Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar
doi: http://dx.doi.org/10.5424/sjar/20110904-011-11

Spanish Journal of Agricultural Research 2011 9(4), 1105-1119
ISSN: 1695-971-X
eISSN: 2171-9292

Combined use of groundwater simulation and multi-criteria analysis within a spatial decision-making framework for optimal allocation of irrigation water

D. Latinopoulos[1], N. Theodossiou[2] and P. Latinopoulos[2]*

[1] *Department of Spatial Planning and Development, Aristotle University of Thessaloniki, Agia Varvara, 59100 Veria, Greece*

[2] *Department of Civil Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece*

Abstract

In arid and semiarid areas in the world, including the Mediterranean region, groundwater has been widely and intensively used for irrigation over the last few decades. Practical as well as economic reasons make its use much more preferable, as compared to surface water, especially to individual farmers. Yet, this rapid and largely uncontrolled expansion in groundwater exploitation, which stimulated the socioeconomic development of numerous rural communities, has produced many negative impacts on aquifer degradation and environmental deterioration. The most common remedy to such problems is the application of specific groundwater management policies that can simultaneously meet socioeconomic and environmental protection goals. In this sense, the paper introduces a methodology for an optimal management of irrigation water, by specifically exploring the socioeconomic and environmental impacts of spatially allocated water conservation measures at the watershed level. The analysis is conducted by developing a multi-criteria decision-making framework, consisting of three distinct models: a hydrogeological, an optimization, and a multi-criteria one, which appraises the results of the other two. The proposed methodology is presented through a case study at a rural Greek watershed, in which groundwater is the sole water source for an intensively practiced agriculture. A system of water use quotas is the resource conservation policy instrument that is examined under a decision-making approach. Results show that some specifically designed and spatially non-uniform quota allocation schemes can meet in an optimum way the relevant criteria.

Additional key words: crop-water functions; sustainable irrigation water management; water quotas; watershed model; weighted summation.

Resumen

Uso combinado de análisis multicriterio y simulación de aguas subterráneas dentro de un marco espacial de toma de decisiones para la asignación óptima del agua de riego

Las aguas subterráneas se han usado intensivamente en las regiones áridas y semiáridas del planeta, incluyendo el Mediterráneo. Hay razones económicas y prácticas que las hacen preferibles a las aguas superficiales, especialmente para agricultores individuales. Sin embargo esto ha conducido a una expansión incontrolada del uso de aguas subterráneas que ha estimulado el desarrollo de muchas comunidades rurales, pero que ha producido impactos negativos como degradación en acuíferos y deterioro ambiental. El remedio más común para estos problemas es la aplicación de políticas de gestión de aguas subterráneas que busque satisfacer simultáneamente los objetivos ambientales y socioeconómicos. Este trabajo introduce una metodología explorando los impactos ambientales y socioeconómicos de una asignación de recursos a nivel de acuífero. El análisis se hace desarrollando un esquema multicriterio consistente en tres modelos: hidrogeológico, optimización, y función multicriterio, que evalúa los resultados de los otros dos. La propuesta se aplica a un estudio del caso de un acuífero rural en Grecia, en el cual el agua subterránea es el único recurso disponible para una agricultura intensiva. El instrumento utilizado para la política de conservación es la asignación de cuotas. Los resultados muestran que unas cuotas diseñadas específicamente y repartidas espacialmente de manera no-uniforme pueden servir para alcanzar los objetivos diseñados.

Palabras clave adicionales: cuotas de riego; funciones de producción de cultivo/agua; gestión sostenible de riego; modelo de acuífero; suma ponderada.

*Corresponding author: latin@civil.auth.gr
Received: 10-01-11. Accepted: 28-06-11.

Introduction

In the Mediterranean region, as in most other arid and semiarid areas in the world, groundwater has been widely and intensively used in a, notably expanding during the recent decades, irrigated agriculture (Llamas and Martínez-Santos, 2005). The principal reasons for its apparent precedence in users' preferences, particularly the individual ones (farmers), against surface water are its easier accessibility, its higher supply reliability and its lesser vulnerability to droughts. From the economic point of view, groundwater irrigation is again a preferred option of almost any single farmer as, in the absence of other financial obligations, abstraction costs are most of the times just a small fraction of the irrigation crops values. Even at the level of collective irrigation, the social – as related to jobs involved – and the economic – as related to profits gained – value, per unit volume of groundwater pumped and used, generally exceeds that of surface water irrigation systems (Garrido *et al.,* 2006).

The above mentioned rapid and largely uncontrolled expansion in groundwater exploitation stimulated the development of rural communities, by generating major social and economic benefits, on one hand, but on the other hand it caused serious adverse problems (Foster and Chilton, 2003). These negative effects result mainly from high water abstraction rates and proliferation of wells over time and include serious impacts on aquifer degradation and/or environmental quality. At the institutional level, *e.g.* in the European Union, a similar distortion can be also observed, as irrigated agriculture is directly influenced by two conflicting major policies, the Common Agricultural Policy (CAP) and the Water Framework Directive (WFD), which largely determine the demand for and the supply of water to agriculture, respectively. Therefore, a careful and complex analysis is always needed to identify managerial solutions that can meet both socio-economic goals (farmers' income and labour demand) and environmental protection (water-use efficiency) (Gómez-Limón *et al.,* 2002). Due to the particularities of the problem, the preferred approach in such analyses is a bottom-up one (*i.e.* from the farm level to the watershed one).

The river-basin or watershed has been acknowledged in many studies to be the most appropriate unit of analysis for water resources management problems (McKinney *et al.,* 1999). Likewise, water management at the watershed level has become a central tenet of current water policies, under the prevailing concept of integrated water resources management. This concept is a core issue in the European WFD, with all country-members striving nowadays to implement their water management policies at the basin level. Still, practising watershed management is a very broad and, at the same time, complex task and, therefore, various types of models should be tried to study efficiently and in an integrated way the major physical, socioeconomic, and political aspects of watersheds (Mirchi *et al.,* 2010). On some occasions, in which several stakeholders are involved in conflictive water management settings, as it is often the case in irrigated agriculture, effective managerial decisions are sought through the application of specific instruments of analysis, like those based on multi-criteria methodologies (*e.g.* Billib *et al.,* 2009) or participatory modelling ones (*e.g.* Martínez-Santos *et al.,* 2010).

The present paper contributes to the issue of optimal allocation of irrigation water by specifically exploring the environmental and socioeconomic impacts of spatially allocated water conservation measures at the basin level. To conduct this analysis, a decision-making framework, based upon a multi-criteria model, has been developed. As the main conservation policy examined is an economic one (*i.e.* a water use quota), the study adds also to the rapidly expanding scientific area of irrigation water economics (Arcas *et al.,* 2010), by focusing on groundwater management, a recently recognized important and interesting area for the application of the tools of economic theory and econometrics (Koundouri, 2004). Indeed, relevant current research is steadily looking, in a very detailed way, at various economic consequences that groundwater conservation policy options produce, either upon the individuals or the society as a whole, and at multiple spatial scales (Blanco-Gutiérrez *et al.,* 2011).

Multi-criteria decision making (MCDM) assists a decision maker to choose the best alternative from a set of several possible ones, within an environment of conflicting and competing criteria. Consequently, a wide range of intricate economic problems can be solved by using suitable MCDM methods (Ballestero and Romero, 1998). Furthermore, these techniques can be implemented to tackle various agricultural management problems (Romero and Rehman, 2003), among

Abbreviations used: CAP (common agricultural policy); GMS (groundwater modeling system); GNP (gross national product); MCDM (multi-criteria decision making); SLP (successive linear programming); WFD (water framework directive).

which ones specifically related to irrigated agriculture, like these concerning the impact of water restriction policies (Recio *et al.,* 2005, 2010), the efficient allocation of water (D. Latinopoulos, 2009) etc. The general conceptual framework presented in the paper comprises three distinct sub models: a groundwater simulation model, an optimization model, and a multi-criteria model, which appraises the results of the other two.

