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MOPECO: an economic optimization model for irrigation water management

Received: 24 June 2003 / Accepted: 2 February 2004 / Published online: 26 March 2004
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Abstract Water is a natural, sometimes scarce, and fundamental resource for life, essential both for agriculture in many regions of the world and also to achieve sustainability in production systems. Maximizing net returns with the available resources is of the utmost importance, but doing so is a complex problem, owing to the many factors that affect this process (e.g. climatic variability, irrigation system configuration, production costs, subsidy policies). The MOPECO model is a tool for identifying optimal production plans, and water irrigation management strategies. The model estimates crop yield, production and gross margin as a function of the irrigation depth. Finally, these gross margin functions are used to determine an optimum cropping pattern and irrigation strategy to maximize the gross margin on a farm in a specific scenario. Since the relationships between the variables are generally non-linear and the number of alternative strategies is quite large, the optimum process is complex and computationally intensive. Genetic algorithms are therefore used to identify optimal strategies. This paper describes the MOPECO model, which comprises three computing modules: (1) estimation of net water requirements; (2) derivation of the relationship between gross margin and irrigation depth; and (3) identification of the crop planning and the water volumes to be applied. The results obtained by applying the MOPECO model to a specific irrigable area in a semi-arid area of Spain, with great deficits and high water costs, are also included and discussed. These results usually show that the irrigation depth for maximum benefits is lower than that necessary

to obtain maximum production. In some areas of Spain, horticultural crops are nearly always part of the optimum alternative. The crops that become part of the optimum alternative are mainly horticultural crops with a high gross margin and low water requirements. The irrigation depths selected for the ideal crop rotation are included among the irrigation depth of maximum economic efficiency and the maximum gross margin irrigation depth. Both are lower than that necessary for the maximum yield. This model helps farmers, extension services, and other agents to analyse, make decisions and optimize water management.

Introduction

In the world today, quite a large surface is irrigated. The European country with the largest irrigated surface area is Spain, with 3,500,000 ha (FAO 2002).

One of the solutions to the current problem of limited arable land and rising population could be the increase and improvement of irrigated lands, deemed “the blue revolution” by some authors (Oweis 1994). Irrigation is already a critical factor in many areas of our planet, including an important part of Europe, where the water resources are often derived from groundwater. Worldwide, irrigated agriculture is responsible for more than 80% of water consumption in arid and semi-arid zones. However, the irrigation costs, the risk of overexploitation of aquifers and the adverse environmental impacts of irrigation are troublesome aspects. Given these concerns, the optimum management of available hydrological resources must be a fundamental objective, both for water management authorities and farmers. Rational and responsible management is essential in order to ensure the sustainability of irrigated agriculture.

Many factors are involved in irrigation planning and management, including the availability of water, commercial capacity, existing structures, limitations and constraints of agrarian policies, etc. This paper presents an analytical model for economically optimum irrigation

Communicated by A. Kassam

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water management which is able to take these complex factors into account. This tool could serve as a decision-making aid to assist farmers, irrigation services and those responsible for hydrologic planning in analysing alternative irrigation strategies.

Nevertheless, conventional irrigation management strategies are planned without taking deficit irrigation into consideration, since economically optimum irrigation strategies imply some degree of under-irrigation (Tarjuelo and de Juan 1999).

Methodology

The relationship between crops, climate, water and soil implies the complex interplay of biological, physiological and biochemical processes. However, practical considerations require that the relationship between applied water and crop yield be simplified in order to arrive at irrigation management decisions (Doorenbos and Kassam 1979; English et al. 1992).

The MOPECO model is made up of three computing modules:

- *Module I* determines seasonal net irrigation depths (Doorenbos and Pruitt 1992; Pereira and Allen 1999).
- *Module II* employs a normal statistical distribution to simulate water distribution for the irrigation system based on Christianen's uniformity coefficient (CU). By considering the crop yield and economic data, the gross margin is related to the irrigation depth for each crop.
- *Module III* identifies cropping patterns and irrigation strategies that maximize total profits on a farm. These optima must accommodate restrictions imposed by the process (such as available water, area, etc), a problem which is solved using genetic algorithms.

MOPECO is a user-friendly computer model which can easily be accessed by technicians and managers of irrigated areas.

Computing module I: water requirements

The objective of this module is to determine the required number and timing of irrigations throughout the crop cycle for maximum

yield (ET_m), (see Fig. 1). Reference crop evapotranspiration (ET_o) is determined as the average of the Penman-FAO and Penman-Monteith methods applied daily. In semi-arid areas the most precise estimate is obtained using the mean values of Penman-FAO and Penman-Monteith (Mantovani 1993; Cabañero et al. 2002).

Computing module II: effect of irrigation uniformity on crop yield, determination of cost and gross margin functions

The functions of the second computing module are the following (see Fig. 2):

- A normal statistical distribution function representing the water applied by the irrigation system (Fig. 3). This function simulates, for different CU values, irrigation quality parameters which allow us to estimate crop yield when integrated in a production function.
- Tested yields are used to estimate gross revenue (yield multiplied by crop price).
- A cost function is developed to quantify the global production costs for different crops. Cropping costs that are linked to yield (e.g. seeding rates, fertilizer use and harvest costs) and therefore indirectly linked to applied water, are treated as a function of yield.
- A function that relates gross margin to the irrigation depth is obtained for each crop. These functions are used in module III to find the management that achieves the highest total profit for the farm.

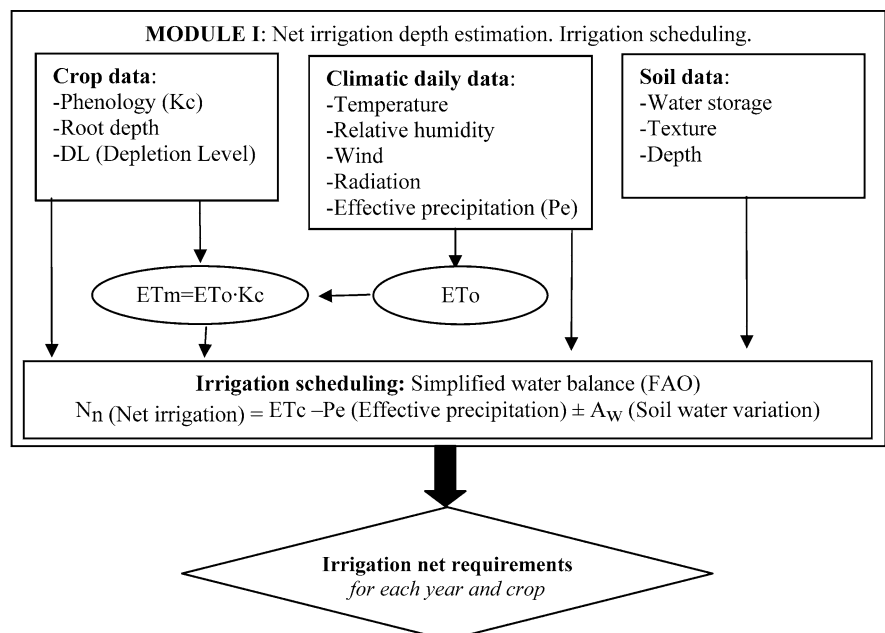
The model starts with the production function of Stewart et al. (1977), which estimates the crop yield based on the relation of evapotranspiration (ET_a/ET_m) (Eq. 1).

$$\frac{Y}{Y_m} = \prod_{i=1}^n \left(1 - k_{yi} \cdot \left(1 - \frac{ET_a}{ET_m} \right)_i \right) \quad (1)$$

where Y = real harvested yield ($kg\ ha^{-1}$); Y_m = agronomic maximum yield that can be achieved in a given area when crop development is not limited by water availability or other factors ($kg\ ha^{-1}$); k_y = proportionality factor, which shows the sensitivity of the crop to water stress (Table 1); ET_a = actual crop evapotranspiration (mm); ET_m = crop evapotranspiration for maximum yield (mm); and i = the developmental stages of the crop.

