Design and development of a planning support system for policy formulation in water resources rehabilitation: the case of Alcázar De San Juan District in Aquifer 23, La Mancha, Spain

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ABSTRACT

To support policy formulation for rehabilitation of the natural environment in the Western Mancha region in Spain, a planning support system was developed and applied. The system is based on a framework developed for planning and decision making, and includes three main components, namely, a water balance model of the groundwater basin, a planning model and an evaluation model. The water balance model, which makes use of GIS and remote sensing, simulates the average yearly recharge of the aquifer system in relation to the land use changes for average meteorological conditions, to help understand the current situation; the planning model, which makes use of mixed integer programming, simulates the reaction of farmers towards the changes in the present subsidy schemes and helps formulate a proper policy instruments; and finally the evaluation model, which makes use of multicriteria decision analysis to support the evaluation of developed policies and selection of attractive scenarios based on the identified criteria and the preferences/opinion of various decision makers.

Key words | decision support systems, multicriteria evaluation, planning support systems, policy formulation, model-based planning support, water resource rehabilitation.

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1 INTRODUCTION

The Western Mancha is a sparsely populated region characterized by a high degree of aridity. The economy is mainly agrarian. Water resources are limited to little more than the groundwater in Aquifer 23 (see Figure 3). The aquifer has a surface outlet in a wetland area called 'Natural Park, Las Tablas de Daimiel'. Many years ago, the low return from rainfed crops like cereals and vineyards influenced farmers to switch to irrigated crops, and to construct wells and 'norias' to extract groundwater from the aquifer. Pumping has dramatically increased since 1970, and in some years the volume of extractions (discharge) was greater than the recharge of the aquifer system. The progressive lowering of the water table in the aquifer has reduced the wetland by more than 60% of its original area and has jeopardized the supply of drinking and irrigation water.

To improve the situation, a plan to reduce the rate of extraction was carried out, and limits on the use of groundwater for irrigation were imposed on the farmers. The European Economic Community and the Spanish government have initiated a program for the rehabilitation of the natural environment in the Western Mancha region. To support this effort, a Planning Support System (PSS) was developed to help in formulating and evaluating the impacts of different policy instruments.

This was a typical policy decision problem, which involved choices on at least two levels. At one level the policy makers were trying to decide on the policy which

could have the largest impact on the rehabilitation of the region. This was difficult due to the uncertainty about the impact of each policy, which was mainly due to the farmers' responses to the contemplated policy. At another level, farmers had their own decision problem: how best to respond to the new policy environment, given their own objectives and constraints. In order to solve these problems, the uncertainty about the farmers' reactions needed to be reduced. This was achieved by modelling the farmers' reactions towards various policy decisions and their impacts on the environment. Using this system, the existing policy problem was substantiated, then attractive policies were generated, appraised and evaluated for their performance.

The system was presented to the Fundación Municipal para el Desarrollo Económico y el Empleo, in Alcázar de San Juan. It was well received at the local level and used as a promising tool for formulation and evaluation of the policies that intended to make a sustainable use of the groundwater resources in Aquifer 23. At the governmental level, however, it was not adopted as an additional tool for policy formulation and evaluation. This was due to the large number of different authorities with local, regional and basin competence on the management of the system. As an example, at basin level the inter-basin transfers from Tajo Basin (hydraulic and hydrological solution) has been used as a solution to the environmental problem at Las Tablas de Daimiel Natural Park, rather than through a more sustainable scheme like the one formulated through this PSS.

As reported by Beaufoy (2000), the scheme of subsidies in the area has had some success: many farmers have signed up and there has been a notable shift in the cropping pattern in the area towards crops which use less water and a corresponding reduction in extraction from the aquifer. However, the scheme has also been criticized in many senses: (a) as a result of repeated droughts during recent years, and in spite of the reduced extractions, the Aquifer 23 system is far from being restored to a sustainable state; (b) the widespread problems of farms with illegal bore-holes outside the scheme has not been addressed; (c) the cultivation of high-water-demanding crops like maize, beet and melon are heavily subsidized by the Common Agricultural Policy of the EEC, which is in

contradiction with the spirit of conservation of the groundwater system.

Nowadays, a committee of independent experts, established by Regional and State governments, is proposing new studies of the system. The objective of this committee is to develop a Plan for the Management of Water Resources and for Sustainable Development of the Upper Guadiana River. At this stage of analysis, this PSS may again be used as a tool for the development of new policy instruments, not only for managing water consumption but also for the identification of a sustainable strategy for water resources management. In this paper the basic principles, components and functions of the system are briefly described.

2 BASIC PRINCIPLES OF PLANNING AND PLANNING SUPPORT SYSTEMS

2.1 Planning support systems definition and components

There are innumerable definitions of planning. The one we like is the definition given by Conyers & Hill (1989). They define planning as 'a continuous process, which involves decisions, or choices, about alternative ways of using available resources, with the aim of achieving particular goals at some time in future'. This definition attempts to incorporate the main functions included in most other definitions, e.g. as a means to choose, to allocate resources, to achieve goals and to plan for the future. On the other hand, 'planning' is a specific type of decision-making; therefore, it should comply with the definition and phases of decision-making process that includes the following main phases (Simon 1960; Sharifi 1999):

(a) Intelligence: examining the environment to identify problem or opportunity situations.
(b) Design: initiating, developing and analysing the possible courses of action. This involves application of decision models that generate solutions, test their feasibility and analyse different alternatives.
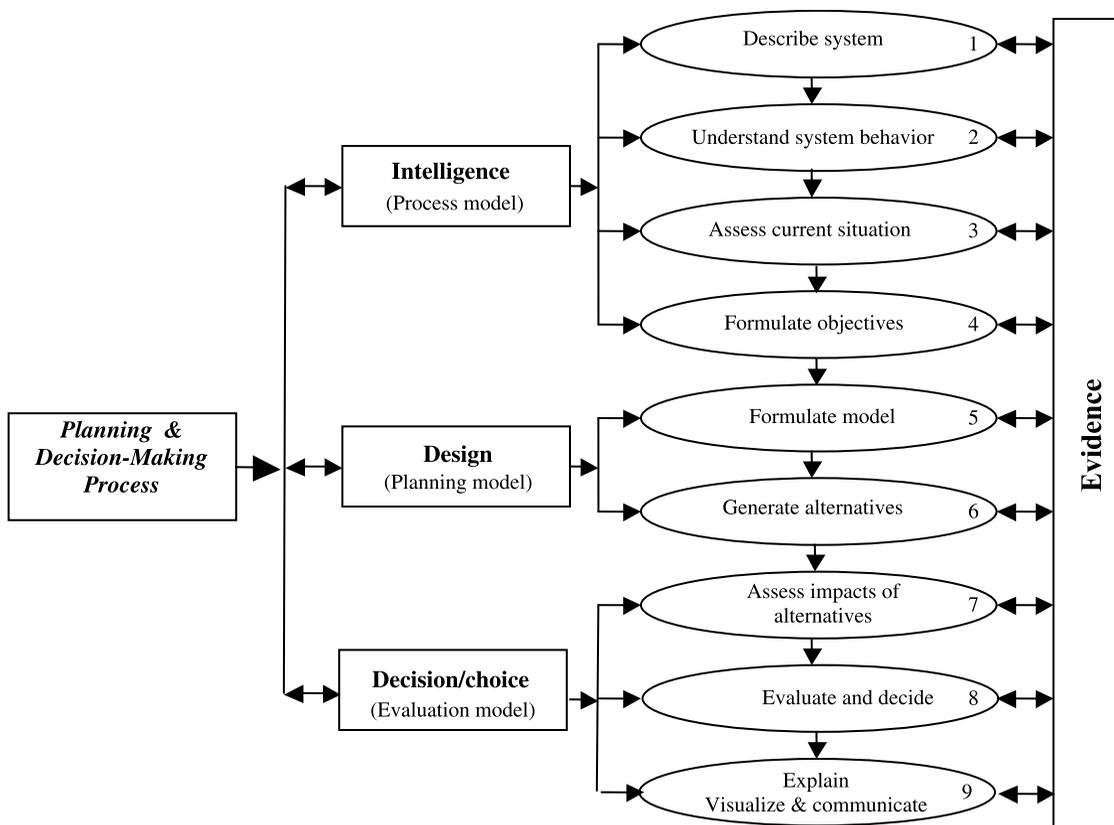(c) Choice: evaluating alternative options and selection of a specific course of action.