The proposed methodology is described and presented within the context of the case study, which refers to a typical watershed in a rural area of Greece. As in most Mediterranean countries, agriculture is a significant sector in the country's economy: the contribution of the agricultural sector to Greek GNP is one of the highest in all OECD countries, while about 17% of the active population makes its living from agriculture. Private initiatives, but mostly a strong political commitment to increase agricultural production and farmers' income, have resulted to a substantial expansion of cultivated land under irrigation during the last 30 years. Today irrigated farming accounts for more than 80% of the nation's total water consumption, half of which often comes more or less from major surface water bodies, while the rest is pumped from numerous groundwater sources (P. Latinopoulos, 2005).

Despite the rather moderate percentage of groundwater use throughout the country, the underground water reserves are in most places either the primary or the sole water source for irrigated agriculture. To conserve as much as possible of this valuable resource in the study area, the application of a standard instrument for irrigation water management is examined. This is a system of water use quotas, which is likely the most widely employed regulatory instrument in similar cases (Koundouri, 2004). The multi-criteria approach that is implemented enables the identification of the best alternatives in practicing this policy instrument by taking into account realistic conflicting and competing criteria, like economic, social and environmental type ones, while, at the same time, putting a particular emphasis upon the spatial allocation of quotas.

Material and methods

Overview of the case study

The proposed methodology is demonstrated through its application on the watershed of the municipality of Nea Moudania, located in Northern Greece, about 50 km southeast of the town of Thessaloniki and on the western part of the Chalkidiki "three-leg" peninsula (Figure 1). This water basin, which drains directly to the northern part of Aegean Sea, is considered a typical Mediterranean one, due to its particular location characteristics, like the subtropical climate, as well as to specific features of water use, like the dominant role of irrigated agriculture and the notable seasonal variation in the total water demand.

The basic criteria for selecting this particular region, spanning an area of 127 km^2, for the case study are the following: (a) agriculture is the principal economic activity of the majority of the local population, (b) groundwater – the sole exploitable water source in the region – is intensively used for irrigation, which accounts for 90% of the total annual water abstraction, (c) water use for the domestic sector is considered to be substantially competitive to the agricultural one during the summer months, because during recent years the coastal villages have been highly developed as tourist resorts, and (d) as an inevitable outcome of all the former, there is a clear deficit in the region's water balance (P. Latinopoulos, 2003).

The whole extent of the watershed constitutes the higher spatial level of the current analysis. However, in order to examine the effect of spatial heterogeneity in both environmental (*i.e.* regarding water management) and economic decisions, a lower level (LAU-2) was also involved in the analysis: that of the seven municipal districts, which are located within the boundaries of the watershed: Nea Moudania, Agios Panteleimon, Dionysiou, Zografou, Portaria, Simantra and Flogita (Figure 1). In a more general sense, the adoption of such a multi-scale modeling approach has been demonstrated to be more realistic and highly recommended (Blanco-Gutiérrez *et al.,* 2011).

From a geomorphologic point of view the study area can be distinguished into the northern mountainous area, where the water demand for both the agricultural and the domestic uses is limited, and the mainly flat southern area, where the total water demand is much higher, due to the intense agricultural practices and the touristic development of the coastal zone. As far as the geological structure of the area is concerned, the formations are dominated by a large volume of terra rosa with continuous alterations of layers of gravel, sandstone, pebbles and sandy silty clay (Papapetrou and Theodosiou, 2010). The mean value of the main aquifer's permeability coefficient, as calculated from a series of pumping tests, is as large as 9.5 m d^{-1}. Although the aquifer is mainly

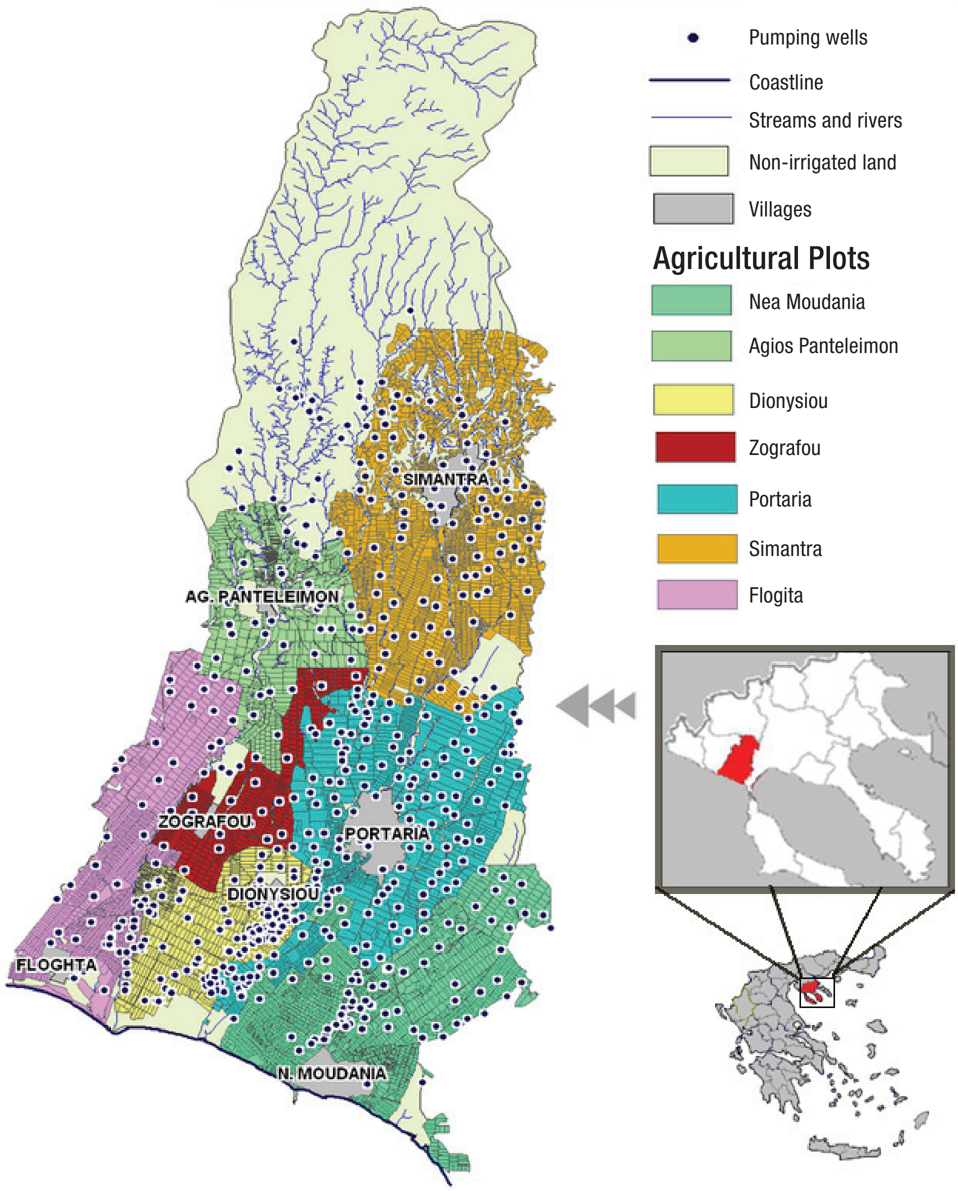

Figure 1. The study area: the watershed of Nea Moudania in Chalkidiki Peninsula.

under pressure, the dense hydrographic network, the numerous wells and some scattered permeable lenses allow a small portion of surface water to infiltrate the aquifer. Finally, the local climate is a typical coastal Mediterranean one, with an average annual rainfall of 417 mm, an average annual temperature of 17^{o}C and a yearly potential evaporation on the order of 700 mm.