Fig. 1 Flow chart of MOPECO

Module I: net water irrigation requirement. K_c crop coefficient; DL depletion level for the crop at which actual ET begins to decline from the potential rate (decimal); P_e effective precipitation (mm); ET_m crop evapotranspiration for maximum yield (mm); ET_o reference crop evapotranspiration (mm); N_n net irrigation water requirement (mm); A_w variation in soil water storage (mm)



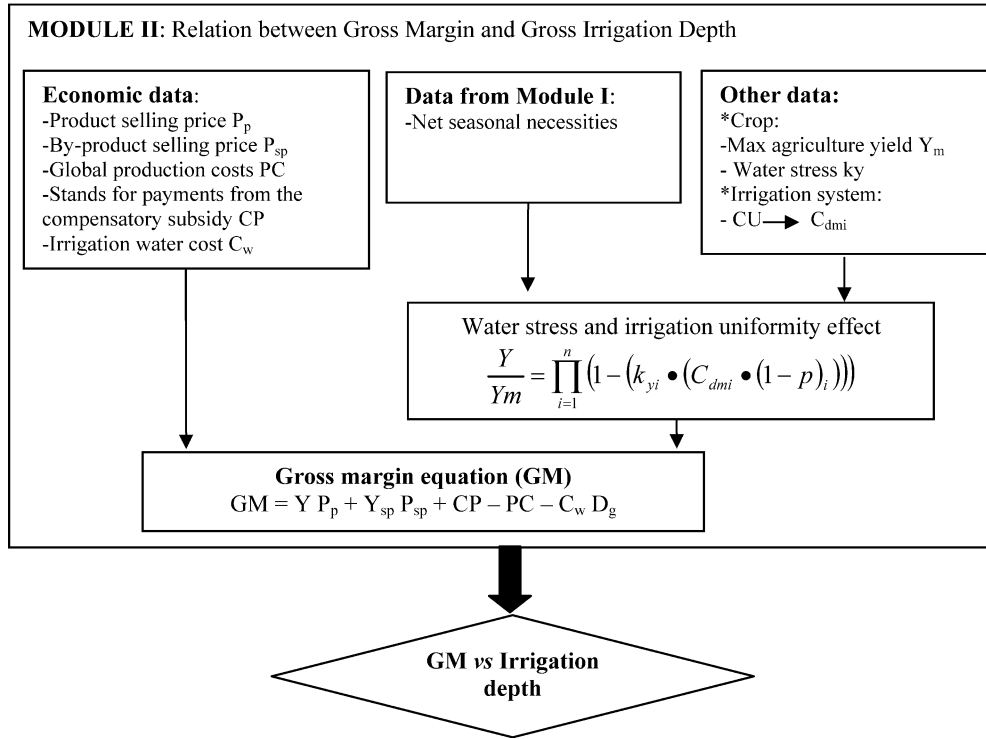


Fig. 2 Flow chart of MOPECO Module II: gross margin versus gross irrigation depth. P_p selling price of the product (€ kg^{-1}); P_{sp} selling price of the by-product (€ kg^{-1}); PC global production costs for actual yield (€ ha^{-1}); CP payments from the compensatory subsidy for some crops (€ ha^{-1}), in Europe by the common agricultural policy (CAP); C_w cost of irrigation water application (€ m^{-3}); Y_m agronomic maximum yield that can be achieved in a given area when crop development is not limited by water availability or other factors (kg ha^{-1}); k_{yi} proportionality factor for each growth and development stage (i), which shows the sensitivity of the crop to water stress; CU Christiansen's uniformity coefficient; Y real harvested yield (kg ha^{-1}); C_{dmi} mean deficit coefficient for each growth and development stage (i); $(1-p)_i$ ET fraction for each of the crop's growth and development stages whose needs are met through the irrigation water applied; GM gross margin (€ ha^{-1}); Y_{sp} commercial by-product yield (kg ha^{-1}); D_g gross depth applied by the system ($\text{m}^3 \text{ha}^{-1}$)

The deficit coefficient in the root zone based on the quantity of water in the irrigated field (C_d) (Hart and Reynolds 1965) is integrated (by means of its effects on ET_d) into the production function as follows (Mantovani 1993; Anyoji and Wu 1994; Ortega 2000):

$$\frac{Y}{Y_m} = \prod_{i=1}^n \left(1 - (k_{yi} \cdot (C_{dmi} \cdot (1-p)_i)) \right) \quad (2)$$

where C_{dmi} = mean deficit coefficient for each growth and development stage (i); and $(1-p)_i$ = ET fraction for each of the growth and development stages of a crop whose needs are met through the irrigation water applied (the rest is supplied by the effective rainfall and the variation of the water stored in the soil).

Global production costs include all the costs associated with the agricultural production process, except fixed costs or structural costs and those relative to irrigation water application. The global production costs include (Loring 1988; Alonso and Serrano 1991; Ortega 2000; de Juan et al. 2003).

– *Direct costs*: production costs (e.g. fertilizers, seeds, treatments, utilization cost of machinery, harvest insurance, drying and rents).

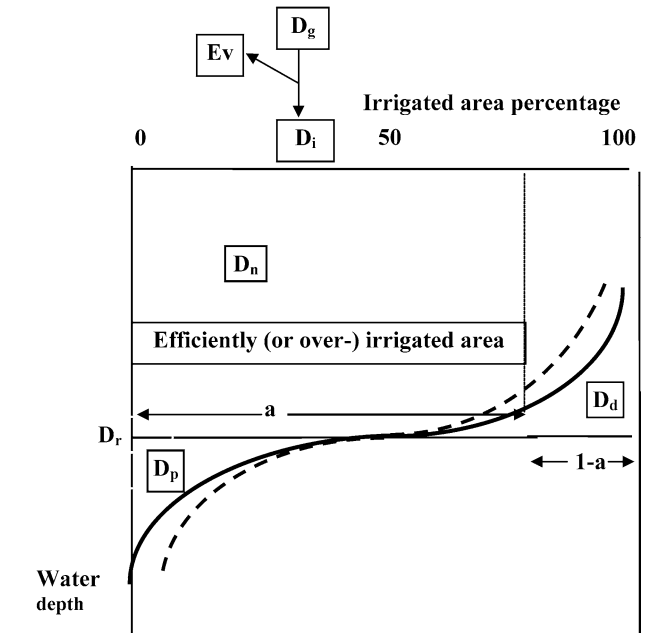


Fig. 3 Normal function of irrigation water distribution over the plot (effect of CU). The curve in broken line corresponds to a CU value lower than the distribution curve in continuous line. D_g gross irrigation depth discharged by the system (mm); Ev losses during the irrigation process (evaporation and drift) (mm); D_i depth applied to the soil and infiltrated (mm); D_n net depth stored in the root zone (mm); D_d deficit depth in the under-irrigated zone (mm); D_p percolated depth in the over-irrigated zone (mm); D_r required depth by the crop (mm); a percentage of adequately or over-irrigated area

– *Financial costs*: the cost of money invested temporarily in each agricultural production campaign. In this study, we use an interest rate of 5%.

Table 1 k_y values for the different crop stages and development of study crops

Crop	Stages of the growing and development cycle			
	I (initial)	II (development)	III (midseason)	IV (late)
Barley	0.20	0.60	0.50	0.40
Soft wheat	0.20	0.60	0.80	0.40
Wheat	0.20	0.60	0.80	0.40
Grain maize	0.40	0.40	1.30	0.50
Oleaginous rape	0.40	0.60	0.80	0.40
Oleaginous sunflower	0.40	0.60	0.80	0.80
Sugar beet	0.70	0.70	1.00	1.00
Garlic	0.45	0.80	0.80	0.80
Onion	0.45	0.80	0.80	0.80
Potato	0.45	0.80	0.80	0.35
Green peas	0.20	0.60	1.00	1.00
Green beans	0.20	0.60	1.00	1.00
Sweet maize	0.40	0.40	1.30	1.00

With regard to irrigation costs, the MOPECO model treats these as being independent from global production costs. The determination of the price of water is very complex due to the multiple objectives of the different water uses (agricultural, ecological, landscape, etc). According to its valuation as a productive factor, some issues that determine irrigation water application costs are: pumping, storage, distribution and the application of water to the plot.

To determine crop costs, questionnaires and personal interviews were given to farmers. These studies reflect, chronologically, the farm work and operations with a definite target yield, along with the most important technical information about the operations carried out (e.g. machinery, labour, performance, running time, time efficiency). This information will therefore allow us to quantify and economically assess the production process.

Finally, by analysing the different yield objectives, we have enough information to model the cost with reference to crop yield.

The gross margin is obtained from the sale of commercial products and from the possible subsidies for each crop minus the production costs (Eq. 3).

$$GM = Y P_p + Y_{sp} P_{sp} + CP - PC - C_w D_g \quad (3)$$

where GM = gross margin (€ ha^{-1}); Y = real harvested yield (kg ha^{-1}); P_p = selling price of the product (€ kg^{-1}); Y_{sp} = commercial by-product yield, if present, it is estimated as a relation between Y/Y_{sp} , (kg ha^{-1}); P_{sp} = selling price of the by-product (€ kg^{-1}); CP stands for payments from the compensatory subsidy for some crops (€ ha^{-1}), in Europe by the common agricultural policy (CAP); PC represents global production costs for actual yield (€ ha^{-1}); C_w = cost of irrigation water application (€ m^{-3}); and D_g = gross depth applied by the system ($\text{m}^3 \text{ha}^{-1}$).

