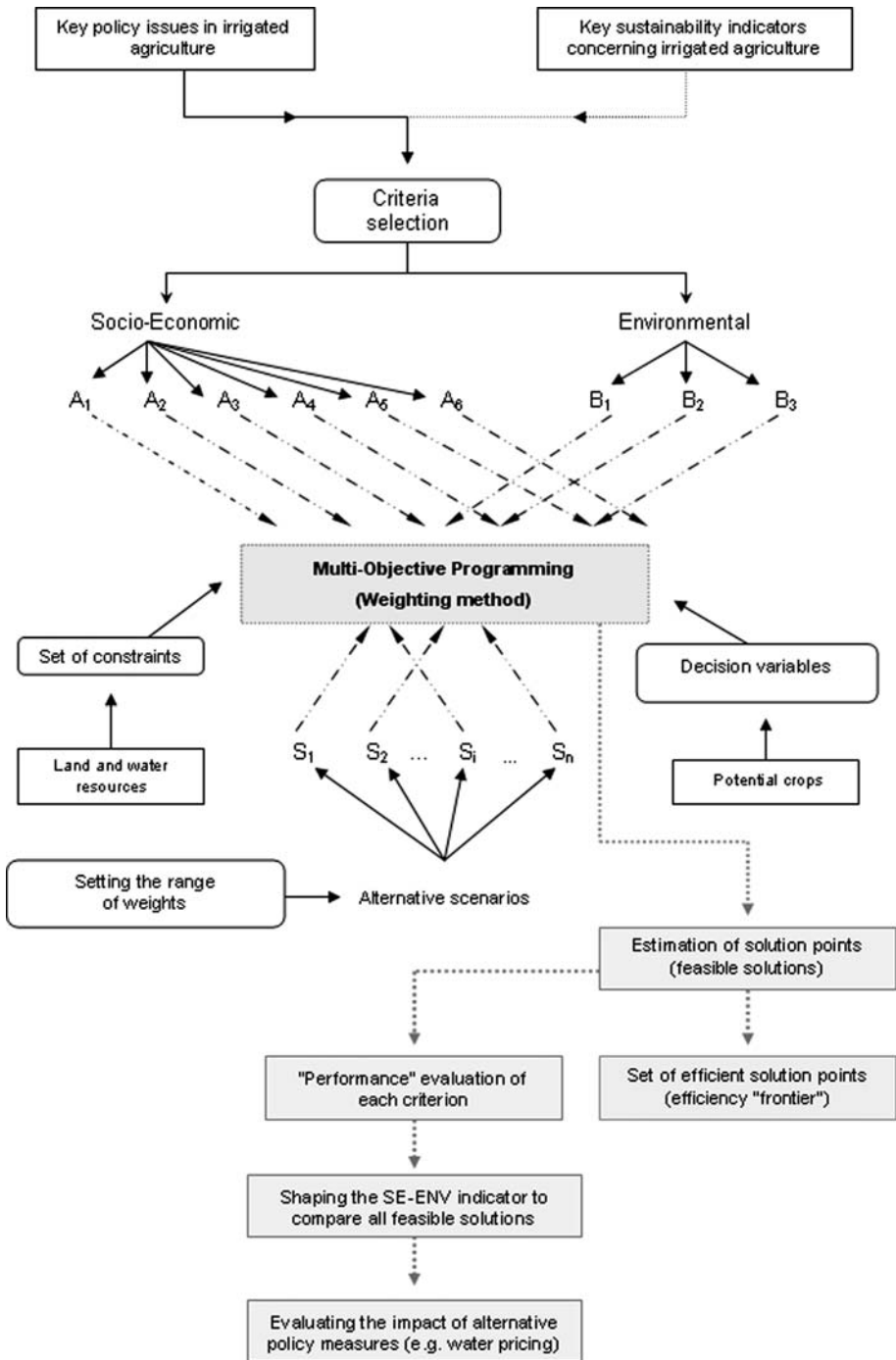


Fig. 1 The conceptual framework

$$\begin{aligned}
 f_1 &= \text{Max (or Min)} \ a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n \\
 f_2 &= \text{Max (or Min)} \ a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n \\
 &\dots \quad \dots \quad \dots \quad \dots \quad \dots \\
 f_k &= \text{Max (or Min)} \ a_{k1}x_1 + a_{k2}x_2 + \dots + a_{kn}x_n
 \end{aligned}
 \tag{1}$$

where, k is the total number of sustainability criteria introduced into the model, n is the number of decision variables and a_{ij} are the coefficients of the decision variables.