Figure 1 │ Framework for planning and decision-making process.

Based on these principles and considering the framework which was developed for landscape planning by Steinitz (1993), the following framework for the planning and decision-making process is developed and applied (Figure 1):

1. Define and describe the system in terms of content, environment, boundaries, space and time: 'description and representation'.
2. Understand how the system operates, which requires establishing the functional and structural relationships among its elements: 'process/behavioural model of the system'.
3. Assess the current state of system, and see if is desirable (system is currently working well?), which requires the ability to appraise and judge the current state of the system: 'evaluation of current situation/problem formulation'.

4. Formulate objectives, clarify the goals and objectives of the decision and identify what should be achieved, and how the achievement should be measured.
5. Study the ways that the current state of the system can be altered or improved, in terms of actions, time and space, which requires development of a simulation model to generate the required type of changes: 'planning model'.
6. Simulate different states of the system under desired changes: 'development of alternative options, plans, scenarios'.
7. Assess the impacts of the different changes introduced, scenarios: 'impact assessment/effects'.
8. Decide on the type of changes: 'decision' which requires the comparative evaluation of impacts of alternatives changes, and decision on the change or conservation of the system as it exists: 'evaluation and decision/choice'.
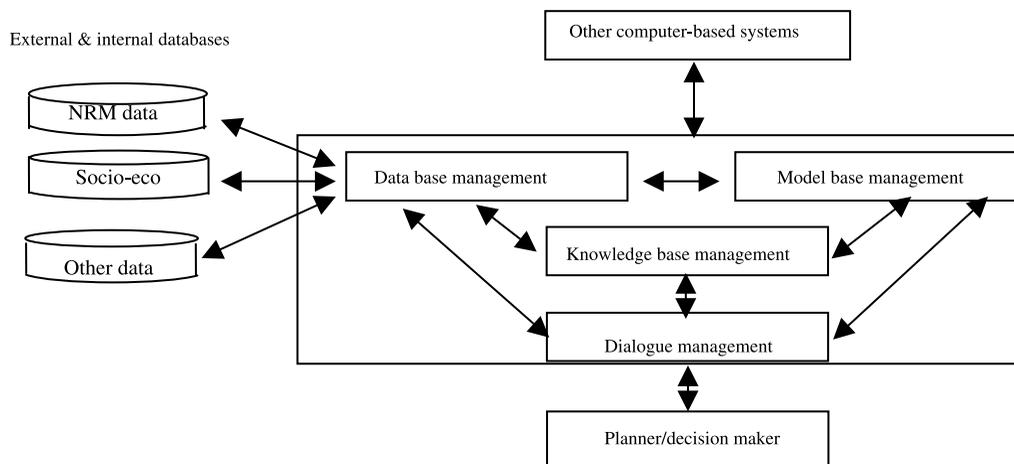
Figure 2 │ Overall architect of a planning support system (adapted from Turban 1995).

9. Explain the choice and communicate the result to the decision-makers through appropriate method (visualization)

'Evidence' is defined here as the total set of data/information that the decision-maker/planner (DM) has at his/her disposal, including the skills, which are necessary to use them. It is therefore the key resource at all stages of planning and decision-making. Evidence may be available in different forms, such as facts, values, knowledge and experiences. The quality of evidence is a very important aspect. Ideally, a planner/decision-maker hopes to have good quality evidence in abundant supply. Frequently, the evidence will be lacking, and the DM has to enhance its quality before it is used in the analysis. The evidence may be in different forms and format, such as numerical, alphabetical, graphical, map, in sound (spoken form), aerial photographs, satellite images, etc.

In this context we define a Planning Support System (PSS) as a class of geo-information systems composed of data/information, models and visualization tools, which are primarily developed to support different phases of the planning process and its functions. PSS contributes to rationalizing planning and related decision-making processes by providing the necessary support to structure and formulate the problem systematically, develop alternative plans or policy scenarios, assess and evaluate their impacts (considering objectives of the relevant

stakeholders) and select a proper policy or plan. Underlying the development of PSS is the assumption that planning is a dynamic process, and therefore requires the relevant support for continuous updating of data, and the generation and evaluation of plans and policies based on the updated data and assumptions. Naturally, a greater degree of access to relevant knowledge and information will lead to the development and evaluation of a more effective number of alternative scenarios, which will result in a better informed planning and public debate.

Main components of the system

Planning support systems, as specific type of decision support systems, include the following main components (Figure 2):

(a) A database management system: which includes databases designed to accommodate and organize the basic spatial and thematic data, provide facilities for selection and manipulation of data as well as interrelating data from various sources.

(b) A model base management system: which includes quantitative and qualitative models that support resource analysis, assessment of potential and capacities of resources at different levels of management. This is the most important component of the system, which forms the foundation of

model-based planning support (Sharifi 2000). It includes three classes of models (Figure 1), which make use of the existing data, information and knowledge for identification of the problem, formulation, evaluation and selection of proper solution. These models are:

- A process/behavioural model describing the existing functional and structural relationships among elements of the planning environment to help analyse the actual state of the system and identify the existing problems or opportunities. This will also support 'resource analysis', which clarifies the fundamental characteristics of land/resources and helps in understanding the process through which they are allocated and utilized (Sharifi & van Keulen, 1994).

- A planning model, which integrates the potential and capacity of the resources (biophysical), socio-economic information, goals, objectives and concerns of the different stakeholders to simulate the behaviour of the system. Conducting experiments with such a model helps to understand the behaviour of the system and allows the generation of alternative feasible scenarios to address the existing problems.

- An evaluation model, which allows the evaluation of impacts of various strategies/scenarios and supports selection of the most acceptable solution that improves the management and operation of the system, and is acceptable to all stakeholders.

(c) A knowledge base: which provides information on data and existing processing capacity and models which can be used to identify the problem, to generate solutions, test their feasibilities, evaluate and appraise their performances, and finally to communicate the results to the decision makers.

(d) A user-friendly interface, which allows smooth and easy communication with the system, visualization and communication of the results of the analysis to the decision-makers in a manageable and understandable form.