The cultivated land in the study area covers a total of 8,700ha, of which about 40% is irrigated. It should be noted that the area has a diverse crop-mix, thus securing both the ecological diversity and the economic stability of small-scale farms. The agro-economic data used in the study were obtained from relevant national databases (National Statistic Service of Greece, 2001) as well as from a questionnaire survey administered in the area (Latinopoulos and Pagidis, 2009). According to these data, 61% of the total agricultural land is devoted to arable cultivations (mainly wheat), 34.3% to trees (mainly olive trees, apricot trees and peanut trees) and 2.7% to horticultural cultivations (tomato, melons, etc.). It is worth noting that the agricultural land in the area consists of about 10,000 smallsize plots, specific characteristics of which have been already collected and studied for various purposes (Mallios *et al.,* 2009). The spatial variation of agricultural water use intensity (*i.e.* the amount of water used in the agricultural sector per hectare of temporary and permanent cropland) throughout the seven municipal districts is illustrated in Table 1.

Current agricultural patterns and practices are highly dependent on irrigation water, leading thus to a severe over-pumping of the aquifer, as all water used in relevant activities derives solely from pumping numerous wells (more than 800 wells in the study area), the majority of which are located in the southern part of the basin (Figure 1) (Latinopoulos *et al.,* 2004). From these wells, of which about 30%-40% are unregistered, farmers are, more or less, free to pump as much groundwater as they desire, because of the very loose mechanisms of controlling the regulatory measures on water abstractions. The only cost related to groundwater withdrawals is that of energy consumption (*i.e.* the cost of electricity required to pump and apply groundwater for irrigation). Therefore, the lack of notable constraints on water use and the current inefficient pricing system seem to be the main reasons for the over-exploitation of the local groundwater reserves. The immediate result of this overuse is a significant deficit in the demand-supply equilibrium in the reference area, coupled with a notable decline in the groundwater levels at an average rate of 0.60 m yr^{-1} (Latinopoulos *et al.,* 2004).

Conceptual framework

General description

The methodology developed and presented in this paper aims at providing a decision-making framework for irrigation water management at the watershed spatial scale. The conceptual framework is illustrated in Figure 2 and described in detail through the rest of this section. As shown in Figure 2, the whole procedure comprises three distinct subsystems (models): (a) the groundwater or hydrogeological model, simulating the aquifer's response to alternative irrigation management scenarios, (b) the optimization model, by which it is examined how farmers seek to maximize their income under specific water constraints and (c) the multi-criteria decision model, through which a social planner can evaluate the socioeconomic impact of the alternative water management scenarios. A modular approach is followed, that is the three models operate independently of each other and the optimization problem is solved in an exogenous way: the input variables from the groundwater into the optimization model, as well as from the optimization into the multi-criteria model, are exogenous.

When linking hydrological and economic models a number of operational and methodological issues and challenges may arise. McKinney *et al.* (1999) underline three important limitations:

— Hydrologic modeling is typically based on simulation techniques, whereas economic models are frequently implemented along with optimization techniques.
— Watersheds, as defined by their physical boundaries, are the typical entities of hydrologic analyses at the spatial level, while economic models refer mostly to administrative spatial boundaries.
— The time-scale adopted in economic analyses is usually a calendar year, which is longer than the time-scale that is used in hydrologic studies (*i.e.* a day, a month or a season).

Regarding the first limitation, it is pertinent to note that optimization and simulation modeling are not al-

Table 1. Water use, irrigated area and main crops in each irrigation zone

Irrigation zone	Water use intensity (m^3 ha^{-1})	Total cropland (ha)	Total irrigated area (ha)	Main irrigated crops
Nea Moudania	2567.2	1317	737	Olive trees
Agios Panteleimon	1124.5	880	225	Olive trees, cotton
Dionysiou	2840.5	728	437	Vegetables, cotton, olive trees
Zografou	1840.1	524	199	Olive trees, vegetables
Portaria	3654.1	1683	1240	Apricot trees
Simantra	1622.1	1570	860	Olive trees
Flogita	1495.5	1023	301	Vegetables, tomatoes, melons

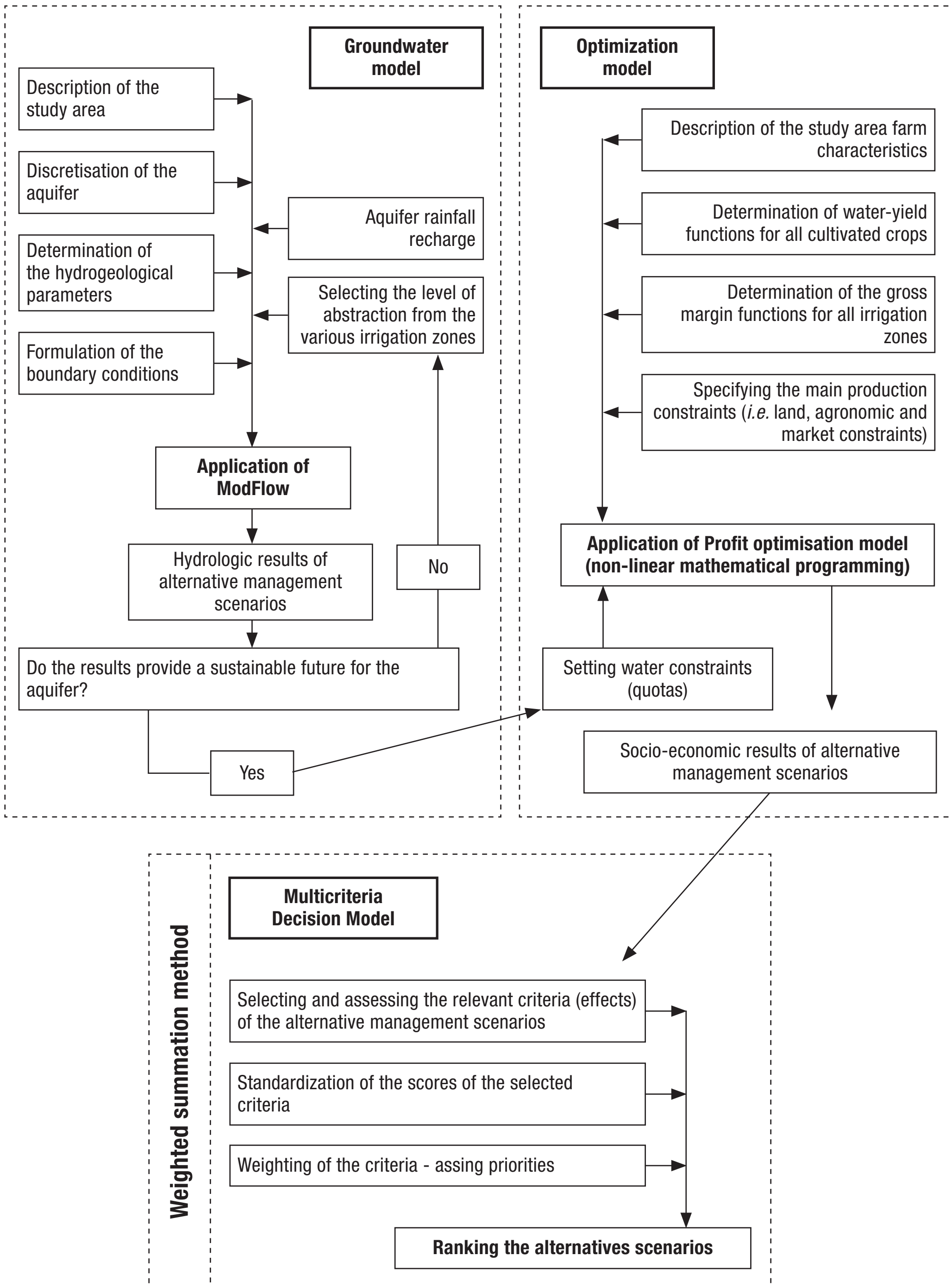

Figure 2. The conceptual framework.