Once the objective functions are selected, the following system (i.e., the mathematical expression of the weighting method) can be solved for various sets of weights, w_i :

$$\begin{aligned}
 \text{Maximize:} \quad & \sum_{j=1}^k w_j f_j \\
 \text{subject to:} \quad & \mathbf{z}\mathbf{x} \leq \geq \mathbf{C} \\
 & w_i \geq 0
 \end{aligned}
 \tag{2}$$

In the above formulation a number of constraints has been included. The set of these constraints is described through the $(q \times n)$ matrix z , whereas \mathbf{C} is the vector of upper or lower limits of the constraints:

$$\begin{aligned}
 z_{11}x_1 + z_{12}x_2 + \dots + z_{1n}x_n &\leq \geq \mathbf{C}_1 \\
 z_{21}x_1 + z_{22}x_2 + \dots + z_{2n}x_n &\leq \geq \mathbf{C}_2 \\
 \dots \quad \dots \quad \dots \quad \dots \quad \dots & \\
 z_{q1}x_1 + z_{q2}x_2 + \dots + z_{qn}x_n &\leq \geq \mathbf{C}_q
 \end{aligned}
 \tag{3}$$

2.3 Performance evaluation indicators

The results of multi-objective programming, as derived from the parametric set of weights, can be further examined in order to assess the environmental and economic effect of each solution. To this aim, all objective functions at the solution points are scaled according to the following performance indicator (M_i):

$$M_i = \frac{g_i(x) - f_{i*}}{f_i^* - f_{i*}}
 \tag{4}$$

where f_i^* is the ideal value of objective i , f_{i*} is the nadir value of objective i and $g_i(x)$ is the corresponding current value of the objective function $f_i(x)$. The resulting values of the indicator M_i range from 0 to 1 (as $f_{i*} \leq g_i(x) \leq f_i^*$). Objectives that are close to 0 are far from a satisfactory level of achievement, while objectives that come close to 1 are completely attained (Latinopoulos and Mylopoulos 2006).

Next, all performance indicators are grouped according to the policy orientation of each criterion and two new indices are created: a socio-economic (SE) and an environmental (ENV) one. The value of the SE index (\bar{M}_A) is estimated as the average value of the M_i indicators for those criteria (i) that can be characterized as socio-economic ones:

$$\bar{M}_A = \text{SE index} = \sum_i^r M_i \quad (5)$$

where r is the number of the socio-economic criteria.

Similarly, the value of the ENV index (\bar{M}_B) is estimated as the average value of the M_i indicators for those criteria (i) that can be characterized as environmental ones:

$$\bar{M}_B = \text{ENV index} = \sum_i^p M_i \quad (6)$$

where p is the number of the environmental criteria.

Thus, all the (feasible) solution points can be described and assessed by means of a vector (\bar{M}_A, \bar{M}_B) displaying the total performance in both policy directions. Within this framework it will be also possible to evaluate the performance of: (a) the current resource allocation and (b) of various policy measures (e.g., water pricing), under the condition that the impact of these measures can be previously simulated in terms of the same decision variables (or directly in terms of the selected criteria).

3 Application in the study area

3.1 Description of the study area

MCDM in irrigated agriculture should be applied in areas that are large enough in order to contain a significant number of farmers practicing agriculture, but not as large as to introduce important sources of variation (Berbel and Rodriguez-Ocana 1998). Besides, according to Massarutto (2003), the sustainable use of water is better to be assessed on a local scale, where all relevant environmental functions should be preserved and the consumption of water should be kept below the level of natural recharge.