2.2 Land use planning process

Tinbergen (1956) and Thorbecke & Hall (1982) consider land use planning as part of agricultural sector and/or regional planning, where the effects of economic policies on patterns of, and changes in, land use are studied. In this approach, changes in land use are considered as the result of the interaction between policy variables (like infrastructure, investments, prices, credit facilities) and exogenous parameters (resource endowments) that lead to the realization of a number of defined goals (welfare, equity, rehabilitation of environment) and possible (undesired) side effects (environmental pollution).

In this context, land use decisions involve choices on at least two levels, e.g. regional and farm levels. At the regional level, a policy maker is trying to decide how best to allocate resources or lead the agricultural development process in the desired direction through a planning system, in the face of uncertainty about the impact of the allocation process on the other systems (economical, cultural and ecological). This uncertainty is related to the way that farmers in the economic system will respond to the new policy. At farm level, farmers have their own decision problem: how best to respond to the new policy, given their own resources and objectives that are influenced by socio-cultural values and impacts of the other systems. In order to reduce the uncertainty about the farmer's reaction and to support an effective decision on a proper policy measure at the macro-level, the impacts of the policy at farm level has to be evaluated.

There are several types of empirical research which can support this type of analysis. Simulation is most frequently used, especially when bounded-rationality is selected as a principle for choice. Following Shannon (1975), we define and use simulation as the process of designing a model of the real system and conduct experiments with the model in order to understand the behaviour of the real system and/or to evaluate various strategies for the operation of the system. As it allows the simulation of the impacts of changes in different controllable/uncontrollable variables, it can serve as a powerful tool in the planning process.

Figure 3 | Map presenting the location of study area.

3 APPLICATION OF MODEL-BASED PLANNING SUPPORT SYSTEMS FOR WATER RESOURCES REHABILITATION

3.1 Introduction to the study area

A case study was developed in La Mancha Province, around the Aquifer 23 system. This is an area of about 5500 km² located in the southern central part of Spain. 80% of this area belongs to the province of Ciudad Real and 20% to the provinces of Albacete and Cuenca (Figure 3). The climate is semi-arid. According to Koppen's classification it should be catalogued as continental Mediterranean, with warm summers and cold winters. Average annual precipitation is around 450 mm, average annual temperature is between 11.5–14.5°C, annual sunshine is around 2800 h and annual evapotranspiration is around 950 mm.

Two main aquifers can be distinguished in the Aquifer 23 system: the upper aquifer, composed of limestone of Miocenic origin with an average and maximum thickness of 35 and 200 m, respectively (Niñerola 1976), and the lower aquifer composed of Jurassic and Cretaceous limestones and dolomites. The upper unit extends all over the plain. It is a free aquifer, very heterogeneous due to sedimentation factors. The lower unit is connected to lateral aquifers (Aquifer 19 in the north and Aquifer 24 in the south) and extends to the eastern half of the plain (around 3500 km²). It is a series of confined aquifers that locally could be considered as free or semi-confined.

Due to the total lack of surface water, groundwater from the aquifer is used mainly for irrigation and also for drinking water supply. Farmers have made huge investments in pumping and irrigation systems. The major problem in the area is caused by the overexploitation of the groundwater reserves, which has led not only to jeopardizing the integrity of the aquifer, but also to large environmental problems, leading to the continuous decline of wetlands in the aquifer's discharge zone at Las Tablas de Daimiel Natural Park (Rodriguez 1994).

The major land use in the area is agriculture, composed mainly of traditional vineyards, garlic, melon and alfalfa. These crops, although very profitable, are also very water intensive. As in many countries in the world, farmers in the area are receiving subsidies from the government. But because of the lowering of the water table in the aquifer, the Ministry of Agriculture has offered the farmers additional subsidies for reduction in irrigation water consumption. Also, the Confederacion del Guadiana (CHG) has established maximum pumping water volumes from the aquifer, depending on the size of the farm and the crops planted.

Due to the large extent of the aquifer system, and based mainly on data availability and counterpart support, Alcázar de San Juan district was selected as the study area. This district is located in an area where the groundwater level was relatively high (Getachew 1994). Alcázar de San Juan district is located in the central northern part of the aquifer. It extends over around 68,000 ha, of which approximately 52,000 ha are within the aquifer's limits.

3.2 PSS concept

Based on the framework presented in Section 2 (Figures 1 and 2) for the planning and decision-making process, and in order to study and assess the possible impacts of different government policies that are formulated for a gradual recuperation of the aquifer and sustainable use of its resources in La Mancha Province, a planning support system for policy formulation and evaluation was developed. The system includes the following main models:

(a) A water balance model of the groundwater basin to analyse the current situation and understand the problem of the aquifer system. This model simulates the average yearly recharge of the aquifer system in relation to the land use changes and considering average meteorological conditions. In developing this model, the annual average recharge of the aquifer system, spatial distribution of rainfall, evapotranspiration, land use and soil properties, and water–soil moisture budget were considered. The role of this model was to relate the use and supply of the water in order to understand the state of the aquifer, quantification of its deterioration trend, and establishing the cause/effect relationship between the determining factors. In these processes remote sensing and GIS played a crucial role.

(b) A planning model composed of a mixed integer-programming (MIP) model. This model simulates the reaction of the farmers towards changes in the present subsidy schemes. Naturally, the reaction results in a change in land use, which in turn will have an impact on the groundwater level. It assumes a rational farmer who considering his resources follows the objective that maximizes his profit. This would lead to an optimal cropping pattern in the region. This model is also used to formulate and assess the impacts of various policy instruments.

(c) A multiple criteria evaluation model to support evaluation of the attractive subsidy schemes (policy instruments) based on the identified criteria and the preferences/opinion of the various stakeholders.

In the following sections each model is briefly explained, and application results are reported.

3.3 Water balance model

The purpose of this model is to understand the state of the aquifer and to study different components of the water balance at the model element scale under different conditions of climate, soil and vegetation, in order to estimate the aquifer's average direct recharge. Three important limitations have to be mentioned before presenting the model overview. The first limitation is a practical one, and is due to the difficulties of applying and verifying the mass balance equation in open systems (Beven 2001*a*). In the study of Aquifer 23, the system was considered to be closed (not including any indirect recharge from inter-aquifer fellows). The second limitation of the model refers to the use of a distributed hydrological model. Beven (2001*b*) presents a detailed discussion of some of the problems of distributed modelling, including the problem of non-linearity, the problem of scale, the problem of equifinality, the problem of uniqueness and the problem of

uncertainty. The last limitation of the model refers to the use of a soil moisture budget model. In this respect, the authors are aware that soil moisture budget models were developed for humid climates and have less validity in semiarid zones. They work best for seasonal patterns of recharge when potential and actual evapotranspiration are of similar sizes, and when precipitation is widespread and relatively uniform. In semiarid zones these models normally underestimate recharge and they are unable to represent the recharge dynamics as reflected in groundwater fluctuations. Unfortunately, estimation of direct recharge using other methods such as Darcian approaches, tracer techniques or direct measurement was not possible because of the lack of data and time limitations. Therefore, a simple water and soil moisture budgeting method for the direct recharge estimation was selected and applied.