ways mutually exclusive. In contrast, when these techniques are used in a complementary way it is very likely to support the final decision making (Mirchi *et al.,* 2010). There are two different approaches that can be followed in order to achieve this outcome: (a) to simulate the alternatives generated by the optimization process, so as to predict the hydrological impacts (Loucks *et al.,* 2005), and (b) to determine the best socioeconomic alternatives under specific hydrological constraints (Recio *et al.,* 2010). The present work follows the second approach, by using the results of the hydrogeological model as control variables (constraints) for the optimization model. Furthermore, two levels of analysis – at the watershed and at the irrigation zones ones – are jointly adopted in order to confront the spatial problem, while a steady-state analysis is assumed in groundwater modeling, so that it can be compatible with the time-scale of the socioeconomic analysis.

Groundwater model

For the simulation of the aquifer's response to alternative management scenarios the well-known computer-based model MODFLOW was used. MODFLOW is a three-dimensional hydrogeological model, developed by the US Geological Survey (USGS, 2010), which uses a block-centered finite-difference approach for the simulation of steady-state or transient flow in confined or unconfined aquifers. The model, as used in this paper, is incorporated in the Groundwater Modeling System (GMS v6.5), which is a comprehensive modeling environment with GIS-based graphical tools. GMS interfaces with MODFLOW and several other groundwater models, thus providing advanced graphical features for viewing and calibrating model results (AQUAVEO, 2010). According to the structure of the aquifer, as derived from a large number of geological sections (Latinopoulos *et al.,* 2004), its boundaries coincide with the respective ones of the watershed, so that the east and west boundaries of the aquifer can be set as no-flow boundaries in the MODFLOW simulation. The southern boundary of the aquifer was set as a constant head one, describing in this way the seashore condition.

In order to simulate the response of the aquifer to different management scenarios, a number of actions were performed, as shown in the upper left flow-chart of Figure 2. A series of data, related to the formulation of the basic simulation model, such as the description of the study area, the discretization of the aquifer, the determination of the hydrogeological parameters and the formulation of the boundary conditions, were first introduced. Next, the water balance parameters were defined. The recharge was set equal to the sum of: (a) a portion of irrigation water infiltrating the aquifer, estimated as the 10% of the total applied water volume, (b) a fraction of the domestic water consumption resulting to the aquifer through various leaks and of course (c) the portion of the total rainfall that infiltrates the aquifer. The latter was differentiated in the northern mountainous area and the southern flat one, by assigning different values to both the rainfall and the recharge coefficient. On the other hand, and in order to facilitate the application of the management scenarios, the discharge (mainly the abstractions from the numerous pumping wells) was assumed to be uniformly distributed along the extent of every irrigation zone. By successively altering one or more of these total abstraction volumes in the irrigation zones and by implementing the results produced from the relevant applications of MODFLOW, a series of different management scenarios can be formulated and examined.

Figure 3 presents a typical collection of aquifer simulations under some preliminary management scenarios. As indicated in Figure 3(a), which shows the present distribution of groundwater levels, a probable continuation of the current irrigation and water abstraction practices would lead to a serious decline of the water table, especially in the most water-productive southern part of the study area, to an inevitably rapid depletion of the local water reserves and to a much more pronounced than today's seawater intrusion along the coastline. However, the situation is not yet irreversible and this is shown in Figure 3(b). The groundwater contours in this figure indicate the aquifer's response to a hypothetical 20% reduction imposed on the current water abstraction from the whole study area; a definitely much more sustainable situation, as compared with the current one shown in Figure 3(a).

In order to define the optimum reduction in water abstractions from each irrigation zone, which is a major task of the present analysis, the use of a spatially distributed groundwater flow simulation model, like MODFLOW, is an absolute necessity. Further simulation examples, like these shown in Figures 3(c) and 3(d), prove that the reduction of water abstraction from any single irrigation zone not only affects in a positive way the immediately underlying part of the local aquifer, but it can be more or less beneficial to other parts of the whole aquifer.

Optimization model

A non-linear optimization model is next formulated to determine the best allocation of water and land resources for each crop within each irrigation zone (see the upper right flow-chart of Figure 2). The model,

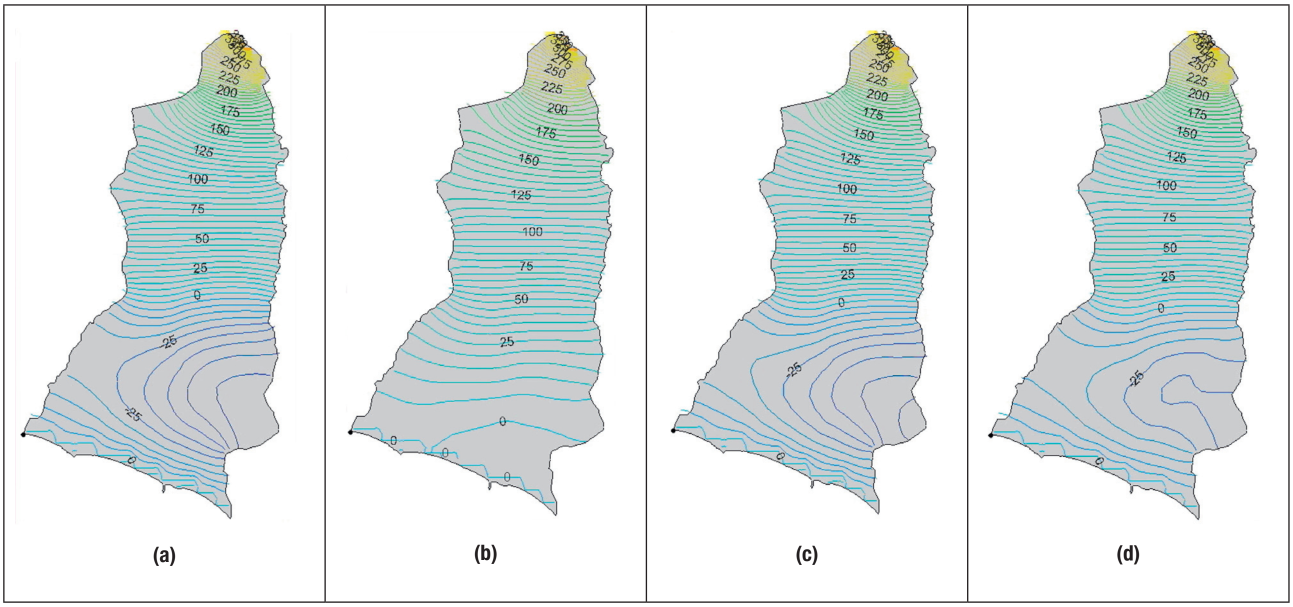

Figure 3. Response of the aquifer in different water abstraction practices: a) continuation of current practice; b) reduction by 20% of the water abstracted from the entire area; c) reduction by 20% of the water abstracted from Simantra; d) reduction by 20% of the water abstracted from Moudania.

which implements the same methodological approach of D. Latinopoulos (2005), consists of three main steps, in each of which it is performed: (a) the analysis of the water effect on the productivity of each crop (*i.e.* the estimation of the water-yield relationship), (b) the derivation of gross margin functions for different types of crops and various irrigation depths, and (c) the final formulation of the optimization model that aims at determining the best allocation of water and land resources in each irrigation zone of the study area.