On this account, three homogeneous, concerning their cropping patterns, irrigated areas (namely the regions of Malgara, Alexandria and Stavros) are selected in Loudias River basin, which is located in Northern Greece (Fig. 2). Within these regions a collective network supplies irrigation water to 47,000 hectares of farmland, with an average annual water consumption of 6,530 m³/ha. The water administration of the broader area is assigned to a General Land Reclamation Board, which is responsible for the water management in 206,600 hectares. This central authority is subdivided into several Local Land Reclamation Boards, of which 21 operate in the study area. The principal activity of these local Boards is the operation and maintenance of the collective irrigation network.

Agriculture is the main economic activity in the study area and, apparently, holds a significant share in the local gross domestic product. Moreover, agriculture is the main water consumer and an extensive source of water pollution, due to the intensive use of agrochemicals. Taking also into account that the estuaries of Loudias River are part of a protected wetland with highly significant ecological value, a remarkable trade-off between the socio-economic contribution of irrigation to the rural society and the implied environmental burden is more than apparent. This trade-off constitutes the origin of the MCDM problem that is examined in the present paper.

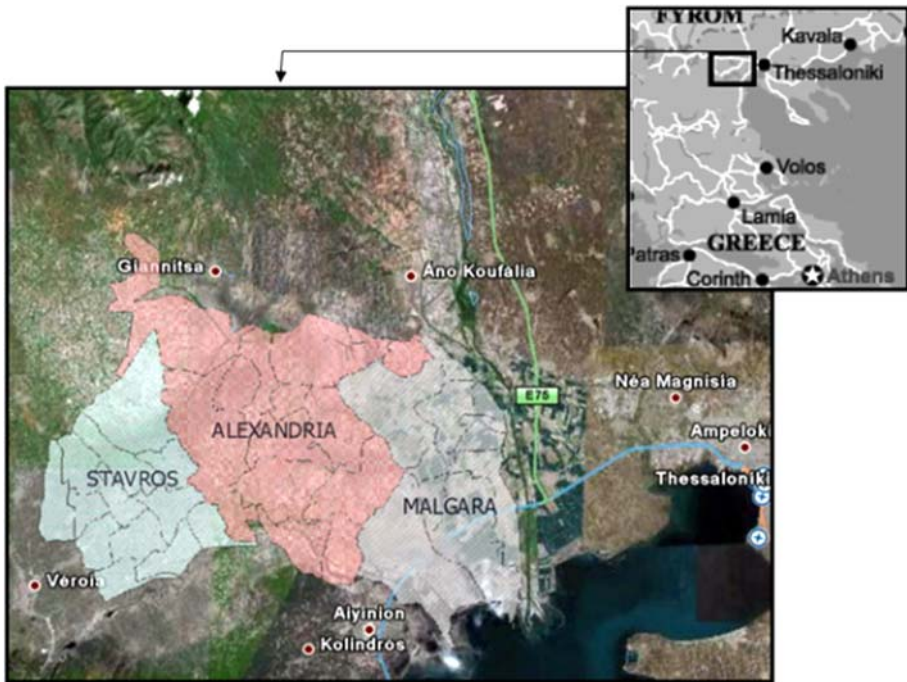


Fig. 2 Study area

3.2 Sustainability criteria and objectives

According to Tiwari et al. (1999) defining sustainability criteria in operational terms is the first step towards integrating all the environmental and economic concerns into a multicriteria analysis. Therefore, the first step of this analysis is to define a set of criteria that incorporates all key policy issues in irrigated agriculture. Although there is a need to formulate an integrated and complex model, it is also prudent to be very selective regarding the number of criteria modelled, in order to exclude those that are closely related to others. On these grounds, and having also in mind the main characteristics of irrigated agriculture in the study area, nine sustainability criteria are included in the MCDM model, through six socio-economic (S_i 's) and three environmental (E_i 's) objective functions. An overview of these objective functions is presented in Table 1.

The first objective of the MOP model is the maximization of farmers' income, approximated by means of the gross margin function. Gross margin is defined as the total income minus the variable costs of production and is expressed as a monetary variable per unit area.