There are mainly two sources of recharge to a groundwater system. Each source is frequently considered separately in order to estimate recharge. The main recharge sources are the direct recharge due to precipitation and the indirect recharge that includes interaquifer flows, irrigation losses and river recharge. The monthly water balance model presented here describes the direct recharge estimation. Indirect recharge was estimated in a parallel study conducted in the area by Getachew (1994).

The water balance model is founded on the method proposed by Thornthwaite & Mather (1957). It is based on long term average monthly precipitation, potential evapotranspiration and combined soil and vegetation characteristics. Donker (1987) has reported the successful application of this method in a semi-arid climate very close to the study area (Málaga, Spain). The Thornthwaite and Mather method models the different water balance components for one point. Using Geographic Information Systems (GIS), it has been possible to model the water balance in two dimensions, taking into account the spatial distribution of rainfall, evapotranspiration, soil and land use. Instead of calculating the water balance for one point, it has been calculated for every element (pixel) of the entire groundwater basin.

A typical computational element for hydrological modelling at grid scale is shown in Figure 4. It illustrates the approach to quantify the spatial variability of hydrological parameters. The processes of rainfall, infiltration,
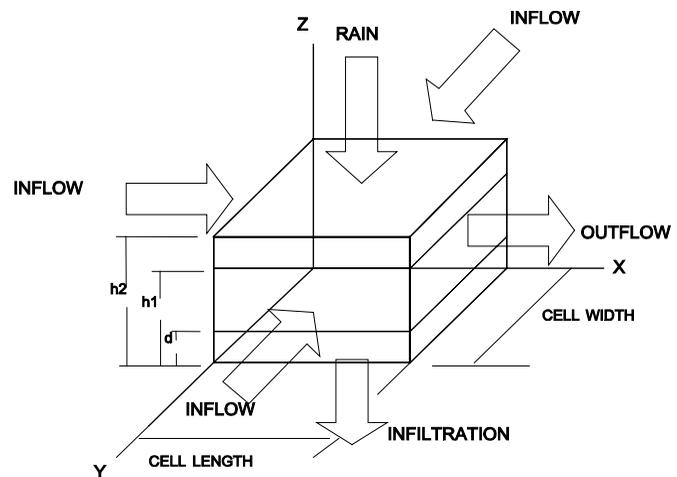

Figure 4 | Element in hydrological modelling at grid scale.

inflow and runoff are computed for each element at every time step. A depth h1 exists at the beginning of each time step and a depth h2 at the end of each time step. A retention storage depth d is assigned depending on the land cover types, the soil characteristics and the present soil moisture. The partitioning of the watershed into computational elements, as shown in Figure 4, was made for the entire groundwater basin. The boundary of the groundwater basin was obtained from an analysis made by Camacho (1989).

Landsat Thematic-Mapper (TM) data for the year 1993 was utilized to derive land use classes, which were used to estimate the agricultural water consumption. The land use map was made by the Fundación Municipal Para el Empleo y el Desarrollo Económico de Alcázar de San Juan (FMPEE), using supervised classification of Landsat satellite images from spring and summer 1993. The classification was further verified during fieldwork. The water consumption estimate was based on the established average use for different crops. GIS was used to carry out the water balance for every element (30 × 30 km) in the entire basin, and to estimate the impact of land use changes on water use. A soil map compiled by Carlevaris (1992), covering about 80% of the aquifer, was digitized and used to establish the soil parameter considered in the water balance equation. For the remaining 20% of the area (northeast) average conditions for the water holding
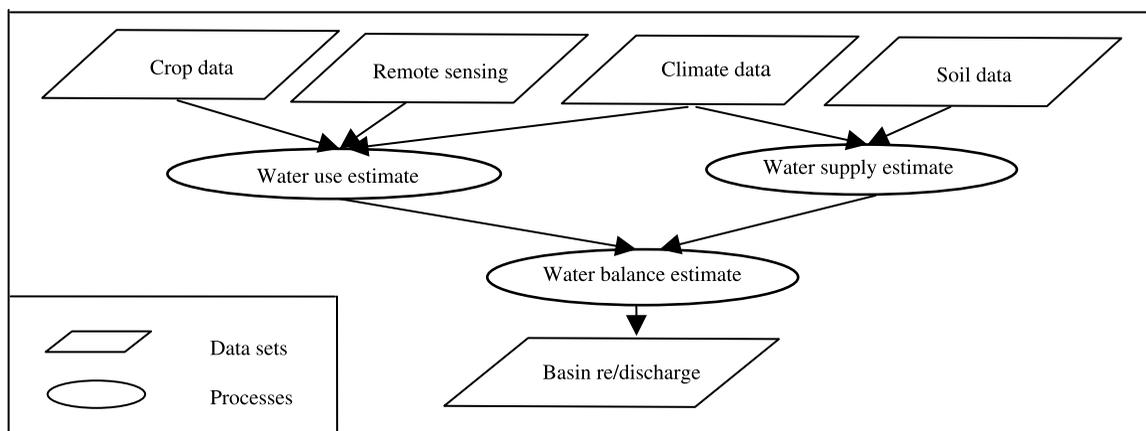
Figure 5 │ Schematic presentation of the water balance model.

capacity parameter were established. Meteorological measurements, consisting of monthly data for rainfall and temperature for the period 1950–1991, were obtained for 10 stations within the aquifer's area.

The model required input series for rainfall, temperature and soil data, the latter to estimate the soil water holding capacity. Potential evapotranspiration was calculated using the Thornthwaite method. The crop's potential evapotranspiration was estimated as the potential evapotranspiration times the consumptive coefficient of the crops identified in the land use map (Figure 5).

The water balance model takes into account the initial soil moisture conditions for every pixel in a square grid of 30 km. Calculations start at the end of the rainy season that corresponds to March. It aims to have soils at water holding capacity (WHC) as initial conditions. However, due to the dry conditions of the area, initial values of soil moisture are very difficult to determine. In the literature it is accepted that the application and results of any hydrological model depend highly on the initial conditions that are always difficult to set. Depending on the annual distribution and magnitude of rainfall, soils may be at or below water holding capacity at the end of the rainy season. For each type of soil three different average initial values of soil moisture including field capacity were analysed (100, 80 and 60% of WHC). The retention storage in the aquifer in the first month of calculations was considered to be zero. As February is usually a month with a surplus of

water, initial water losses were also considered to be equal to zero.

Due to the low drainage density in the basin and because during the whole year all the rivers remain dry, the surface runoff component in the budgeting model was neglected. For each pixel and each month of the year the aquifer's direct recharge was calculated using the mass continuity equation. This equation establishes that the inflow minus the outflow for each pixel is equal to the change in soil moisture storage during the period studied. The equation used considers previous soil moisture storage that can be estimated from the initial conditions of the model or from a solution of the equation in a previous month. It also considers the dryness of the soil, precipitation and actual evapotranspiration for the particular month.

The application was based on long-term average monthly precipitation, potential evapotranspiration and combined soil and vegetation characteristics. Calculations were made using the Integrated Land and Water Information System (ILWIS). Available ILWIS procedures were used in order to estimate the spatial variability of the meteorological and physical data.