The simulation process is carried out for several irrigation depths (between 12 and 60) by means of the normal function.

Computing module III: annual crop rotation optimization using genetic algorithms

Once the relationships between gross margin and gross irrigation depth has been established for each crop, the objective is then to identify the crop planning that optimizes irrigation water use (Zekri and Romero 1992; Ortega 2000). The optimization criteria are based on two key variables: the expected farm profit and the economic risk associated with annual climatic variability.

The problem is complex due to:

- The wide searching domain which includes crops both traditional and novel to farmers.
- A non-linear relation exists among the variables that must be considered. The relation between the gross margin and the gross irrigation depth is essential when studying these variables.

- The restrictions that must be included (available water, surface, CAP, etc.) increase the number of variables associated with each crop. Three variables for each crop have been considered: area, recommended irrigation depth and, if applicable, fallow land. In this case, simple broad application methodologies (linear applications) are not usable.

To deal with this situation, we have resorted to different methodologies based on multi-criteria optimization (Romero et al. 1987; Berbel 1988), benefits expected (MOTAD) (Tauer 1983), risk and uncertainty (English 1981; Alaejos and Cañas 1993) and other solutions based on dynamic programming, evolutionary computation, etc (Hillier and Lieberman 2001). The optimization methodology is based on genetic algorithms, a technique that is used increasingly as a solution to engineering problems (Ortega 2000; Kuo et al. 2000; Montesinos et al. 2001).

Optimization by means of genetic algorithms

The desired objective is to maximize the farm's gross margin as the sum of the gross margins of each crop. The expression of gross margin is:

$$GM_F = \sum_{i=1}^N A_i (1 - A_{aside_i}) \cdot GM_i = \sum_{i=1}^N A_i (1 - A_{aside_i}) \cdot (Y P_p + Y_{sp} P_{sp} + CP - PC - C_w D_g) \quad (4)$$

where: GM_F = total gross margin of the farm (€); N = number of crops; i represents each crop analysed; A = area of each crop (i) (ha); A_{aside_i} = area set aside by common agricultural policy (CAP); and GM_i = crop i gross margin (€ ha^{-1}).

The genetic algorithms conduct a random search for a set of structures (individuals), while an iterate wave will select those individuals which best adapt to the desired solution (Goldberg 1989; Davis 1991; Holland 1992). This adaptation to the desired solution can be compared to the natural evolutionary process of survival of the fittest. In other words, those best adapted have more possibilities of surviving and, therefore, of transmitting their own characteristics to future generations. The individuals are characterized by a determined genotype, which represents the structure of the characterized information (the same for the entire population). Information contained in each individual is called phenotype.

A genetic algorithm basically follows the flow chart shown in Fig. 4. The process begins with an initial population (usually randomly generated) where once the individuals have been evaluated and classified according to their "aptitude" (the best adaptation to the desired solution), those that will take part in the reproduction process are selected. This is done with new population elements (offspring) whose phenotypes are obtained through the combination of the parents' phenotypes. In order to maintain a constant

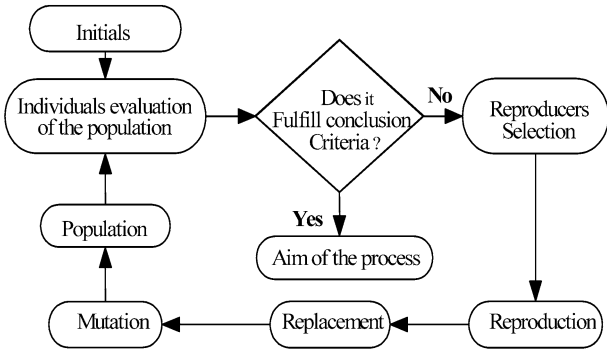


Fig. 4 Flow chart of the genetic algorithm

population throughout the whole process (as far as number is concerned), the new individuals will substitute for those less fit from the previous generation, thus renewing part of the population in each generation. Finally, before continuing the process, mutations will be randomly caused in the whole population (changes in some bits) with little impact on the set of individuals. The whole process is cyclical until reaching the maximum generation or a previously established top number (Ortega 2000).

When using MOPECO, the genetic algorithm will take into consideration the elements and sequences of the following processes.

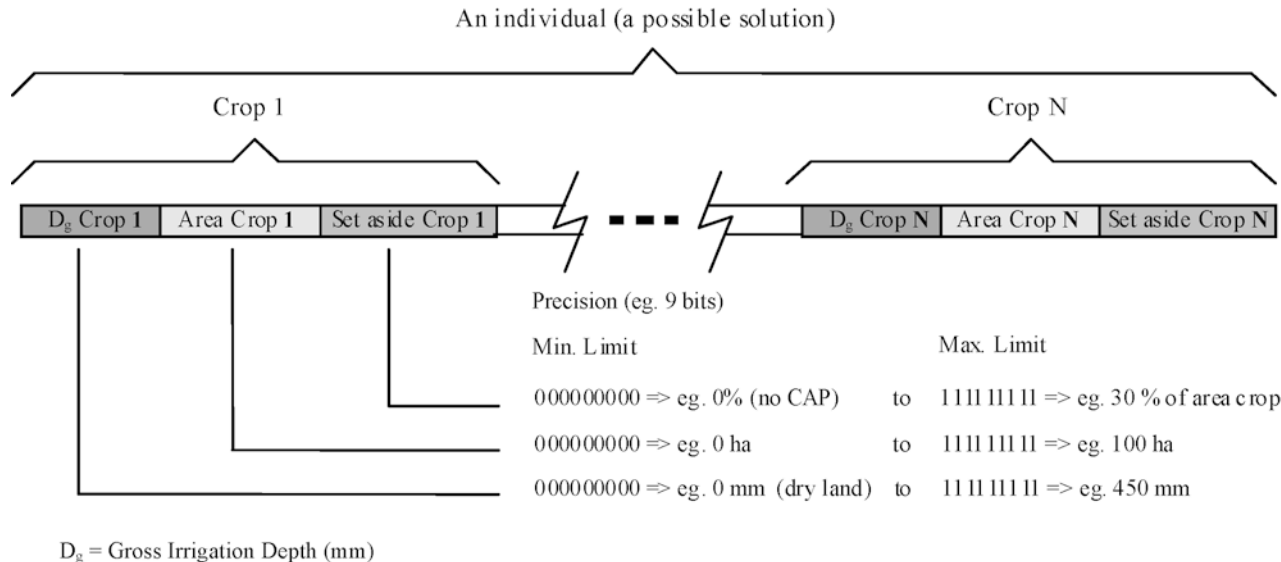
Coding

This is established by means of binary chains from an individual's phenotypes, so that each combination constitutes a solution in the dominion of the problem.

The appropriate coding of information is a key factor in this type of problem (Holland 1992). In the problem studied, three variables have been selected for consideration: the surface area of each crop; recommended gross irrigation depth and fallow land (CAP crops).

In Fig. 5, the structure of the population's genetic code (genotype) can be seen. Each value for irrigation depth, area or set-aside land corresponding to a crop is called a "gene". In order to code each gene, a whole value of 32 bits has been used (length of the data

Fig. 5 Schematic representation of the codification of the possible individuals in the population



bus in current PC processors). In this way, process discharge speed and high precision of results are obtained simultaneously.

Evaluation function and aptitude

In order to select individuals, it is necessary to establish functions that evaluate their aptitude level. An evaluation operator adapted to the problem under analysis must be established, taking into account the surroundings where the individuals in the population evolve. This operator evaluates the genetic codes of all the individuals in the population, assigning each one of them a "fitness" value that allows us to select those that best adapt to the objective of maximizing the gross margin. The appropriate combination will turn the binary values of each gene to floating point values in a ranking from 0 to 1, by means of the following expression:

$$x = x_{min} + gen \times \frac{x_{max} - x_{min}}{2^{Len} - 1} \tag{5}$$

where x = decoded value; x_{min} , x_{max} are minimum and maximum values that x can adopt, respectively; gen = value of the gene; and Len = length of bits of the gene.

In order to obtain the value of the proportion of land occupied by each crop we use a bidding system. This system adds all the values of the area corresponding to the crops taken into account, calling the value obtained "total limit area". By dividing the area of each crop by the total limit area, we obtain the rate per unity of occupation over the total. With this distribution, the whole area of the farm would be assigned to crops, not contemplating the possibility of land not being cultivated (fallow land). The bidding system has the advantage of bringing about great variability in the results. If a crop modifies its bid, it will cause a variation in the land value of other crops and consequently in the final individual's gross margin. In this way, the possibility that the evolution of the population stagnates around optimal premises is reduced. A similar procedure has been used for the variable corresponding to the irrigation depth assigned to each crop.