The main task of the first step of the model is to estimate, for every potential crop, the relationship between yield and irrigation water consumption. General expressions of these functions are recommended by FAO (Doorenbos and Kassam, 1979). However, the FAO yield-response functions were not taken for granted herein but they were adjusted in order to relate water consumption with yield through a concave function (Eq. [1]). Such a function conforms to the shape of the empirical water production function that is commonly used in agriculture (D. Latinopoulos, 2005).

$$Y_{i,j(w)} = -a_{i,j} + b_{1i,j} \cdot w_{i,j} - b_{2i,j} \cdot w_{i,j}^{2} \qquad [1]$$

where $Y_{i,j(w)}$ is the predicted yield of crop i in irrigation zone j, related to the variable level of irrigation water consumption ($w_{i,j}$), and a, b_1, b_2 are coefficients, which are estimated according to local climate, soil and crop characteristics, as well as, to irrigation network efficiency and irrigation scheduling.

In fact, the above coefficients are the result of a linear regression analysis performed on the predicted crop responses for variable levels of water consumption, while the rest of the input data is considered as constant. The predicted crop responses are, in turn, calculated by CROPWAT, a computer program for irrigation planning and management, developed by the Land and Water Development Division of FAO (Smith, 1992).

The second step of the optimization model is to calculate the gross margin functions for each crop and within every irrigation zone. These functions depend on crop yields and, therefore, on water consumption (Eq. [2]).

$$GM_{i,j(w)} = Y_{i,j(w)} \cdot P_i + S_i - TVC_i \qquad [2]$$

where $GM_{i,j}$ is the gross margin function (€ ha^{-1}) for crop i and irrigation zone j, P_i is the commercial price of the product (€ kg^{-1}), including any subsidy per unit of output, S_i is the per-area subsidy (€ ha^{-1}), and TVC_i is the total variable cost, including: the cost of seeds, fertilizers, chemicals, machinery, labour and the electricity/fuel cost of pumping water.

Once the gross margin functions are estimated, the optimization problem can be next formulated as a nonlinear mathematical programming model. The specification of this model relies on the neoclassical rationality hypothesis, stating that farmers maximize their individual profits through the optimal allocation of land (acreages) and water resources, under a set of land, water, agronomic and market constraints. The aim of this analysis is to simulate farmers' behavior at the local territorial level (*i.e.* the irrigation zone), so as to be able to predict their future response to different water supply (quota) scenarios. The objective function, that requires the maximization of the gross margin, is a second-degree function with two control variables: water consumption and cultivated area of each crop (Eq. [3]).

$$Max \sum_{i=1}^{n_j} GM_{i,j(w)} \cdot A_{i,j} \qquad [3]$$

where $A_{i,j}$ is the total cultivated area of crop i in irrigation zone j, and n_j is the number of cultivated crops in the cropping plan of each irrigation zone.

The objective function is subject to a set of agronomic, market and land availability restrictions, which are all considered as endogenous to the irrigation zone spatial level of analysis. On the other hand, water restrictions in each irrigation zone (TW_j) are exogenous constraints, arising from the groundwater model in order to achieve water sustainability at the watershed's area level.

$$\sum_{i=1}^{n_j} A_{i,j} \cdot w_{i,j} \leq TW_j \qquad [4]$$

Successive linear programming (SLP), at the outset of the solution process, is applied to approximate the nonlinear model with a linear one in a small neighborhood of the current point. One of the drawbacks of this method is that it cannot provide a global optimum but only local optima. To cope with this, a trial and error method is carried out for different starting points of the adjustable variables, while a significant number of iterations are also performed (D. Latinopoulos, 2005).

As already mentioned, the water constraints are exogenous and arise from the groundwater model in the form of a regional quota (restrictions on the total volume of groundwater withdrawn from the wells in each irrigation zone). Therefore, the optimization model can act as a response model to the potentially imposed quotas, in order to limit the negative economic impacts on farmers' income. The reasons for selecting this "command and control" policy for groundwater management, instead of applying other economic instruments, also suitable for water conservation, like administering a water pricing policy or creating a water market, besides its wide employability (Koundouri, 2004), is that it can assist in: (a) achieving some moderate objectives of water savings, and (b) avoiding significant economic burden on farmers, as it inflicts lower income losses. Besides, it is a common fact that the elasticity of irrigation water demand in Mediterranean agriculture is very low, requiring thus high water prices (higher income losses) for rather limited water savings. Furthermore, when quotas are applied, water use efficiency is usually increasing and the desired abatement level can be easily reached.

An example of the application of the optimization model is presented in Table 2. This table illustrates the local economic effects of a specific uniform quota applied on irrigation water: a 20% reduction of the water abstracted in each irrigation zone. A general conclusion, which can be drawn from these results, is the significant cost disparity of water savings among the various irrigation zones. Specifically, when the abatement cost is expressed in per hectare income losses, farmers from the south-eastern part of the basin (Portaria and Moudania) seem to pay much more than others for the same

Table 2. Economic effects from a uniform 20% reduction of water consumption (2009 data)

Name of the municipal district	Average income loss (€ ha^{-1})	Total income loss (€)	Average cost of water savings (€ m^{-3})
Nea Moudania	189.9	250,138	0.370
Agios Panteleimon	35.0	30,760	0.155
Dionysiou	187.8	136,790	0.331
Zografou	121.5	63,745	0.330
Portaria	253.2	426,160	0.347
Simantra	96.0	233,920	0.297
Flogita	98.5	100,680	0.329

percentage change (reduction) in water use. A similar but smaller deviation is found when the average cost of water savings is taken under consideration (income losses per cubic meter of water saved). A more detailed image of the "income – water savings" relationship in all irrigation zones is presented in Figure 4.

Multi-criteria decision model

The aim of the specific MCDM is to evaluate the socioeconomic impact of alternative water management scenarios, particularly of those resulting from the application of water restriction policies. In this regard, it is essential to constitute the last step of the analysis, so as to appraise the final results of the two previous models (see the bottom flow-chart of Figure 2). The theoretical framework focuses on the decision making of a social planner, who aims to rank a set of predetermined alternatives concerning the spatial allocation of water use quotas (*i.e.* the upper limits of water abstraction in each irrigation zone), on the basis of some socioeconomic objectives. To this end the "weighted summation" method – a special form of the multi-attribute value theory – is implemented. The concept of this method is to make all attributes comparable, to prioritize them and to aggregate the weighted standardized scores. The final outcome of this procedure can help the decision maker not only to rank the alternatives but also to detect the strengths and weaknesses of each policy (van Herwinjen, 2010).

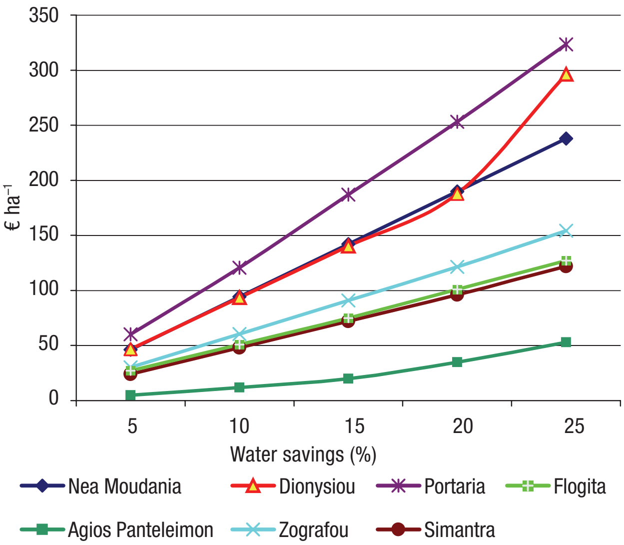

Figure 4. The cost of water savings.