Results

For each month, maps of direct recharge were produced for the entire aquifer. Using the annual recharge as

criteria, results were grouped in five categories from low to high. GIS visualization functions were used to identify the location of the main direct recharge spots. Results of the model showed an average annual direct recharge of around 43×10^6 m^3/yr or 8.0 mm/yr. Getachew (1994) estimated the indirect recharge of the aquifer at 40×10^6 m^3. According to this, the total annual average recharge of the system should be around 83×10^6 m^3. In comparison with the total estimated discharge (around 135×10^6 m^3/yr), this quantifies the trend of decreasing groundwater level and triggers a decision.

3.4 Mixed integer-programming (MIP) model

One approach to managing the declining groundwater level in the aquifer system was to assign a fixed amount of water to the farmers. The Confederación del Guadiana has limited farmers to extract an average of 225 mm of water per year (well above the average recharge), depending on their farm size. In fact, with efficient irrigation systems and appropriate management, water was not a constraining factor for some crops. However, for some other crops water was a limiting factor.

In spite of the government policies the aquifer continued its decline. It meant that less water had to be allocated in future years to sustain the aquifer. Crop selection should be based on water requirements and water availability. The selection must maintain economic income while less water is used. In order to make the best use of rainfall and the limited supply of irrigation water, a more efficient water management is required.

From 1993, the European Economic Community (EEC) and the Spanish government were implementing four kinds of subsidies in the study area:

– subsidies for type of crop,
– subsidies for reduction in water use for irrigation,
– set-aside subsidies,
– subsidies for reforestation.

Subsidies for type of crops

One annual subsidy was given to stimulate the cultivation of specific crops either in irrigated or rainfed conditions. These subsidies were established each year and were based on the EEC Common Agricultural Policy. They were given on an area basis (per ha). Farmers receiving these subsidies had to maintain fallow at least 15% of the total area of the farm.

Subsidies for reduction in the use of water for irrigation

Both the Confederación del Guadiana (CHG) and the Irrigators Association established the maximum yearly amount of groundwater available for irrigation (in m^3/ha). This endowment was calculated based on crop water requirements and farm size. The total water use for each farm was derived through multiplication of the area by its corresponding water requirement, as established by the CHG. An average value of consumption of water per hectare was obtained by dividing the total water used over the total number of hectares. The result was compared with pre-established figures for the use of water. Subsidies were given when they were applicable. Depending on the amount of water used, three types of subsidies were granted. Subsidies were given for programs of reduction in water use of 50%, 70% and 100%.

Set-aside subsidy

Farmers in irrigated lands opting for set-aside subsidies received compensation. These subsidies are aimed at stimulating farmers to leave part of their land fallow. In rainfed lands this subsidy was lower. Farmers could receive simultaneously payments for water reduction and the set-aside subsidy.

Subsidy for reforestation

The subsidy for reforestation included the costs of reforestation, plus a premium for maintenance. For five years farmers received an average annual payment and a compensatory premium for twenty years. Farmers could take simultaneously the subsidy for reforestation and the set-aside subsidy. It was not possible for them to take the subsidies for reforestation and a reduction in water at the same time. For non-irrigated lands subsidies for
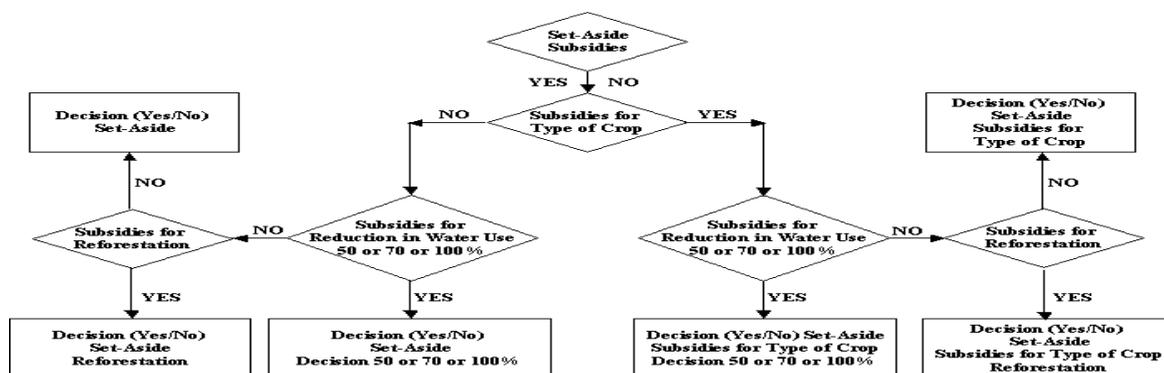
Figure 6 | Schematic of farmer's subsidies decision process, valid for irrigated lands. For non-irrigated lands, subsidies for reduction of irrigation were not applicable.

reduction in water use were not applicable. A schematic flow chart of the possible farmers' decisions with respect to the different subsidies is presented in Figure 6.

MIP model formulation

To simulate the behaviour of each class of farmer (big, medium and small) holding different type of land (irrigated and non-irrigated), and seeking for the cropping pattern that maximizes their profits considering various subsidies schemes, an optimization model was developed. The optimization was based on irrigation water availability, land availability, crop rotation, production policies and existing subsidies schemes. Subsidies are offered for crop type, reduction in water use (50%, 70%, 100%), set-aside and reforestation. The optimum cropping pattern for each type of farm and land was the basis for the calculation of the total cropping pattern in Alcázar de San Juan district. The planning period has been assumed to be one year. However, the results can be considered as an average over a span of time of five years (duration of the program of subsidies for reduction in water consumption).

For model development, information related to the most common crops cultivated in Alcázar de San Juan district such as yield, variable costs, fixed costs, gross margin, sale price and net income were estimated. Crop water requirements were obtained from estimations made by the CHG. Crop calendars were identified during fieldwork. For irrigated lands 17 crop rotations were selected. In non-irrigated lands six crop rotations were

considered. Selection was made according to the more common rotations in the area listed by the Ministry of Agriculture. Three farm sizes were considered as indicated in Table 1.

The annual income, annual water requirements and monthly labour requirements for each rotation were calculated based on the assumption that, where the rotation enters the 'optimum' plan, the crops considered in that rotation would be cultivated each year in equal proportions. For example, a farm following a rotation of four years of fallow and six years of crop would have 4/10 of its area in fallow and 6/10 in crop, rather than having the whole area under fallow for four years followed by six years under crop.

In order to study the farmer's decisions with respect to the different combination of subsidies, a mixed integer-programming model was developed. It simulates the behaviour of farmers with respect to different subsidy policies, and estimates their economic and environmental impacts. It was mixed because the farmer's decision outcome with respect to a particular subsidy was either positive '1' or negative '0'. In the problem formulation, the objective function for optimization was the profit maximization for each of the three farm sizes in both rainfed and irrigated conditions. Decision variables were either the rotation type or the crop type, and the decisions for each subsidy scheme. Constraints included type of farm (irrigated/rainfed), water and land availability, and policy and marketing constraints with regard to the traditional vineyard cultivation, garlic, cereals and tubers.