Sanctions are used to ensure that crop restrictions regarding total area and assigned water are met (Michalewicz 1998). This is necessary since it would not be advantageous to entirely eliminate an individual who obtains good benefits but fails to a small degree to comply with established limits. If we did not allow him to participate in the reproduction process, he could not contribute his genetic code to the evolution of the population. The sanction consists in reducing the gross margin of the individual who does not comply with the restriction. The excess of gross margin generated by the variable that does not comply, multiplied by a sanction factor, is subtracted from the individual's gross margin. In

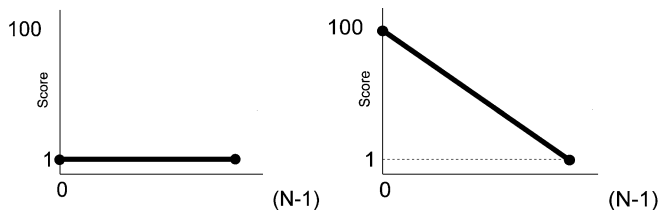


Fig. 6 Allocation of scores in the selective process: effect of selective pressure

this way we can be sure that the individual who does not comply will not be chosen, but will continue working with part of his genotype.

To calculate the land set aside, we begin with the value of the area occupied by the crop and we multiply it by a value in the margin 0,1, thus obtaining a rate per unit of the crop area for which it is destined.

In order to determine the benefit produced by a crop, we obtain the area that it occupies, subtract the set-aside land, calculate the water consumed by the crop and divide this water by the area without the set-aside land. The result will be the applied irrigation depth. With this last value, by consulting the table of benefits by hectare for this crop based on the applied irrigation depth, we will obtain the total benefit of the cultivated area. Then the possible CAP subsidies for each crop are calculated and added to this, thus obtaining the total benefit.

Next, the limits of area, water and set-aside for the crop are verified and the corresponding sanctions are imposed. The total benefit obtained on the farm is the sum of the benefits for each crop.

The evolution module classifies individuals according to the benefit obtained by the solution that they contribute to, assigning them a score which is based on the position that each individual occupies after classifying the population according to the benefit obtained by each individual, by means of the equation:

$$\text{Score} = \frac{N - X - 1}{100} \times P_s + 1 \quad (6)$$

where N = number of individuals; X = position that the individual occupies between 0 and $N-1$; and P_s , selective pressure.

Figure 6 is the allocation of the scores with selective pressures zero and one hundred, respectively.

The value of selective pressure quantifies the advantage for an individual who has attained a higher benefit at the moment of selection for reproduction. If this parameter is 0, all the individuals will have the same probability of being chosen (Score = 1 for each individual). With the selective pressure value, the time search for the optimal value can be reduced, although the result will be a loss in the diversification of genes in the population.

During the optimization process, the benefit obtained by the fittest individual in the population of each generation was compared with the benefit obtained by the optimal individual up to that time. If the benefits are equal, then the population has not evolved. The situation can be repeated a certain number of times. This value, which is stored in the program, is called "blockade".

The blockade value is used to stop the optimization process when the population can no longer evolve, e.g. when we have arrived at the optimal state, or when a "blockage" has taken place around some optimum site. The detection of the latter allows us to

apply a determined process to the population or to an individual which "removes" the population from the optimum site. It is then possible to evolve towards a better solution.

The unblocking process consists in altering the genetic code of the optimal individual obtained up to that time (Hinterding et al. 1997). To achieve this goal, we used a characteristic specific to this problem, which in this case is the strong dependency between the water variables and area assigned to each crop and also their interrelation with the other crops.

In fact, if we considered two crops (crop-1 and crop-2) with their assigned values of water and area, it is possible for the value of water-1 with area-1 to provide high benefits, but if we start with the resources used by crop-1 and use them in crop-2, this could contribute to greater benefits, simultaneously increasing the two variables. As in the evolution of the genetic algorithms, it is more likely to change a single value. If for example, the assigned area-1 diminishes, this crop may have more water than it needs. However, crop-2, with a greater amount of assigned area, may not have enough water. In this case, the benefit would diminish and this intermediate solution would be worse than it was to begin with.

In order to avoid the situation discussed in the previous paragraph, we need the algorithm to modify variables two by two in order to obtain better solutions. To do so, we start with a reference crop and simultaneously modify the area and water variables for two crops, changing 4 bits of the genetic code of the best individual (each bit belongs to each one of the mentioned values); and finally we assess the new solution. If it is better than what we began with, it is introduced into the population.

Selection of the reproducers

After assigning each individual a score, we come to the selection for the reproduction process in which it will participate. Preferably, the individuals with the highest scores will have a greater probability of reproducing, although any individual may be chosen in the selection process (Mitchell 1996).

The method used for the selection of the individuals is as follows: an accumulated score is calculated by assigning the first individual its score. A value is assigned to the following individual, which is the highest accumulated score of the previous individual plus its own score and so on. This is shown in the example in Table 2, where a selective pressure of 100 has been chosen.

The accumulated score value for the last individual, which we call "total", allows a normalization of the accumulated values that are obtained by dividing the accumulated score of each individual into this amount. In this way, the last value of this standardized column will be 1 and the value of all the previous individuals will be included between 0 and 1.

For the selection of the N (even number) individuals that will participate in the reproduction process, the following process is set up for each one of them: a random value between 0 and 1 is calculated and the whole population is explored until a greater value of accumulated score than this random value is found (Fig. 7).

Once the pairs have been randomly established, we come to their reproduction. In this case, we have established two offspring for each pair. We obtain a random whole number of bits of genes, between 0 and the number minus one. This value is used to divide the chains corresponding to the offspring into two parts. For the chains of the first offspring, one will be occupied by the bits of the father's gene (same position) and the rest by bits of the mother's gene. The second offspring is done in a complementary way, as

Table 2 Allocation of the accumulated score

	Gross margin	Order	Score	Accumulated score (AS)	AS/Total score
Individual 1	2,500	2	2	2	0.2
Individual 2	3,500	0	4	6	0.6
Individual 3	2,000	3	1	7	0.7
Individual 4	3,000	1	3	10	1.0

Fig. 7 Selection of an individual for the reproduction process

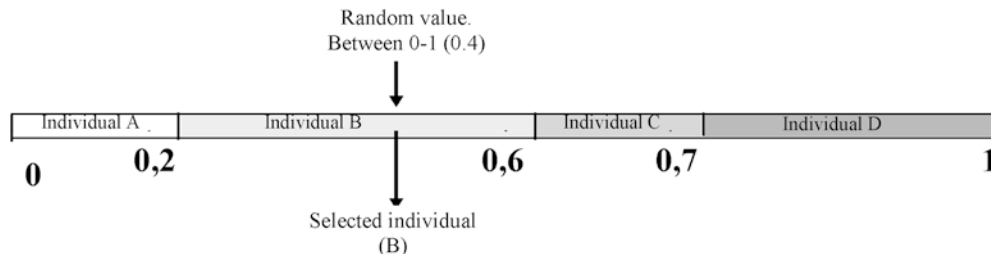
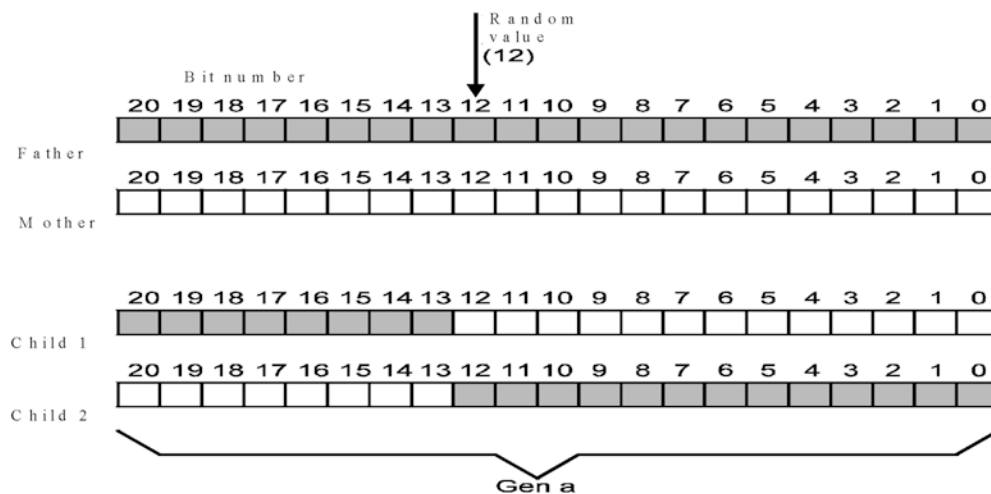


Fig. 8 Crossing of individuals, gene by gene



indicated in Fig. 8. In this way, we cross the individual's genetic code the same number of times as there are genes in the population.