The next objective refers to securing human labour in the primary sector. Human labour is estimated as the sum of all farming activities in each reference area and is expressed in terms of labour time per unit area. It should be mentioned that the direction of optimization (i.e., maximization) is opposed to farmers' MCDM, where human labour time is usually minimized. The reason is that, in regional policy-making, keeping the workforce intact is a

Table 1 Decision criteria in the multi-objective analysis

| | | Criteria—objective functions |
|-------------------------|----------------|--|
| Socio-economic criteria | S ₁ | Maximization of farmers' income (gross margin) |
| | S ₂ | Securing of human labour on the primary sector |
| | S ₃ | Minimization of risk on farmer's income |
| | S ₄ | Maximization of total labour efficiency (crop output per unit of labour input) |
| | S ₅ | Maintaining the current cropping patterns (minimum investment costs on new perennial crops) |
| | S ₆ | Safeguarding the current revenues of water agencies |
| Environmental criteria | E ₁ | Limitation of irrigation water consumption according to the water availability in the reference area |
| | E ₂ | Limitation of fertilizer (nitrogen) use according to the legislation of European Union |
| | E ₃ | Maximization of irrigation water use efficiency (economic output of production per volume of water consumed) |

prerequisite for the social coherence and the economic development of rural areas (Latinopoulos 2006).

Temporal variations in crop yields and prices induce uncertainty to farmers' income. On this account, the third objective of the model is the minimization of risk on farmers' income. Farmers' risk is estimated by means of the negative semi-variances of gross margin and is expressed in terms of a monetary variable per unit area (Romero 2000).

The next objective targets at maximizing labour efficiency. To formulate this objective, a function of economic output per unit of total labour input is utilized. In order to express the economic output as a parameter that is independent of labour requirements (i.e., to not include labour cost), the gross product function was chosen as the numerator of this objective function.

The fifth objective aims at maintaining the current cropping patterns in order to avoid: (a) investment costs in new perennial crops and (b) additional expenditure for the eradication of existing perennial crops. In practice, the second component is difficult to be calculated, as it is data-demanding. Hence, the applied function minimizes only the investment cost of new crops.

In the framework of MCDM in irrigated agriculture it is also necessary to take under consideration the economic viability of those agencies that are responsible for the operation and maintenance of reclamation works. The objective is, thus, to safeguard (i.e., maximize under specific constraints) the current revenues of the water agencies, namely the Local Land Reclamation Boards.

Concerning the environmental criteria (objectives) selected in this model, special attention was paid in securing water availability. For this reason, the total water consumption by irrigated agriculture must be specified according to the water balance of the reference area (i.e., the river basin) and the demand for other competitive water uses. Consequently, the selected objective function minimizes the total water requirements (expressed in terms of water volumes per unit of irrigated area), according to the regional water resources constraints.

Water quality control is also included in the MOP model, by considering the potential water pollution due to the excessive use of fertilizers. On this account, the objective is to

limit (minimize) the total fertilizer consumption per unit of agricultural area, according to the standards imposed by the legislation of the European Union.

Finally, the last objective, included in the MOP model, concerns the maximization of the efficiency of irrigation water use. Water use efficiency is estimated as the economic output of a cultivated area divided by the total crop-water requirements in the corresponding area. Economic output is again approximated by means of the gross product function so as to avoid the usage of the cost of irrigation water.

3.3 Selecting decision variables and model constraints

The decision variables of the MOP, x_j , represent the hectares covered by the j -th crop (land resources allocation) in each reference area. Water consumption (water resources allocation) enters the model indirectly, by means of: (a) water requirements of various crops, and (b) deficit irrigation to high water consuming crops. Specifically, the main types of crops, used as decision variables in the multicriteria model, are as follows.

1. Current cultivated (irrigated and non-irrigated) crops.
2. Potential dry-farming crops.
3. Current crops with variable level of irrigation water consumption - deficit irrigation (parameterization of water consumption from 70% to 100% of water requirements for maximum crop productivity).
4. Crops under organic farming.
5. New perennial crops with significant investment costs.

The set of constraints that complements the multi-objective weighting method can be classified into the following seven categories.