Table 1 │ Farm size distribution in irrigated ('Irr') and non-irrigated ('non-Irr') land in the Alcázar de San Juan (source: Ministry of Agriculture)

Range (ha)	Number of farms		Area (ha)		Area (%)		Av. farm size (ha)	
	Irr	Non-Irr	Irr	Non-Irr	Irr	Non-Irr	Irr	Non-Irr
0–20	590	1416	5114	7590	22.86	25.96	8.67	5.36
20–50	161	318	5118	6586	22.88	22.53	31.79	20.71
> 50	85	99	12,137	15,059	54.26	51.51	142.79	152.11
Total	836	1833	22,369	29,235	100	100	26.76	15.95

Restrictions expressing the relationships between the different subsidy schemes were also considered.

With respect to rotations, two approaches were considered. The first one took rotations as the decision variables (approach 1). The second approach considered each crop as an activity and included market and rotations constraints obtained from the analysis of the cropping pattern evolution in the case study area (approach 2). The cost of the land was not included in the economic analysis. Due to the strong tradition of vineyard cultivation it was assumed that the area under vineyards would remain the same. Studies made with respect to the evolution of this crop between 1984–1995 strongly supported this assumption.

The matrix structure of the model is shown in Table 2. When crop rotation is considered as activity (approach 1), the model results in 246 variables and 133 constraints. The number of non-zero elements in the matrix equals 1182. The matrix density is 2.97%. When crops are considered as separate activities (approach 2), the number of variables becomes 1980 and the number of constraints 136. The number of non-zero elements in the matrix equals 1390; the matrix density is 4.21%. The optimization package for linear and mixed integer programming OMP (Beyers & Partners 1993) was used for the problem solution. For solving the optimization problem, it uses the branch and bound method (Williams 1985).

Before experimentation, the model has to be calibrated and validated internally and externally. Internal validity refers to the existence of the causal relationship between variables, or absence of relationship, which implies the absence of cause. If internal validity is lacking no statement about the cause and effect can be made. The external validity refers to the possibility of applying/extrapolating the result of the experiment to the real world cases. Validation of the simulation model is the investigation of the correspondence of the model with the real life situation: in other words, if the model presents a realistic representation of reality. The correspondence test was carried out by a study of the trends in various runs of the model, as well as comparison of the model results with an estimate of the actual land use map. The land use map, which was obtained from a supervised classification of the 1993 Landsat image (corresponding to the first year of the subsidies scheme), was used for the calibration and validation of the MIP model (Table 3). Compared to previous years, cropping patterns in 1993 showed a reduction in the irrigated area. Results of the model predicted a further reduction of around 40% of the irrigated land after 1993.

According to the government estimates, the enforcement of the programme of subsidies for water reduction, big farmers opted for the 70% reduction in water consumption, medium farmers for the alternative of 50% reduction. Small farmers were expected to be not interested on this type of subsidy. The MIP model predicted the same results. In rainfed lands results of the model indicated that big and medium farmers would opt for cultivation of sunflowers. Small farmers would opt either for reforestation or for the traditional vineyard cultivation. In

Table 2 │ Matrix structure of the MIP model. W=Water subsidies. A=Set-aside subsidies. R=Subsidies for reforestation. MAX= maximize

	Decision variables										Resource constraints
	Crops in irrigated lands						Crops in rainfed lands				
	Farm size big–medium–small						Farm size big–medium–small				
	Subsidized crops			No subsidized crops			Subsidized crops		No subsidized crops		
Constraints	W	R	A	W	R	A	R	A	R	A	
Water availability											
Land availability											
Policy constraints											
Water subsidies											
Crop subsidies											
Subsidies for abandon											
Subsidies for reforestation											
Objective function	Net income										MAX

irrigated lands medium farmers would opt for the cropping of sunflowers while big and small farmers would decide to crop melon and irrigated cereals. It is important to note that the model results were very sensitive to the crops which received subsidies. In 1993 low subsidies were given to crops with high water requirements. With the exception of melons, the model predicted a decline in the area of these crops. In 1993 high subsidies were given to the cultivation of sunflowers and vecht; it explains the big trend of the farmers to sunflower cultivation. However, almost 70% of the net income for sunflowers was due to subsidies, making the cultivation of this crop attractive.

With respect to vineyards, the model results indicated that this crop might not appear in the optimum cropping pattern strategy. However, because of the cropping tradition and its high social value, farmers were expected to continue with the vineyards. A policy stimulating the cultivation of vineyards under many varieties could be

Table 3 │ Comparison between results of the landuse classification (1993) and results of the two considered approaches, for the Alcázar de San Juan district

Land cover	Land use classification (ha)	Approach 1 (ha)	Approach 2 (ha)
Rainfed vineyard	9729	9729	9729
Irrigated vineyard	2037	2037	2037
Fallow	5667	3354	4012
Rainfed (no vineyard)	14,098	—	15,764
Irrigated (no vineyard)	20,674	11,671	10,635
Others (reforestation and abandon of lands)	390	19,506	9437
Total	52,595	51,595	51,595

Table 4 | Average income in (pesetas/ha) for each farm size, estimated by the two approaches

Approach	Farm type	Big farm	Medium farm	Small farm	Average all farm sizes
1	Irrigated	146,320	152,924	140,564	146,602
1	Rainfed	48,792	48,795	31,083	42,890
2	Irrigated	159,835	147,233	108,511	138,527
2	Rainfed	54,281	54,305	31,083	46,556

helpful to the economic improvement of vineyards. However, a policy like this would be against the EC plans, which are in favour of the abandon of vineyard fields.

Comparison between the land use classification from Landsat data of 1993 and the results of the model (Table 3) shows a reduction of tendencies in the irrigated area, combined with an increase in the reforested and abandoned lands. For each type of farm, the average results of farmers' total net income were calculated (Table 4). In general, from the total average income per hectare, 30% correspond to subsidies given by the Common Agricultural Policy (subsidies for crops, set-aside and reforestation), 25% to subsidies for reduction in water use and 45% to crop income. Small farms in both irrigated and rainfed lands had lower income than the other farms, because of the assumption that they would continue cultivating vineyards. This explains the reason why small farmers in irrigated lands would only pay 7 pesetas/m^3 for water, while medium and big farmers would offer around 30 pesetas/m^3.

Results

The MIP model predicted the decline in cultivation of crops with high water needs (alfalfa, sugar beet and maize) and their replacement by crops with lower water demand. It also showed that some existing land use patterns (vineyards) would continue to exist, because they represent a long tradition. The model also predicted a reduction in the area of irrigated land, because the farmers would set aside a part, and showed that the applied subsidy policies would

stimulate the reduction in use of groundwater for irrigation. However, if the average annual recharge of the aquifer (83×10^6 m^3) is compared to the annual discharge (135×10^6 m^3), it can be clearly seen that, although subsidies are effective, the water table in the aquifer would continue decreasing. Logically, the water table depletion would be reduced, but sooner or later the groundwater reserves would finish if mining of groundwater continues. However, it is still possible, for a number of more dry years, to allow the same level of agricultural production as in wetter years, through further mining of groundwater.