The percentage of individuals that participate in the reproduction is variable. In order to implement this particular case, 30% has been chosen, i.e. 150 individuals (75 pairs).

Restrictions

The characteristics of the problem impose restrictions or limitations to the possible solutions. There non-feasible phenotypes must be detected and penalized in the process.

The main restrictions in our application are the limits of assigned area and water in each crop. The common agricultural policy (CAP) is also a basic restriction, as far as the percentage of areas that must or can be left as set-aside.

Computing module III: choosing solutions by risk analysis

Once the methodology of optimization by genetic algorithms has been applied, a result for each climatic year is obtained. Each year's solution represents a prescribed plan of action consisting of a cropping pattern and a corresponding optimum irrigation scheduling for each crop.

To select an alternative among the solutions that would provide the greatest gross margin for each of the climatic years, a new variable is introduced. The economic risk is associated with each one of the alternatives (Tauer 1983). This risk is defined as the difference between the gross margin achieved and a reference gross margin (Ortega 2000).

The possible reference values depend on the preferences of the analyst. To standardize the procedure as much as possible, an unequivocal reference gross margin can be identified for each setting, the maximum net income possible under that setting, without limitations on water resources and without any other restrictions.

GM_p is the potential gross margin of a setting and GM_a is the real gross margin achieved in any productive setting. For a given climatic year, the risk (R) associated with the contrasted alternative is given by the following equation:

$$\text{Risk } (R) = GM_p - GM_a \quad (7)$$

The cumulative risk associated with a specific alternative corresponds to the sum of risks, determined for each year, as a consequence of the application of this crop rotation throughout the climatic series of study (Eq. 8).

$$\text{Accumulative Risk} = j \cdot GM_p - \sum_{n=1}^i GM_{i,j} \quad (8)$$

where j = years of analysis; i = analysed crop planning alternatives.

Table 3 shows a solution matrix to determine the risk associated with each selected crop rotation and part of an example for crop planning. After this process, the alternative that presents the lowest accumulated risk is the one recommended.

This approach, based on comparison with a potential gross margin of reference for each possible scenario (GM_p), allows us to analyse the risk due to other factors, such as crop price variability or the output of marketable products (Ortega 2000). GM_p is the greater gross margin of all the analysed crops, without restriction and for the average costs and prices. In this case it is the onion, with a gross margin of 5,728 € ha⁻¹ (Table 3). It is recommended to use a clear and constant reference value for all the analyses. $GM_{i,j}$ is the result to apply the obtained optimal crop rotation for each year (i), in the example year 1984 (of minimum risk), on each of the analysis years (j), in our case climatic series 1974–2000.

The final risk is the sum of all the differences between the potential gross margin (GM_p) (maximum) minus the real gross margin obtained with the analysis alternative for each year of study. The risk is expressed in accumulated € ha⁻¹ during the analysed series (Table 3). Thus, whichever is the lower for this value, the

Table 3 Accumulated risk for the selected crop rotation each year of analysis (example for the year 1984)

Year	Crop rotation selected in the I stage (genetic algorithms)				
	1	2	3	Example: 1984	I
1 (1974)	$GM_p-GM_{1,1}$	$GM_p-GM_{2,1}$	$GM_p-GM_{3,1}$	$5,728-1,597 = \text{€}4,131 \text{ ha}^{-1}$	$GM_p-GM_{i,1}$
2 (1975)	$GM_p-GM_{1,2}$	$GM_p-GM_{2,2}$	$GM_p-GM_{3,2}$	$5,728-1,655 = \text{€}4,073 \text{ ha}^{-1}$	$GM_p-GM_{i,2}$
3 (1976)	$GM_p-GM_{1,3}$	$GM_p-GM_{2,3}$	$GM_p-GM_{3,3}$	$5,728-1,737 = \text{€}3,991 \text{ ha}^{-1}$	$GM_p-GM_{i,3}$
4 (1977)	$GM_p-GM_{1,4}$	$GM_p-GM_{2,4}$	$GM_p-GM_{3,4}$	$5,728-1,237 = \text{€}4,491 \text{ ha}^{-1}$	$GM_p-GM_{i,4}$
<i>J</i> (last year)	$GM_p-GM_{1,j}$	$GM_p-GM_{2,j}$	$GM_p-GM_{3,j}$	$GM_p-GM_{1984,27(2000)}$	$GM_p-GM_{i,j}$
Risk	$j \cdot GM_p - \sum_{n=1}^j GM_{1,j}$	$j \cdot GM_p - \sum_{n=1}^j GM_{2,j}$	$j \cdot GM_p - \sum_{n=1}^j GM_{3,j}$	€96,260	$j \cdot GM_p - \sum_{n=1}^j GM_{i,j}$

objective will be closer to the potential benefit. The analysis can be complemented with statistical parameters that show of the inter-annual variation of the risk. Normally, the solution of smaller risk also corresponds with smaller inter-annual variability.

Thus, the MOPECO model provides a tool for choosing among multiple options, involving complex relationships between many variables, and taking risks into account (Zekri and Romero 1992).

Reference setting for the application of the model

The model was used to analyse irrigation strategies in the Castilla-La Mancha region (Spain). The region is identified as Hydrological System 08.29 in the oriental Mancha. It covers 8,500 km² in the southeastern Iberian peninsula (Fig. 9). A regional aquifer supplies water to 105,000 irrigated hectares and 300,000 inhabitants. The renewable resources of the aquifer are about 420 hm³ per year (Martín de Santa Olalla et al. 2003).

As a consequence of groundwater exploitation, the level of use exceeds the renewable supply. Thus, the objective is to maximize the efficiency in the use of irrigation water in all respects (e.g. economic, application, etc). The average volume of water available for this type of operation is 4,000 m³ ha⁻¹ per year, according to the system's working plan. The cost of irrigation water application in the area (C_w) is high, either 0.06, 0.10 or 0.15 € m⁻³, which influences the decision-making process. These costs include extraction, storage, distribution and application costs (Ortega 2000).

Most physical characteristics of the region are rather homogeneous, which simplifies the application of the model (topography, climate, resources availability) (Martín de Santa Olalla et al. 1999). The region is primarily a vast plain at a mean altitude of 700 m, with some variation in elevation near the borders.

The climate is semi-arid with a mean annual precipitation lower than 400 mm and an ET_o higher than 1,200 mm. Intense drought periods are common and annual precipitation is highly variable. Precipitation during the cropping season is very low, especially in summer.

In applying the model, 27 years of daily hydrological data were used to analyse the impact of annual climate variability. The data series spanned the years 1974–2000, and were derived from data gathered from the Los Llanos meteorological observatory (longitude 1°51' W; latitude 38°57' N; altitude 704 m), which is representative of the regional climate. The most relevant data are: mean temperature; 13.7°C; mean precipitation; 372 mm (although June to September is less than 100 mm, and April is the rainiest month of the year).

The existing farms in the area present different characteristics with respect to area, farmer's level of education, irrigation system, etc. Taking size as the basic characteristic that defines a farm, although closely related to other parameters, the representative farm type can be established for 68% of irrigated area and for the 70% with the following characteristics (Tarjuelo et al. 1999):

- average area: 50 ha
- irrigation system: solid set system
- spacing: the most usual one is 18×18 m
- mean application rate: 6 mm h⁻¹
- CU: 82%.

The most representative crops in the area are large-scale herbaceous (e.g. winter cereal, maize), together with some industrial crops (sunflower, beet) and other horticultural crops (garlic, onion) although with less area. In any case, the crop area regulated by the common agricultural policy (CAP) is greater than 60% of the total. Irrigated agricultural surface in the area greatly depends on the evolution of the CAP (Castillo 2003). The crops analysed and their economic data and yields can be found in Table 4.