The general multi-criteria analysis process followed in this paper develops into four steps:

— Identification of the irrigation water management (policy) alternatives, which are going to be compared. Different policies, like allocation of water quotas among the irrigation zones, are selected to safeguard the aquifer from a possible future depletion, in a way that their final outcome will be almost identical in terms of the status of groundwater table levels.

— Selection and assessment of the relevant criteria (effects). Four socioeconomic criteria are used to evaluate the alternative policies: a) total cost of implementing the policy options (total farm income losses in the reference area resulting from the proposed water restrictions, € yr^{-1}); b) applicability (qualitative variable indicating the difficulty to apply each policy); c) equity on economic results (variance of income losses among the seven regions of the basin); and d) social effects (labour loss due to crop-mix changes, man-months yr^{-1}). All the aforementioned criteria are assessed through the optimization model.

— Standardization of the scores of the selected criteria and weighting of the criteria. Goal standardization is used, so that all the effect (criteria) scores are linear interpolations between a specified minimum and maximum effect score. Pairwise comparison is also implemented in order to attribute the final weights to the selected criteria.

— Final ranking of the alternative policies.

For the implementation of the above described MCDM process the DEFINITE software package was

Table 3. Alternative water management scenarios

Scenario 1	Uniform allocation of water quotas among the seven irrigation zones – 15% water savings in each zone.
Scenario 2	35% water savings in the northern part of the watershed (Simantra, Agios Panteleimon) and 10% in the rest of the watershed.
Scenario 3	25% water savings in the south-western part of the watershed (Flogita, Zografou, Dionysiou) and 10% in the rest of the watershed.
Scenario 4	20% water savings in the south-eastern part of the watershed (Portaria, Moudania) and 10% in the rest of the watershed.

implemented. This computer program, developed by Janssen and van Herwinjen (2006), is an efficient decision-support toolbox, especially designed to solve a wide range of discrete choice problems, like the one presented herein.

Results and discussion

The final and most significant task of the application of the precedent analytical procedure in the study area is to rank a set of sustainable water management scenarios, on the basis of their socioeconomic impacts. For the selection of the environmentally most sustainable scenarios – *i.e.* the optimum spatial allocation of water quotas – a trial-and-error adjustment was made on the input data of the groundwater model, namely upon the abstraction levels from the irrigation zones. This procedure led to a series of results, where the emphasis was given to the variation of effects produced on the magnitudes and the spatial distribution of groundwater levels. Moreover, these groundwater simulations provided a respective number of comprehensive images of the expected future conditions of the groundwater body. Among the numerous results obtained in this way, four scenarios were finally selected as decision alternatives to the multi-criteria decision problem (Table 3). The rationale of this choice is to develop distinct spatial allocations of water use quotas, which will secure a sustainable future for the aquifer, or in other words will prevent its depletion, at minimum water saving targets. The MODFLOW results produced by the application of these scenarios are presented in Figure 5.

Once the decision alternatives are determined, the next step is to use the local water constraints (water quotas) in order first to solve the optimization model and second to assess the relevant criteria of the specific management scenarios. The performance measures of the selected criteria (*i.e.* total cost, applicability, equity on economic results, social effects) are shown in Table 4.

By assuming equal weights on each criterion, the final ranking of the multi-criteria decision model, as well as the contribution of each criterion on the final ranking are estimated. Figure 6 illustrates the outcome of the multi-criteria analysis (final ranking), while Table 5 depicts the criteria scores for the alternative scenarios. According to these results, the second scenario, that is the one of higher water savings targets imposed in the northern part of the watershed, seems to be the policy that produces the highest score. Uniform allocation (Scenario 1) and greater restrictions in the south-western part of the watershed (Scenario 3) are the subsequent preferred policies. According to this ranking, the worst policy option is the one that focuses on saving water in the most productive irrigation zones (Portaria and Nea

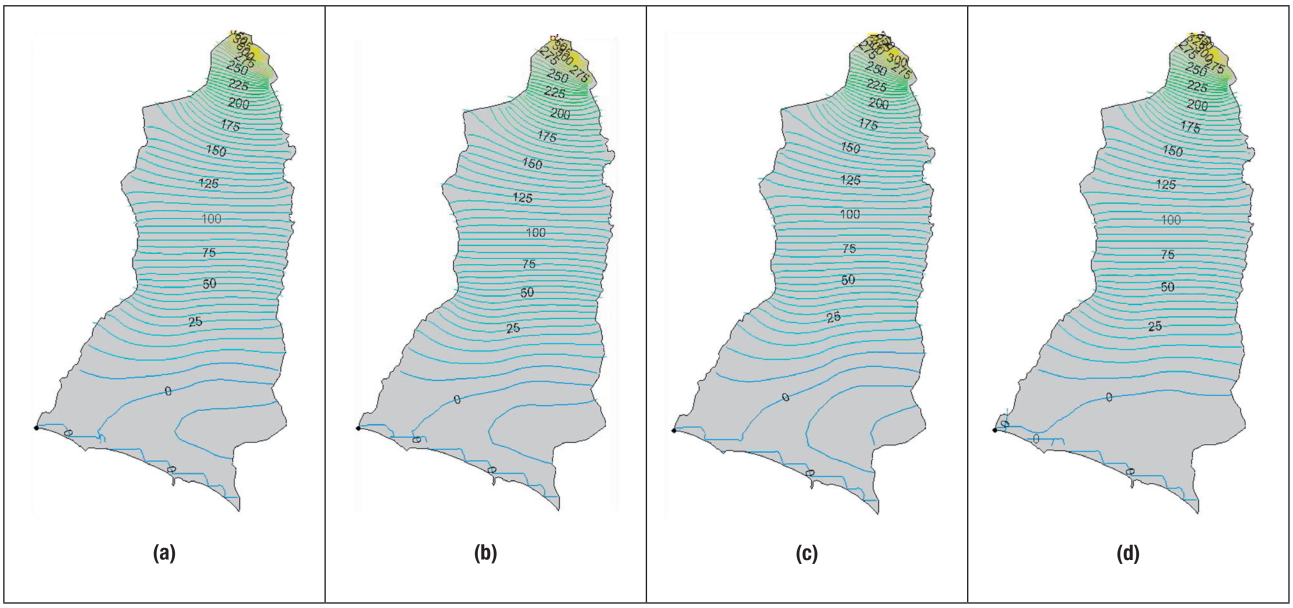

Figure 5. Response of the aquifer to the selected management scenarios: (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4.

Moudania). As shown in Table 5, the main criteria determining the final classification of water management alternatives are "equity" and "total cost". Specifically the former, which refers to an equal spatial distribution of income losses among the seven irrigation zones, contributes largely to the dominance of Scenario 2, as well as to the high ranking place of Scenario 1.

Sensitivity analysis of (multiple criteria) weights may provide a means for examining the extent to which vagueness about decision-maker's preferences makes any difference to the final overall results. Specifically, such an analysis for the weight of the "total cost" criterion, indicates that the condition that safeguards the predominance of Scenario 2 is the following: weight $_{\text{total cost}}$ < 0.32. Above this value Scenario 3 seems as the most favourite alternative. Concerning the "equity" criterion, the corresponding condition is: weight $_{\text{equity}}$ > 0.19. Below this value Scenario 3 is once again the most favourable one. The overall effect of weighting on the final ranking is illustrated in Figure 7. In this figure, extreme priorities are successively assigned in each criterion by setting its (priority) weight equal to the sum of the other three weight values. The resulted water policy classifications show the prevalence of Scenario 2 in most weighting perspectives, with the only exception when giving high priority to the "total cost" criterion. On the other hand, Scenario 4 is always the worst policy option, thus indicating the need to develop an allocation scheme that will "protect" the most productive areas.