3.5 Multicriteria evaluation model

Results of the previous section showed that the MIP model is rather well simulating the behaviour of the farmer with respect to different subsidy schemes. The next step in simulation is experimentation with the model in order to formulate different policies and to study their impact from different perspectives. Using the MIP model 10 scenarios that were deemed to be attractive and include extreme variations of the present subsidy scheme were generated as follows:

- current subsidies scheme implemented in the area (scenario 1),
- policy without subsidy for crop type (scenario 2),
- policy without subsidy for reduction in water use for irrigation (scenario 3),
- policies without subsidy for abandon of lands (scenario 4),
- policies without subsidy for reforestation (scenario 5),
- policy without any kind of subsidies (scenario 6),
- 25% reduction in subsidy for sunflower and peas (scenario 7),
- 50% increase in subsidy for cereals (scenario 8),
- scenario 7 + scenario 8 (scenario 9),
- water pricing policy (groundwater cost = 10 pesetas/m^3), without considering subsidies for reduction in water use for irrigation and without constraints about maximum water use (scenario 10).

The next step in the planning process is the assessment and evaluation of different scenarios from different

Table 5 | Impact matrix of all the analysed scenarios for the Alcázar de San Juan district

Criteria	SCEN 1	SCEN 2	SCEN 3	SCEN 4	SCEN 5	SCEN 6	SCEN 7	SCEN 8	SCEN 9	SCEN 10
Total income Alcazar (millions pesetas)	4658	4394	4135	4607	4642	2900	2576	4748	4696	4807
Employment (avg. men/month)	1318	1271	1465	1063	1320	1463	1348	1201	1493	3029
Total water for irrigation ($m^3 \times 1000$/year)	43,282	40,218	42,279	43,282	43,282	42,279	43,282	38,505	49,061	105,580
Government expenditures (millions pesetas)	2444	2521	1739	2731	2403	0	569	2737	2436	700

perspectives, considering different criteria. This is carried out through application of a multicriteria evaluation model. In this process, the overall utility of alternatives was evaluated on the basis of their impacts in terms of the decision criteria and the associated values that decision-makers assign to them. The latter is generally referred to as weight. In this experiment, the following four criteria were considered for multicriteria evaluation:

- income generation (estimated in pesetas),
- total employment (estimated in average man/month),
- irrigation water use (estimated in m^3/yr),
- government expenditures (estimated in pesetas).

Within these criteria, income and employment are considered as benefit criteria (the higher the better) and the irrigation water use and government expenditure as cost criteria (the lower the better).

A project impact matrix represents performances of each alternative scenario on each criterion. Using MIP, impacts were estimated and presented in Table 5. As can be seen in the table, values of total income were very low in the case of scenarios 6 and 7. For the remaining scenarios income values were very similar at around 4,300 million pesetas. With respect to employment all the alternatives, with exception of scenario 10, gave similar results. These values compared well to the figures obtained from the Agrarian Census 1991: 1,450 people were working in the agricultural sector. Scenario 10 gave a very high level of employment because of the vast area cultivated under melons. In relation to consumption of water for irrigation, almost all the alternatives showed figures of

around 43 million m^3/yr (direct recharge of the aquifer). However, scenario 10 presented a very high water consumption, which is again explained because of the large area cultivated under melons. Government expenditures varied between the scenarios.

As can be seen from Table 5, each criterion is measured/assessed with different units. The first step in the multicriteria evaluation is to convert all measurements to one unit, which is the utility of different criteria as perceived by the analyst or decision-maker's 'value judgment'. The result is 'partial evaluation evaluation/ attractiveness' of the scenarios based on each criterion. This process is also referred as standardization or normalization. Since detailed information on the utility of each criterion was not available, row-max and interval standardization methods were applied for the weighted sum and ELECTRE-2 method, respectively. This produces a utility of '1' for the maximum score of each benefit criteria, and relatively smaller values for the others. As a result of this process, the performances of all scenarios on each criterion are represented in utility values (between 0 and 1), which are comparable. To find the overall attractiveness of each scenario, all the partial attractivenesses should be somehow aggregated using an aggregation rule. In decision models based on utility theory, weights are used for aggregating partial attractiveness. The interpretation of the weights depends on the shape of the utility function. In the most commonly used linear utility function, weights are used as price coefficient for criteria, and ratios between weights represent trade-off ratios between criteria. As the partial utility functions may be non-linear, the weights then correspond to non-constant price

functions for criteria, and weight ratios represent variable tradeoff ratios between them. As explained earlier in this study the linear utility function was assumed for all criteria. Since from the perspective of different stakeholder/decision-makers different criteria may have a different level of importance, this priority has to be identified and considered in the aggregation process. In this study, three classes of stakeholders, namely farmers, environmentalists and government, were considered. Considering the problems of weight determination as described by Lahdelma *et al*. (2000), the weights or level of importance related to each criterion were estimated through inquiries carried out with the main interest groups. In total 13 inquiries were conducted: 8 to farmers, 1 to environmentalist and 4 to government politicians. The inquiries were made using two methods:

- direct rating, in which the decision-maker is asked to divide 100 points between all considered criteria based on their importance,
- qualitative pairwise comparisons of criteria using the Satty scale: 'Equally important (1); Moderately more important (3); Strongly more important (5); Very strongly more important (7); Absolutely more important (9); and (2,4,6,8) can be used for intermediate values' (Satty 1980).

After weight information is obtained from stakeholders, there is the difficulty of aggregating conflicting weights into a single set of weights that would represent the overall preferences of each group. Various averaging procedures may produce weights and lead to a solution that no one wants. In fact, the overall preferences of the group cannot, in general, be represented by any single set of weights. Here only the use of weight intervals or weight distributions may give a sound starting point. In this study, an average weight was derived for each group and used at the initial phase of analysis, and converted to a weight interval during the sensitivity analysis.

From the analysis of inquiries it was decided to discard the response given by a farmer cultivating in rented land. This was because their answers were far from the average of the group of farmers interviewed. Two farmers assigned equal preferences to the entire criterion. On this basis the weight set 'W1' was created. An average weight

Table 6 | Sets of weights considered in the analysis

Criteria	W1=equal weights for all the criteria	W2=weights estimated using direct assessment	W3=weights estimated using pairwise method
Profit	0.25	0.35	0.292
Employment	0.25	0.15	0.11
Water use	0.25	0.40	0.542
Government expenses	0.25	0.10	0.056

for each criterion was calculated from the remaining inquiries. The analyst's set of weights was also considered. Results were included as weight set 'W2'. For estimation of the weight set 'W3', an average ranking of all criteria was made and used for their pairwise comparison based on the Satty scale. To simplify this procedure, during the inquiries it was only asked whether criterion 'A' was more, equal or less important than criterion 'B'. Then, based on the answers, they were categorized by the analyst according to the Saaty scale. From all the inquiries an average weight for each criterion was calculated. Mean standard deviations were smaller than 25% for all the criteria. Results of the three weight sets are shown in Table 6.

For the aggregation of the partial attractiveness into the overall attractiveness two different aggregation rules, the weighted summation and an out-ranking methods 'ELECTRE-2' (Roy 1973), were chosen and applied. They were selected based on the type of available information, as well as their transparencies and applicabilities in this type of analysis. The software used for this application was the DEFINITE program (Janssen & van Herwijnen 1992; Janssen *et al*. 2000).