Fig. 9 Castilla-La Mancha region (Spain) and location of Hydrological System 08.29 (marked area)

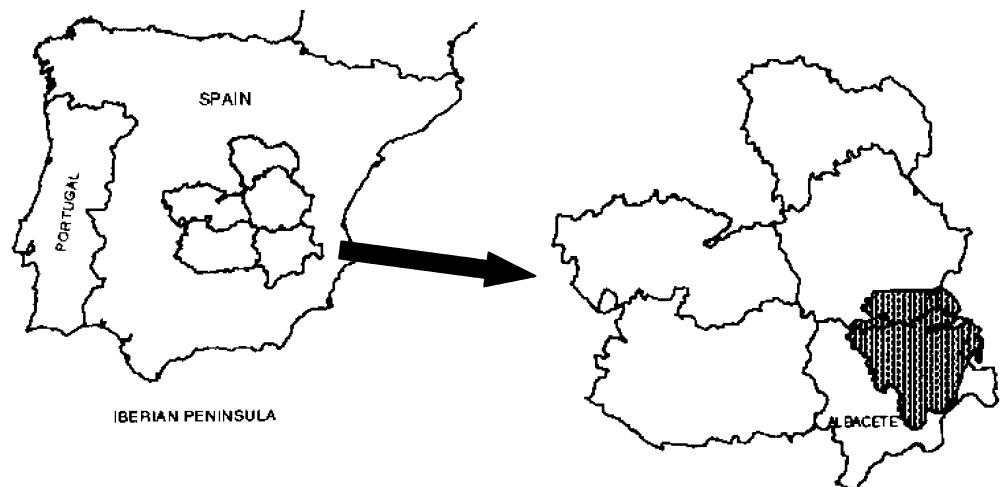


Table 4 Mean sale price of the commercial products and by-products in Hydrological System 08.29 and its coefficient of variation (CV), CAP subsidies in the irrigated area and maximum farming yield

Product	Product price (€ kg ⁻¹)	CV (%)	Byproduct price (€ kg ⁻¹)	CV (%)	CAP subsidies (€ ha ⁻¹)	Max. yield (kg ha ⁻¹)
Grain maize	0.144	4.4	–	–	327.1	15,000
Barley	0.138	4.7	0.042	2.0	219.9	6,500
Soft wheat	0.159	4.1	0.042	2.0	219.9	4,800
Hard wheat	0.174	–	0.042	–	219.9	6,000
Sunflower	0.216	11.5	–	–	552.1	4,000
Colza	0.204	11.4	–	–	552.1	4,000
Sugar beet	0.051	3.3	–	–	–	90,000
Alfalfa (hay)	0.123	3.5	–	–	–	23,000
Sweet maize	0.126	1.4	0.013	1.0	–	19,000
Green peas	0.240	0.7	0.090	1.5	–	10,000
Green beans	0.186	1.0	–	–	–	14,000
Garlic (peeled and packed)	0.105	19.2	–	–	–	9,000
Onion	0.102	18.4	–	–	–	90,000
Potato	0.108	27.2	–	–	–	50,000

Results and discussion

The results obtained by the application of the model to irrigated agriculture in Hydrological Region 08.29 for each of the three computing modules are shown below.

Results from computing module I: estimation of net irrigation requirement

Table 5 shows the mean seasonal net irrigation depths necessary for ET_m for the crops studied. These values are accompanied by the variation coefficient associated with the year-to-year climatic variability.

Different crop groups can be distinguished by their annual water requirements and the associated coefficients of variation. The cereals which grow in spring (barley, wheat) have net water requirements lower than 400 mm. A high coefficient of variation is added (nearly 20%) due to the precipitation during their cycle.

The crops with higher net irrigation water requirements are species with a summer cycle. Examples are grain maize, with mean requirements of 642 mm, and sugar beet with 741 mm. In this case, the coefficient of variation is about 10% because summer precipitation is of little importance compared with the annual crop water requirement.

This inter-annual variation of the net irrigation depth appears in Fig. 10 for the case of garlic and the four ET_a/ET_m ratios analysed.

The results obtained are supported by experience in the area. This experience is centred on the studies and recommendations of the advisory services that operate in the area (Montoro et al. 2002; de Juan et al. 2002). In addition, different studies have also been used for confirming and validating the irrigation requirements (Martín de Santa Olalla et al. 1992; Cabañero et al. 2002).

Results of the application of the computing module II: gross margin versus irrigation depth

Figures 11 and 12 show gross margin versus gross irrigation depth for the three water costs and for both sample crops: garlic and maize. The results that are shown are for the year 1997, representative of a climatically average year.

This maximum gross margin value increases with irrigation depth up to a maximum value (Figs. 11 and 12), depending on the crop and water cost, and can be considered the optimal gross irrigation depth. The gross margin increase is much faster in crops with a high gross margin and low water requirements (Fig. 11). For depths greater than the optimum there is a decrease in the gross margin. The gross margin reductions that are registered (Figs. 11 and 12) can be very serious for economic viability of the less profitable crops. Also, if these crops have high water requirements, as maize does (Fig. 12), the water cost is a very important input for the crop. In the case of maize, for the average year and the medium cost

Table 5 Mean and coefficient of variation (CV) of net irrigation depths for the study period (1974–2000)

Crop	Net depth (mm)	CV (%)
Barley	341	21
Hard wheat	367	19
Soft wheat	371	19
Grain maize	642	10
Oleaginous rape	211	31
Oleaginous sunflower	465	11
Sugar beet	741	10
Alfalfa	657	11
Garlic	381	19
Onion	556	10
Mid-season potato	592	10
Late potato	516	11
Green peas	220	28
Green beans	371	13
Sweet maize	500	11

Fig. 10 Inter-annual evolution of the seasonal net irrigation depths for garlic cultivation in the different schedulings used

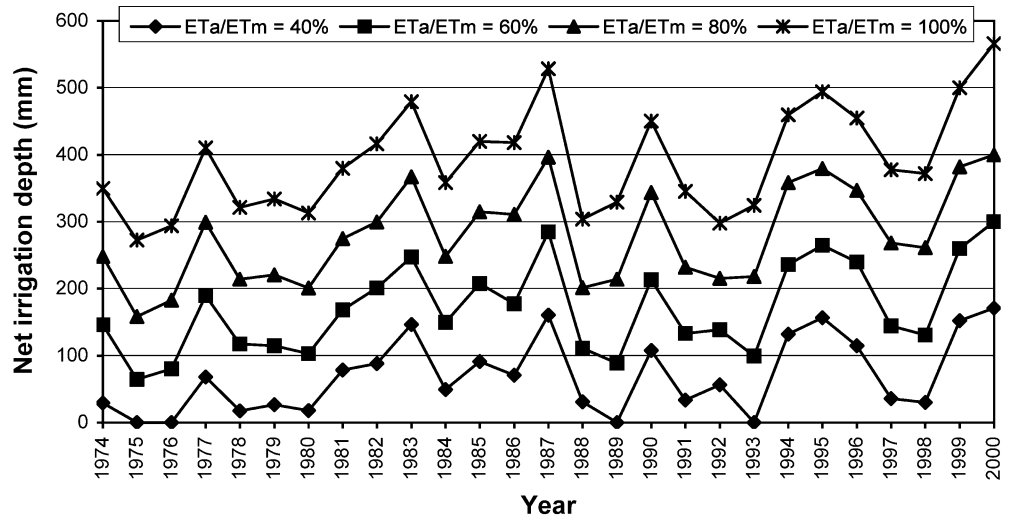


Fig. 11 Function that relates the gross margin obtained with the gross depth applied by the irrigation system (CU = 82%) in garlic (1997)

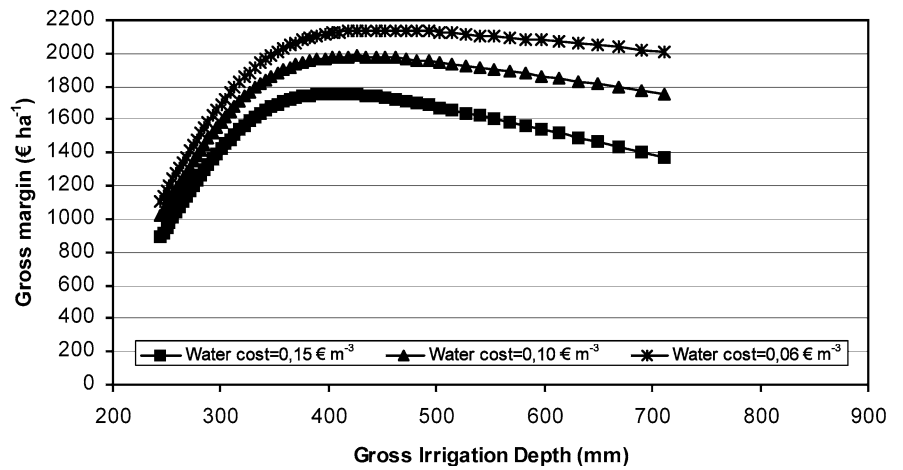
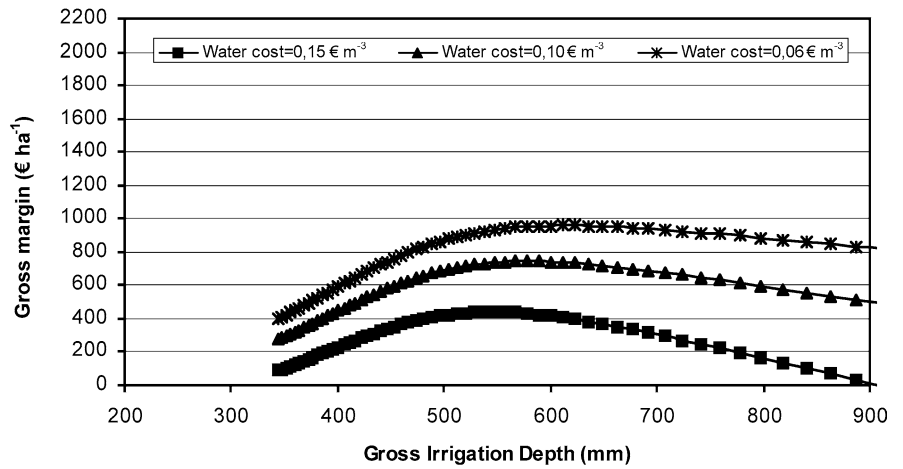