1. Total cultivation area constraints.
2. Agricultural policy and CAP constraints (e.g., constraints concerning historical quotas as well as the minimum area for the set aside activity).
3. Market constraints (upper or lower limits are set to ensure the well functioning of the marketing channels and the supply of local processing industry).
4. Rotational constraints (upper limits to all crops, except of tree cultivations, in order to alternate the cultivation of all plots).
5. Constraints on total water consumption in irrigated agriculture during the critical (summer) months.
6. Maximum and minimum levels of water applied in each irrigated crop, during the year.
7. Special environmental constraints (e.g., cropping patterns in protected wetland areas).

3.4 Solution of the multi-objective programming model

The number of alternative linear programming problems that the weighting method should solve is equal to m^{k-1} ; m being the number of values given to the weights and k the number of the model objectives. Taking, thus, into account the number of the selected criteria (nine, as shown in Table 1), it was almost impossible to use a large number of different weighting factors. Hence, five weight values, at the [0.05–0.30] interval, were used for the

parameterization of the range of weights, under the condition that they satisfy the following constraint.

$$\sum_i w_i = 1 \quad (7)$$

The number of decision variables in each reference area varies from 56 (in Malgara region) up to 74 (in Alexandria region), depending on local cropping patterns and agricultural characteristics. Similarly, the number of constraints also fluctuates between 36 (in Malgara region) and 47 (in Alexandria region), depending on climate, market conditions and current policy restrictions. Therefore, in order to facilitate the implementation of the above-mentioned methodology, a computer software program, called MOPEN was used. This software program, developed by Caballero et al. (2005), is specially designed as a tool for solving linear multi-objective and goal programming problems of moderate size.

4 Results and discussion

4.1 Establishing an efficiency frontier in decision-making

The final outcome from the application of the precedent analytical procedure is the estimation of the two-dimensional performance indicator (SE-ENV) for all feasible solution points of the weighting technique. All resulted indicators, for each reference area, can be diagrammatically represented in order to locate a set of efficient solutions (efficiency frontier). This set is a number of solutions for which it is impossible to improve the total performance of the environmental objectives (ENV index) without worsening the total performance of the socio-economic ones (SE index) and vice-versa. Figure 3 illustrates the results of the weighting method and the efficiency frontier for all 3 reference areas, according to the SE-ENV classification system. In addition, the aggregate performance of the current resource allocation (current situation) is also depicted on these scatter-diagrams in order to be compared with the efficient solutions.

From the analysis of Fig. 3 it can be concluded that alternative allocations of land and water resources may generate significant modifications in irrigated agriculture. It should be also noted that, despite the distinct differences in the range and the dispersion of the feasible solutions among the three regions, their efficiency frontiers show a remarkable resemblance. A possible explanation for this is the fact that all areas are part of a river basin with common environmental constraints and similar socio-economic characteristics.

One further point, worth mentioning, is that, according to the results of the model, current decisions in irrigated agriculture turned out to be exclusively oriented towards the socio-economic objectives. Consequently, there are several possible allocation schemes that can be applied in order to improve the performance of environmental indicators and achieve a more sustainable use of natural resources. However, the transition to environmentally friendly allocations (i.e., solution points on the right of the current situation point) seems to be always at the expense of farmers' prosperity. Hence, the final outcome of some socio-economic objectives should be "sacrificed" in order to attain a well-balanced solution between the two policy directions.