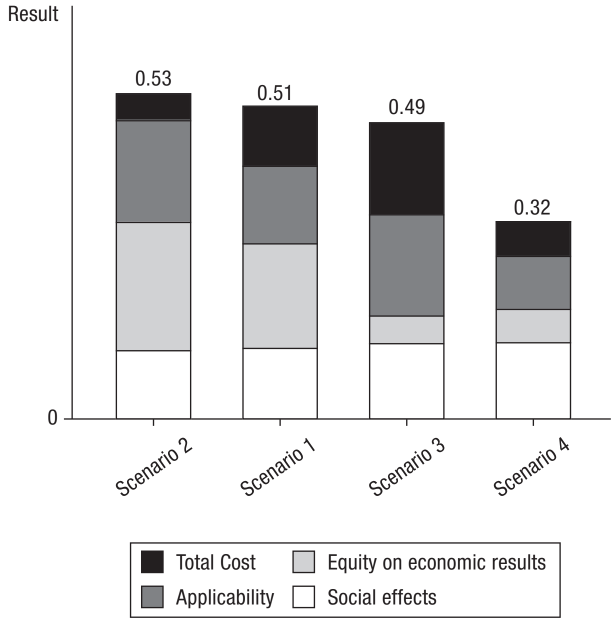

Figure 6. Multi-criteria decision model results: ranking of the alternative scenarios.

Conclusions

Groundwater management, in regions where irrigation is by far the major consumer of local water re-

Table 4. Problem definition matrix

	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total cost[1]	€	919,450	964,204	876,938	953,591
Applicability[2]	---/0	--/-	-	-/0	--
Equity on economic results[3]		3,133.7	1,547.2	8,275.7	7,696.5
Social effects[1]	man-months	718.2	724.1	704.1	702.0

[1] Per year (aggregate values for the study area). [2] Qualitative variable described on a seven point ordinal scale (ranging from "---"= very difficult to "0"=easy). [3] Variance of income losses (expressed in € ha^{-1}) among the seven regions of the basin

Table 5. Total and individual criteria scores for the alternative scenarios

	Total	Total cost	Applicability	Equity on economic results	Social effects
Scenario 1	0.51	0.40	0.50	0.69	0.45
Scenario 2	0.53	0.18	0.67	0.85	0.44
Scenario 3	0.49	0.62	0.67	0.17	0.49
Scenario 4	0.32	0.23	0.33	0.23	0.49

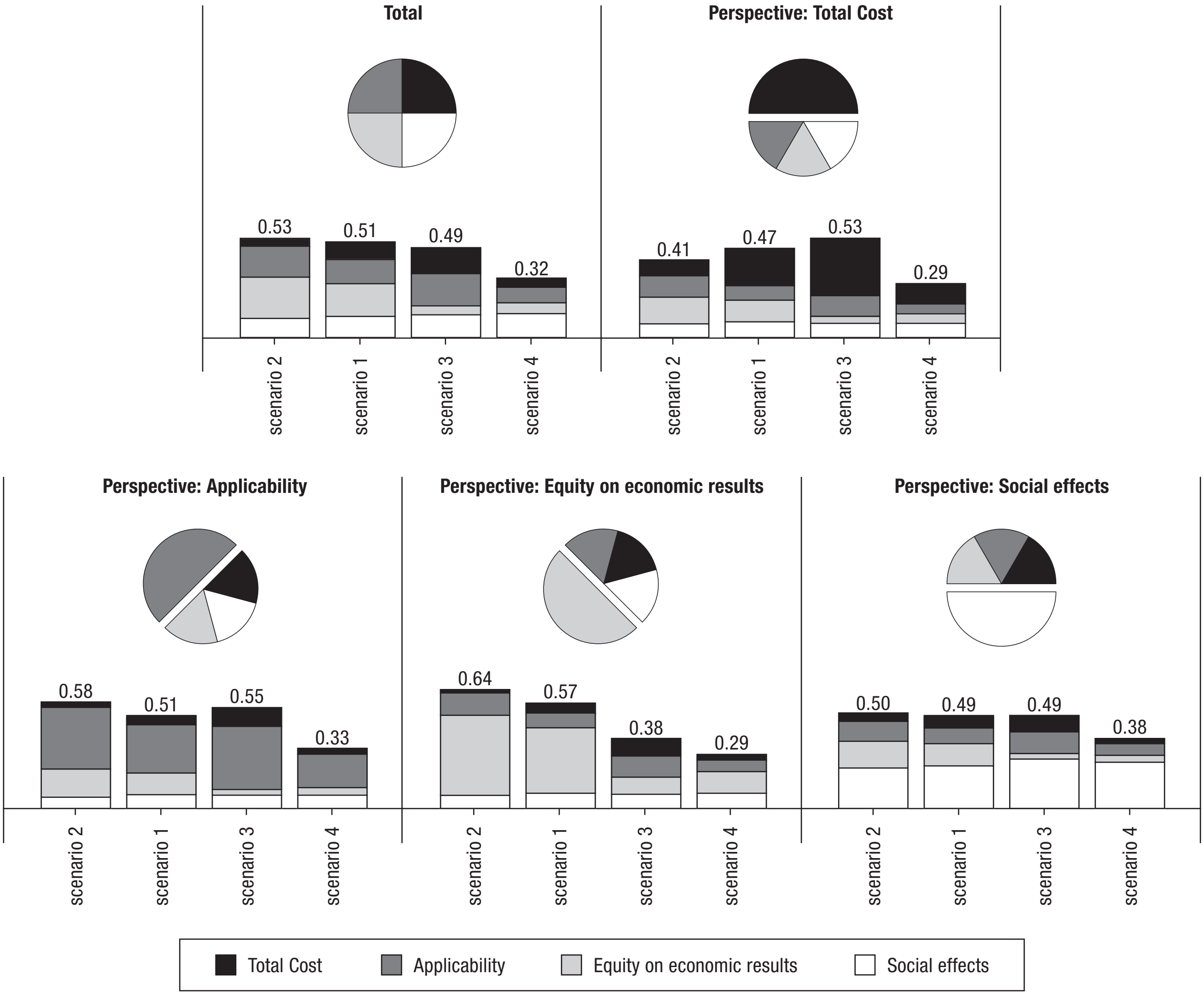

Figure 7. Ranking of the alternative scenarios under various weighting perspectives.

sources, is and will continue to be the focus of intensive research. Experiences from recent investigations indicate that there are still many uncertainties about the potential of various policy instruments for groundwater management, such as water quotas, water pricing and water markets. The main reason for this is that the majority of relevant studies (*i.e.* on the use of economic instruments) are limited to the specific regional conditions. Nevertheless, the added value of each particular investigation lies in its own specific contribution in widening the collection of empirical experiences and in providing new insights.

The methodology developed in this paper attempted to combine environmental targets with socioeconomic criteria along the process of imposing managerial measures on groundwater use. Furthermore, it attempted to formulate a decision-making framework that would be as realistic as possible for the two main stakeholders of the problem: the farmers (by simulating their potential behaviour/reaction towards various scenarios of water supply or policy measures), and the decision maker, *i.e.* the responsible for the region social planner. The application of a MCDM proved to be a useful managerial tool, the output of which provides the principal guidelines, which the social planner should follow in applying sustainable policies in irrigated agriculture. With this multi-criteria-based approach one can examine the efficiency of water-supply options and, in particular, of various systems of water use quotas, that differ from each other as to the spatial allocation of maximum allowable irrigation water consumptions.