Results of the multicriteria analysis for the two methods are shown in Figures 7(a,b). Results were quite sensitive to the set of weights. When set W1 was selected, the weighted summation results indicated scenario 10 as the best alternative. This could be expected, as this scenario removes the limitation on the use of water and therefore produces high income and employment at very little cost to the government. However, using the
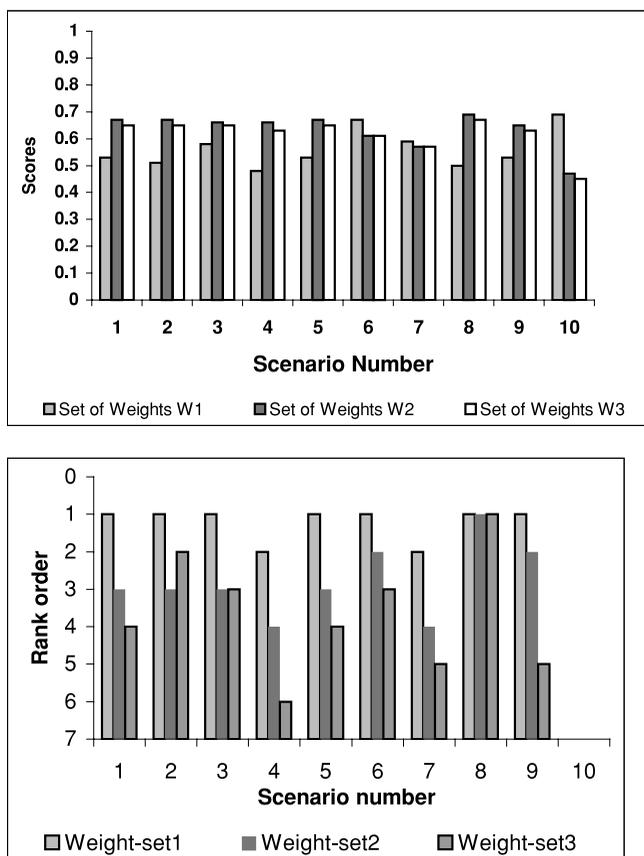
Figure 7 │ (a) Results of weighted summation. (b) Results of ELECTRE-2 method.

ELECTRE-2 method, the same conclusions were not derived; given the thresholds for concordances and discordances no distinction could be made between scenario 10 and the others.

When other sets of weights were used scenario 10 was poorly ranked. This is due to the very high use of water, which is considered as the source of existing problems in the region (highest weight, Table 6). Results of the weighted summation method using weight sets W2 and W3 indicated scenario 8 as the best. Scenarios 5, 1, 2, 3, 4 and 9 were ranked almost the same at the next level, and scenarios 6, 7 and 10 as the worst, and therefore could be discarded from further analysis. For the ELECTRE-2 method again scenario 8 ranked as the best. From the evaluation results it was not directly clear which scenario could be classified as the next best (considering the selected thresholds). However, it was evident that

scenarios 4 and 7 were always outranked by other alternatives. Although scenario 10 could not be ranked it was dominated by almost all other alternatives.

Looking at Figures 7(a,b) and Table 5 it can be concluded that, based on the selected criteria, scenario 8, which is a policy to increase the cereals subsidies, appears to be the best, as it uses the least amount of water and produces high income, good employment, at the high cost of government expenditure. Although scenario 9 produces high employment and income with less government expenditures, since its water use is the second highest, it is not recommended as the next option. Scenario 6 creates the second highest employment at no government costs; however, since its income is low and its water use is relatively high it is also not selected as the next policy option.

Scenario 2, which is the policy without subsidy for crop type, is picked up as the second best option, as it has the second least water use, good income and employment rate and low government expenditures. This is followed by scenario 3, which is the scheme without subsidies for reduction in water use, followed by scenario 1, which is the 1993 scheme of subsidies in the area. Although in 1993 all the farmers were accepting this type of subsidy, the reduction in water use seems to be motivated by the maximum water endowment established by the government and not by the given amount of subsidies. In this sense it would be reasonable to maintain these subsidies only for a period of five years, as the government planned. Alternatives considering a reduction in the subsidies for sunflowers or pea cultivation or set-aside were ranked as the worst. A policy considering a water market pricing with cost of groundwater equal to 10 pesetas/m3 would not be effective.

Results

The multicriteria analysis indicated that a policy considering increases of 50% in subsidies for cereals would be better than the subsidy scheme implemented in the area in 1993, or any other subsidy schemes. However, this strategy would not lead to a recovery in the aquifer's water table. Reduction in water use for irrigation is most effective through a policy of maximum groundwater

endowment established by the government, and not through subsidies set to discourage the use of groundwater. In order to re-establish the natural equilibrium discharge–recharge in the aquifer system, strong restrictions on the use of groundwater for irrigation have to be implemented. The cropping pattern in the area would change dramatically as a consequence of policies diminishing subsidies for sunflowers, peas or set-aside. An adequate and planned policy for subsidies for crops has to be implemented and continued.

4 DISCUSSION AND CONCLUSIONS

The study is an illustration of a case in which the concept of model-based Planning Support Systems (PSS) proved to be applicable and usable. The concept is particularly useful to support logical, rational and transparent decision-making processes. The developed system was innovative in the sense that it was based on an integration of the results of three different models, namely a resource analysis, a planning and a multicriteria evaluation model. Specifically the system included the following models:

(a) A water balance model of the groundwater basin which, considering average meteorological conditions, simulates the average yearly recharge of the aquifer system, with respect to the land use changes. This model was used for 'resource analysis' and understanding of the behaviour of the system 'representation/behavioural model'. In this model remote sensing and GIS played a crucial role.

(b) A mixed integer-programming model simulated the farmers' reactions/decisions to the different subsidy schemes. This model, which was based on rational farmers who wanted to maximize their profits, was used as a 'planning model' to formulate and assess the impacts of various policy instruments.

(c) A multicriteria evaluation model, which allowed planners to consider the impact of different policy instruments with the priorities of different actors (farmers, environmentalists and government) and select the most attractive options.

(d) All models together, integrated in a system, provided a framework for rational analysis of situation and formulation of policies, assessing their possible impacts, and a tool for analysing different policy options and transparent reasoning for selection of proper policies.

The results obtained with the system are specific for water resources rehabilitation in the study area of La Mancha, Spain. However, the concept of PSS as developed and applied in this study is general and can be applied and extended to other areas and disciplines. This is an especially useful concept for making use of ever-increasing detailed digital data and knowledge related to the resources and the processes through which they are or can be utilized. The concept might turn out to be particularly useful in cases where options/scenarios have to be formulated; and decisions have to be made, on the basis of an evaluation of various scenarios/options that are developed on the basis of a detailed resource analysis and an analysis of the resource allocation at a disaggregated level. Thematic areas where the concept can be further developed and applied are in the field of agriculture, land rehabilitation, water resource management, forest resources, etc.

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ABBREVIATION LIST

CHG   Confederacion del Guadiana
DM   Decision maker

EC   European Community
EEC   European Economic Community
FMPEE   Fundación Municipal Para el Empleo y el
          Desarrollo Económico de Alcázar de San Juan
GIS   Geographic Information System
ILWIS   Integrated Land and Water Information System
MIP   Mixed Integer-Programming Model
PSS   Planning Support System
TM   Thematic Mapper
WHC   Water Holding Capacity

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