Fig. 12 Function that relates the gross margin obtained with the gross depth applied by the irrigation system (CU = 82%) in maize (1997)



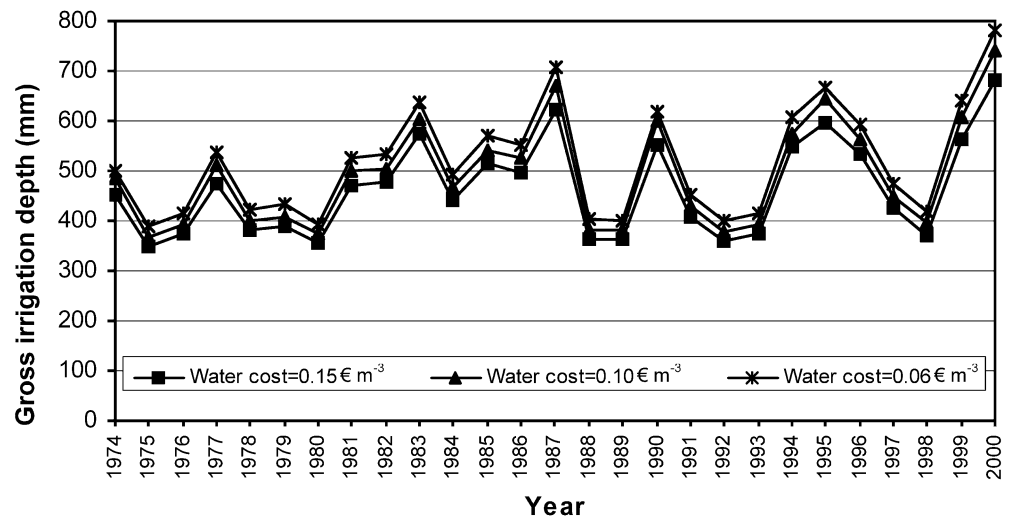
of the water, the optimum depth is 577.7 mm, with a gross margin of 743.0 € ha⁻¹ (Table 6). In the same cases, the gross depth that satisfies the ET_m is 741.0 mm, which means that the gross margin will be 647.3 € ha⁻¹, decreasing 13% with regard to the optimum gross

margin. This result is very important, because a large number of farmers in this area, and many other areas around the world, are still scheduling irrigations with a maximum yield criterion for all crops and economic scenarios, thus decreasing the gross margin.

Table 6 Comparison between the optimum gross irrigation depths, gross margin and economic efficiency with the parameters corresponding to the maximum economic efficiency depths (1997). GM = gross margin; Ratio = characterization of the economic efficiency

Crop	Optimum irrigation depth (maximum gross margin)			Maximum economic efficiency (gross margin/depth)		
	Depth (mm)	GM (€ ha ⁻¹)	Ratio (€ m ⁻³)	Depth (mm)	GM (€ ha ⁻¹)	Ratio (€ m ⁻³)
Barley	318.3	327.8	0.10	206.8	245.4	0.12
Soft wheat	329.9	326.4	0.10	292.9	308.4	0.11
Hard wheat	316.5	216.0	0.07	286.6	206.0	0.07
Oleaginous rape	206.2	566.9	0.27	163.5	507.0	0.31
Oleaginous sunflower	339.2	538.0	0.16	225.3	440.6	0.20
Garlic	426.4	1,982.4	0.46	331.5	1,794.0	0.54
Green peas	283.8	938.1	0.33	226.7	859.1	0.38
Green beans	384.0	1,026.5	0.27	327.6	960.8	0.29
Sweet maize	542.4	1,334.7	0.25	460.5	1,247.0	0.27
Mid-season potato	651.3	2,919.3	0.45	504.9	2,612.0	0.52
Late potato	572.4	2,283.6	0.40	450.7	2,059.4	0.46
Grain maize	577.7	743.0	0.13	503.6	696.2	0.14
Onion	662.9	3,853.8	0.58	512.9	3,486.1	0.68
Alfalfa	647.7	1,244.7	0.19	552.7	1,153.5	0.21
Sugar beet	773.4	2,190.8	0.28	618.5	1,993.3	0.32

Fig. 13 Inter-annual evolution of the optimum gross irrigation depth in garlic (CU=82% and three water costs)



The optimal irrigation depth is different for every year of the studied series (Fig. 13), although the evapotranspiration ratio (ET_a/ET_m) is between 0.85 and 0.97. This value remains stable for each crop throughout the climatic series.

The necessary irrigation depth for maximum yield is always higher than the economic optimum irrigation depth determined by this analysis. Maximizing yield is therefore suboptimal from an economic point of view. In grain maize, assuming an intermediate cost of irrigation water application, the optimum gross irrigation is 575 mm, whereas the irrigation requirement for maximum yield is nearly 800 mm.

The two irrigation depths discussed above must be considered in the management of irrigation water:

- Depth for maximum yield, where $ET_a = ET_m$.
- “Optimum” depth that maximizes the gross margin for each crop separately and with no restrictions (Figs. 11 and 12) referred to gross margin (€) for each unit of cultivated area (ha).

The ratio of gross margin/gross irrigation depth allows us to determine the economic efficiency of water use (€ m⁻³). Figure 14 shows the evolution of economic efficiency according to the gross irrigation depth for garlic. The economic efficiency of water use in garlic is high; the maximum values would be between 0.49 and 0.58 € m⁻³, according to the price of water. These maximum values are linked to an irrigation depth that maximizes the gross margin for water volume consumed; therefore they can be defined as “maximum economic efficiency”. This depth, in all the cases, is significantly lower than those already mentioned (maximum yield and maximum gross margin). For the main part of the crops it corresponds to values around 0.70–0.94 of ET_a/ET_m .

Table 6 shows the comparison between the economic parameters gross margin and economic efficiency according to the maximization criteria for each of them. The maximum economic efficiency is obtained by irrigation depths lower than those of maximum gross margin (optimal irrigation depth). This situation takes

Fig. 14 Evolution of the economic efficiency of irrigation water use in garlic crop (simulation year: 1997)

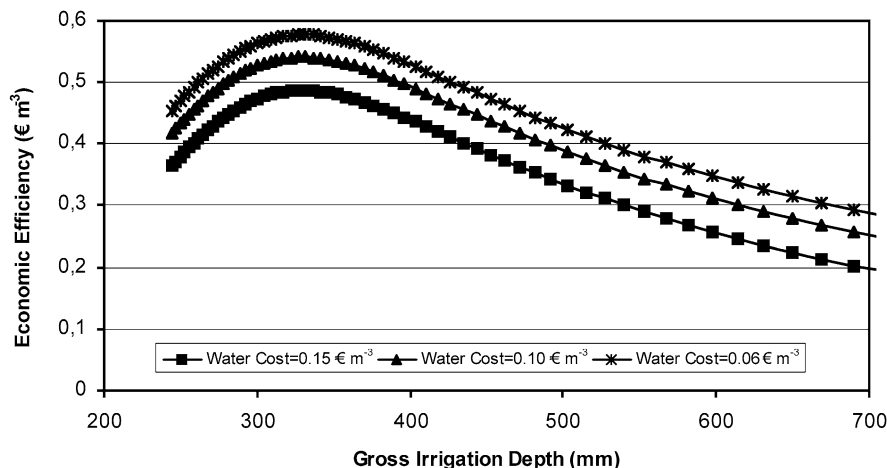


Table 7 Crop rotation in 1987 (dry year) and 1997 (type year). Participation of the crops (percentage), recommended gross depth and gross margin with a mean irrigation availability of 4,000 m³ ha⁻¹ per year

Crop	Simulation year					
	1987			1997		
	Area (%)	Depth (m ³ ha ⁻¹)	Gross margin (€ ha ⁻¹)	Area (%)	Depth (m ³ ha ⁻¹)	Gross margin (€ ha ⁻¹)
Garlic	15.0	5,121	1,682.1	15.0	3,571	1,848.5
Onion	16.0	8,106	3,522.7	20.0	5,347	3,615.8
Green peas	10.0	3,400	774.5	14.5	2,340	873.7
Sweet maize	0.0	–	–	10.0	4,606	1,247.0
Potato	9.0	7,953	2,169.8	10.0	5,129	2,621.1
Late potato	8.0	5,582	1,777.5	10.0	4,508	2,059.1
Sugar beet	5.0	8,750	1,675.0	10.0	6,357	2,002.4
Sunflower	35.0	–	300.3	10.0	–	365.1
Set-aside	2.0	–	–	0.5	0.0	–

place because the yield increase is not able to pay for the necessary production cost increases.