Overall, the use of the MCDM brings out the managerial scenarios that optimize the socioeconomic criteria, which have been already selected, weighted and evaluated by the decision maker. The final results of the presented study show that: a) a spatially uniform allocation of quotas is not the optimum solution of the problem; b) by reducing the water consumption in the more productive zones, the preselected environmental targets can be met, yet at high socioeconomic costs; and c) none of the examined management scenarios is a global optimum one; still, there are scenarios, like Scenario 3, that under several weighting criteria combinations seem to be superior to other ones, and which should be in favour in future water management policies.

The main conclusions drawn from this investigation are: (a) Decision making for groundwater management, especially when irrigated agriculture is the major consumer, is a very complex process. (b) Typical water policy alternatives essentially reflect the targets (decision criteria) of the social planner. Yet, the selection, weighting and evaluation of these criteria constitute one of the most significant phases in decision making. To this end, this process should be, at the highest possible degree, a participatory one, meaning that all potential stakeholders should be engaged in its design as well as in its implementation.

References

AQUAVEO, 2010. Groundwater modeling system (GMS) [on line]. Available in http://www.aquaveo.com/gms [20 December, 2010].

ARCAS N., ALCON F., GÓMEZ-LIMÓN J.A., DE MIGUEL M.D., 2010. Review: The evolution of research regarding the economics of irrigation water. Span J Agric Res 8 (S2), S172-S186.

BALLESTERO E., ROMERO C., 1998. Multiple criteria decision-making and its applications to economic problems. Kluwer Acad Publ, Boston, USA. 168 pp.

BILLIB M., BARDOWICKS K., ARUMÍ J.L., 2009. Integrated water resources management for sustainable irrigation at the basin scale. Chil J Agr Res 69 (Suppl. 1), 69-80.

BLANCO-GUTIÉRREZ I., VARELA-ORTEGA C., FLICHMAN G., 2011. Cost-effectiveness of groundwater conservation measures: a multi-level analysis with policy implications. Agr Water Manage 98(4), 639-652.

DOORENBOS J., KASSAM A.H., 1979. Yield response to water. FAO Irrig Drain Paper No. 33, Rome, Italy.

FOSTER S.S.D., CHILTON P.J., 2003. Groundwater: the processes and global significance of aquifer degradation. Phil Trans R Soc Lond B 358, 1957-1972.

GARRIDO A., MARTÍNEZ-SANTOS P., LLAMAS M.R., 2006. Groundwater irrigation and its implications for water policy in semiarid countries: the Spanish experience. Hydrogeol J 14, 340-349.

GÓMEZ-LIMÓN J.A., ARRIAZA M., BERBEL J., 2002. Conflicting implementation of agricultural and water policies in irrigated areas in the EU. J Agr Econ 53 (2), 259-281.

JANSSEN R., VAN HERWINJEN M., 2006. A toolbox for multicriteria decision-making. Int J Environ Technol Manage 6 (1-2), 20-39.

KOUNDOURI P., 2004. Current issues in the economics of groundwater resource management. J Econ Surv 18 (5), 703-740.

LATINOPOULOS D., 2005. Derivation of irrigation water demand functions through linear and non-linear optimization models: application to an intensively irrigated area in Northern Greece. Wa Sci Technol 5 (6), 75-84.

LATINOPOULOS D., 2009. Multicriteria decision-making for efficient water and land resources allocation in irrigated agriculture. Environ Dev Sustain 11, 329-343.

LATINOPOULOS D., PAGIDIS D., 2009. Assessing the impacts of economic and environmental policy instruments on sustainable irrigated agriculture. Proc. 2nd Intnl. Conference Environmental Management, Engineering, Planning and Economics (CEMEPE) and SECOTOX Conference, Mykonos, Greece, June 21-26. pp. 1893-1898.

LATINOPOULOS P., 2003. Development of a water resources management plan for water supply and irrigation in the municipality of Moudania. Research project. Department of Civil Engineering, A.U.Th., Thessaloniki, Greece [in Greek].

LATINOPOULOS P., 2005. Valuation and pricing of irrigation water: an analysis in Greek agricultural areas. Global Nest J 7 (3), 323-335.

LATINOPOULOS P., THEODOSSIOU N., MALLIOS Z., PAPAGEORGIOU A., XEFTERIS A., 2004. GIS-based integrated water resource management in the greater area of the municipality of Moudania. Proc. Conference Protection and Restoration of the Environment, Mykonos, Greece, June 28-July 1.

LLAMAS M.R., MARTÍNEZ-SANTOS P., 2005. Intensive groundwater use: silent revolution and potential source of social conflicts. J Water Res Pl-ASCE 131, 337-341.

LOUCKS D.P., VAN BEEK E., STEDINGER J.R., DIJKMAN J.P.M., VILLARS M.T., 2005. Water resources systems planning and management: an introduction to methods, models and applications. Studies and Reports in Hydrology series. UNESCO Publishing, Paris, France. 680 pp.

MALLIOS Z., PAPAGEORGIOU A., LATINOPOULOS D., LATINOPOULOS P., 2009. Spatial hedonic pricing models for the valuation of irrigation water. Global Nest J 11 (4), 575-582.

MARTÍNEZ-SANTOS P., HENRIKSEN H.J., ZORRILLA P., MARTÍNEZ-ALFARO P.E., 2010. Comparative reflections on the use of modelling tools in conflictive water management settings: the Mancha Occidental aquifer, Spain. Environ Modell Softw 25 (11), 1439-1449.

McKINNEY D., CAI X., ROSEGRANT M.W., RINGLER C., SCOTT C.A., 1999. Modeling water resources management at the basin level: review and future directions. International Water management Institute, Colombo, Sri Lanka. SWIM Paper 6, 71 pp.

MIRCHI A., WATKINS D. Jr., MADANI K., 2010. Modeling for watershed planning, management, and decision making. In: Watersheds: management, restoration and environmental impact (Vaughn J.C. ed). Nova Science Publishers, Hauppauge, NY, USA. 420 pp.

NATIONAL STATISTIC SERVICE OF GREECE, 2001. Agricultural Statistics, 2001. Athens.

PAPAPETROU M., THEODOSSIOU N., 2010. Stochastic analysis of the geological structure of groundwater aquifers. Int Conf Protection and Restoration of the Environment X, Corfu, Greece, July 5-9.

RECIO B., IBÁÑEZ J., RUBIO F., CRIADO J.A., 2005. A decision support system for analysing the impact of water restriction policies. Decis Support Syst 39(3), 385-402.

RECIO B., GARCÍA-MOUTON E., CASTELLANOS M.T., MORATÓ M.C., IBÁÑEZ J., 2010. An econometric system to assess the economic impact of water restriction policies in Spain. Span J Agric Res 8(3), 526-537.

ROMERO C., REHMAN T., 2003. Multiple criteria analysis for agricultural decisions. Elsevier Science Publishers B.V., Amsterdam. 200 pp.

SMITH M., 1992. CROPWAT - A computer program for irrigation planning and management. FAO Irrigation and Drainage Paper No. 46, Rome, Italy.

USGS, 2010. MODFLOW and related programs [on line]. Available in http://water.usgs.gov/nrp/gwsoftware/modflow.html [23 December, 2010].

VAN HERWINJEN, 2010. Weighted summation [on line]. Available in http://www.ivm.vu.nl/en/Images/MCA2_tcm53-161528.pdf.