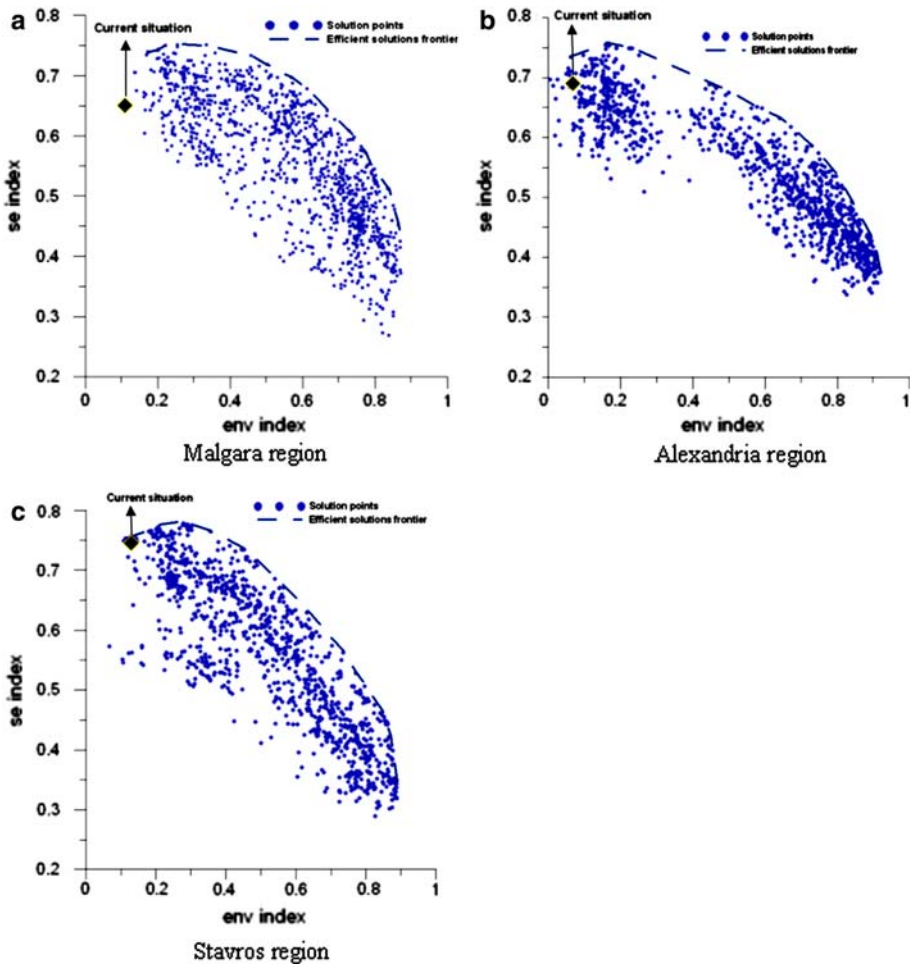


Fig. 3 Efficient solutions frontier in the reference areas

4.2 Evaluation of water pricing policies

Once the efficient allocations of land and water resources are estimated, a further step is to select the right policy measures, aiming to come as close as possible to the solution that satisfies the decision-maker (policy-maker). Therefore, the effect of several different agricultural or water policy measures could be assessed within the framework of the aforementioned efficiency frontier.

In this paper, the implications of varying water prices are evaluated for a reasonable range of water charges (from zero pricing to charges equal to 0.20 €/m³). For this purpose, another MCDM model was implemented—this time at a farm level—in order to simulate agricultural decisions for various water pricing scenarios (Latinopoulos 2006). The Multi-Attribute Utility Theory model that was used aimed at specifying

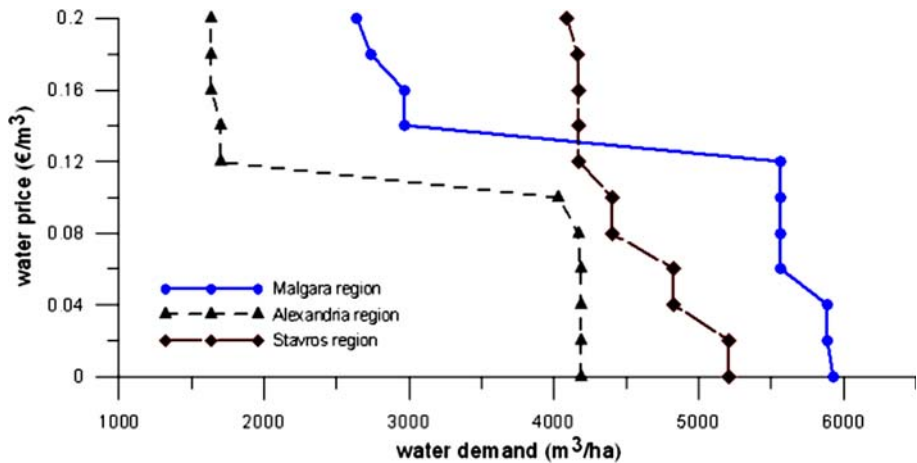


Fig. 4 Water demand curves in the reference areas

farmers' utility functions in all reference areas. The maximization of these functions for different water pricing scenarios results to the corresponding optimal allocation of crop and water resources and, consequently, to the derivation of irrigation water demand curves (Fig. 4).