The results obtained have been validated by the following means:

- The economic data have been obtained by means of surveys and personal interviews with the farmers and skilled personnel in the area, in addition to using the usual calculation methods. We have also been able to count on the help of the collaborating agrarian companies, which have collected sufficient precise data. The precision of these data is a key aspect, since it conditions all the results.
- The production function, integrating the CU effect, has been used by several authors. In addition to local testing, the validity of the models used in some crops has been verified (Martín de Santa Olalla et al. 1992, 1994; de Juan et al. 1999; Fabeiro et al. 2001).

Results from the application of the computing module III: optimum crop rotations and risk analysis

Module II determines the relation between gross margin and the irrigation depth for an individual crop. Module III uses this relation to optimize crop rotation on the

whole farm. Crop rotation must satisfy certain restrictions: (1) available area on the farm, (2) maximum or minimum area for the different crops considered, (3) availability of irrigation water, (4) European restrictions imposed by the CAP, (5) environmental constraints. All these restrictions should ensure that the simulation setting reflects the real situation.

When using MOPECO, the total area restriction corresponding to the specified productive setting has been considered by limiting the maximum area of some crops, mainly horticultural (garlic, onion, sweet maize, green peas, green beans, potato, onion) and some herbaceous crops (sugar beet). These restrictions on maximum area, generally about 15% of the total available area of the farm, have been imposed to obtain real solutions, since market perspectives are very important when searching for solutions for a large irrigated area. The results correspond to the average price of water and sale of products.

In each year of the climatic series analysed (1974–2000), a solution that maximizes the gross margin for the farm is obtained, according to the water demand for each year.

Table 7 shows the results obtained by the optimum crop rotation with a restriction in the mean available water resources of 4,000 m³ ha⁻¹ per year in 1987 and 1997. When the mean availability of water resources is

reduced, dry farming becomes part of the optimum strategy (10% of the total area) in average years of the series, e.g. 1997, while crops with high gross margin are usually well irrigated.

Generally there is a high percentage of horticultural crops (garlic, onion, potato) included in the rotational crops, thus replacing the traditional herbaceous crops in the area, which are economically dependent on the common agricultural policy (CAP) compensatory payments (e.g. maize, barley) (Tables 7 and 8). This diversification strategy, when considering market restrictions and European and worldwide policy modifications (market globalization), can be essential for the economic viability of irrigation. Also, in the crop rotations selected, scarce and expensive water must be used with economic optimization criteria.

In 1987 (dry year), the crops with higher gross margins were part of the optimum crop rotation, but in some cases (onion, potato) they did not utilize the maximum available area. Dry farming becomes an important fraction of the total (37%) (Table 7). An important reduction in the gross margin and the mean gross margin for the setting analysed is registered. The mean gross margin obtained in 1997 is 1,953.3 € ha⁻¹, decreasing to 1,418.4 € ha⁻¹ in the dry year (1987). In all cases analysed, the hypothesis of mean sale prices for commercial productions and the price of water application for irrigation (0.10 € m⁻³) was assumed.

The “recommended” gross irrigation depths are between the “optimum irrigation” (maximum gross margin for each area unit of each crop) and the “maximum economic efficiency depths” (maximum gross margin for water volume). This “recommended” gross depth is the one with the maximum gross margin on the farm according to the optimum crop planning (Tables 7 and 8). Generally, it corresponds to a value between 0.73 and 0.97 of ET_a/ET_m , depending on the crop and water availability. The drier the year or the lower the water availability, the more closely the recommended solution approximates maximum economic efficiency.

The crop rotations for the other years in the climatic series analysed are similar to those for the years 1997 and 1987. It is important to note that crops such as grain maize or winter cereals are not selected in the optimization process. This fact must be considered, because many crops that occupy large areas are of decreasing interest, and should therefore be partially replaced by horticultural crops (Ortega 2000).

Analysing the results of this study, there is a new irrigation depth to be considered in the economic optimization of irrigation water use: the depth that maximizes the gross margin for the crops considered in the optimum productive planning, which is one of the results of Module III.

Taking the crop rotation obtained as a basis, it is necessary to find a solution for most years by means of risk analysis. The aim is to select the alternative that provides a high gross margin with a minimum risk level, which would be known by the farmer in advance.

Table 8 Recommended solution: minimum risk crop rotation (year 1984)

Crop	Available irrigation water		
	4,000 m ³ ha ⁻¹ per year		
	Area (%)	Depth (m ³ ha ⁻¹)	Gross margin (€ ha ⁻¹)
Garlic	15.0	3,982	1,805.4
Onion	18.0	6,943	3,064.7
Green peas	16.5	1,703	843.5
Sweet maize	8.0	5,015	1,085.4
Potato	7.5	5,632	1,204.8
Late potato	8.0	5,278	1,917.4
Sugar beet	8.0	7,152	1,897.4
Sunflower	18.0	–	292.7
Set-aside	1.0	–	–

In 1984, the crop rotation showed a low risk value for 4,000 m³ ha⁻¹ per year of available water (Table 8). This is one of the alternatives recommended, according to the methodology presented in this model (optimum and with low risk).

In 1984, the rainfall value was slightly higher than the rainfall accumulated in the mean year of the climatic series. The risk of this crop rotation is determined according to the reference gross margin. This average value, associated to the climatic variability, is 3,565.0 € ha⁻¹ per year, which is the minimum of the different alternatives evaluated (Table 3). It indicates the gross margin which the farmer does not perceive with regard to the reference objective. The reference objective is the crop with the highest gross margin, with no restriction and with the lowest irrigation water application costs.

The participation of some of these crops (e.g. sunflower) as a dryland crop is significant within the irrigated area, helping to optimize the use of the scarce water by transferring its application to other crops which provide a higher gross margin.

In all the studied cases, the procedure of optimization based on genetic algorithms has been very effective, with no blockade in the local maximum of the problem. Each optimization process is solved within a time lapse of 1–2 h, depending on the characteristics of each process.

Conclusions

When planning the strategies for the optimization of irrigation water use, it is necessary to consider the following gross irrigation depths:

- Depth for maximum yield ($ET_a = ET_m$), according to the classic criteria used for irrigation scheduling.
- “Optimum” depth, the one for maximum gross margin. This depth introduces economic strategies for deficit irrigation and is much lower than the previous one (0.85–0.97 of ET_m).
- Depth for “maximum economic efficiency”; significantly lower than the “optimum” depth (0.70–0.94 of ET_m).

– “Recommendable” depth for the optimization of productive planning on a farm, considering restrictions of water, area, etc. This depth is between “optimum” and “maximum economic efficiency”, while it maximizes the farm’s gross margin (0.73–0.97 of ET_m).

The horticultural crops are very common in the optimum crop rotation, due to their high gross margin. The most important of these are onion, potatoes and garlic.

It is important to consider the possibility of dry farming for economic optimization when water supplies are limited. Non-irrigated crops complete the productive plan once water has been allocated to the crops with higher gross margin.

The solutions that offer minimum economic risk together with climatic variability are obtained in years that show typical climatic variability. Registered rainfall and its distribution throughout the agronomical cycle is the primary risk factor.

The genetic algorithms method is efficient and reliable for solving complex optimization problems.

The possibilities of application and use of a model like this one are multiple for farmers, water managers and advisory services. It is a useful tool for initial evaluation of certain actions in an area, regarding aspects such as hydrological planning, subsidy policies and the effects of variations in water application costs.

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