The optimal, according to farmers, allocation of water and land resources in each pricing scenario is further used to estimate the values of the nine objective functions in all three reference areas. The performance indicators, based on these values, are then calculated, introduced in the SE-ENV frontier and finally compared with the counterpart indicators derived from the former procedure. The final outcome is illustrated in Fig. 5. As shown in this figure, higher water prices cause a shift of solution points towards the environmental friendly resource allocations. However, in most cases, this positive effect comes usually along with a downgrading in the levels of socio-economic objectives, and especially in terms of total labour and farmers' income.

Concerning now the spatial implications of irrigation water pricing, it should be pointed out that there are notable differences among the three regions. Specifically, different water charges induce a significant variability of the two-dimensional performance indicator (SE-ENV) in Malgara and Alexandria regions, while in Stavros region only minor changes occur. This outcome can be partly attributed to regional dissimilarities in the price elasticity of irrigation water demand (see Fig. 4). In fact, higher price elasticity entails greater sensitivity of resource allocation to water charges (farmers respond to higher prices by modifying their cropping patterns and choosing less water intensive crops) and, therefore, a larger divergence of the solution points. On the other hand, lower elasticity (e.g., in Stavros region) entails similar resource allocations in various pricing scenarios, where the only varying objective functions are the objective functions of: (a) farmers' income, which diminishes due to higher water charges, and (b) agency's revenues, which are increasing at higher charges. Finally, as shown in Fig. 5, the pricing scenarios that appear to be the most efficient ones (in the sense that their solution point is closer to the efficiency frontier) are the most extreme ones: prices lower than 0.04 €/m^3 maximize the socio-economic objectives, while prices higher than 0.14 €/m^3 maximize the environmental ones.

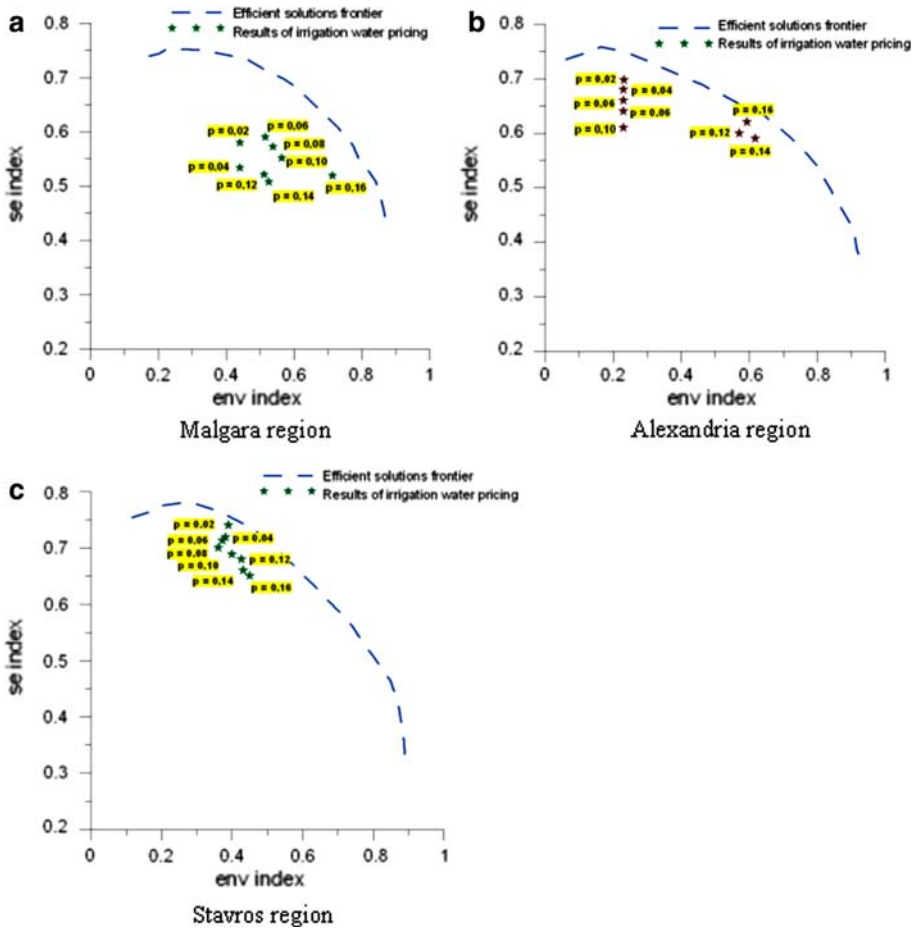


Fig. 5 Water pricing policies assessment at the SE-ENV frontier

5 Conclusions

Decision-making in irrigated agriculture is a complex procedure that should take into account the different and sometimes conflicted objectives of various stakeholders. In addition, any policy-making should be based on the concepts of sustainability, considering all the potential economic, social and environmental implications of the proposed measures. Consequently, it is quite meaningful that all future measures should be assessed according to a common framework, which will incorporate a set of key policy issues (criteria) concerning irrigated agriculture, taking also note of the main characteristics of the reference area.

This paper provides an analytical framework for incorporating environmental and socio-economic concerns into agricultural and water resources management decision-making. Multi-objective programming is implemented, aiming to depict all feasible and efficient resource allocations, as well as various trade-offs between rural development and environmental protection. The outcome of this process may assist the policy-maker to underline

some possible resolutions that will ameliorate the current situation. The main conclusion, derived from this methodology and its implementation at a representative irrigated area in Northern Greece, is that the current policy is profoundly favouring farmers' welfare, usually at the expense of water resources quality and availability. Thus, any future policy should seek for a resource use that would set in balance socio-economic development and environmental conservation.

Furthermore, the analytical multicriteria framework was used together with a MCDM model at the farm level (based on the multi-attribute utility theory), in order to evaluate the potential impact of various water pricing policies at the reference area. According to this analysis, it becomes evident that alternative pricing scenarios result to solution points with significant divergence in terms of economic and environmental efficiency. It is also clear that water pricing efficiency doesn't only depend on the choice of the appropriate charge but also on the elasticity of water demand. That is, higher elasticity seems: (a) to increase the flexibility of resource allocation and (b) to favor the attainment of environmental objectives.

However, policy-makers should also consider that sustainable resource allocation in irrigated agriculture cannot be accomplished only by charging volumetric prices on irrigation water. On the contrary, in order to attain a higher level of economic and environmental efficiency, pricing mechanisms should be further supplemented by other measures such as: (a) indirect subsidies to low income farmers (to mitigate the negative socio-economic impacts of high charges), or (b) quotas on irrigation water consumption in areas with low elasticity of water demand.

Appendix

Appendix 1. Acronyms

| | |
|------|----------------------------------|
| CAP | Common agricultural policy |
| ENV | Environmental index |
| MCDM | Multi-criteria decision making |
| MOP | Multi-objective goal programming |
| SE | Socio-economic index |

Appendix 2. Mathematical symbols

| | |
|-------------|--|
| a_{ij} | Coefficients of the decision variables of the MOP model |
| C | Vector of upper or lower limits of the MOP model constraints |
| E_i | Environmental objective functions |
| $f_i(x)$ | Objective functions of the MOP model |
| f_i^* | Nadir value of objective i |
| $f_i^{\#}$ | Ideal value of objective i |
| $g_i(x)$ | Current value of the objective function $f_i(x)$ |
| M_i | Performance indicator of objective i |
| \bar{M}_A | Performance indicator of socio-economic indicators |
| \bar{M}_B | Performance indicator of environmental indicators |
| S_i | Socio-economic objective functions |

Appendix 2. continued

| | Criteria—objective functions |
|-------|-------------------------------------|
| w_i | Weight of objective i |
| x_j | Decision variables of the MOP model |
| z | Constraints matrix of the MOP model |

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