Multi-objective water allocation in the Alqueva region

RUI FRAGOSO*, VLADIMIR BUSHENKOV**, CARLOS MARQUES***

Jel classification: Q20, Q250, C60, C610

Abstract

Alqueva dam in the Alentejo Region was developed to solve water scarcity in the South of Portugal and to ensure permanent availability of water for household and industrial consumption, irrigation, production of electric energy, ecological and environmental purposes. Competition among some of these multiple water uses requires an integrated management framework. This paper uses Interactive Decision Maps (IDM) technique to explore and achieve efficient and equitable water allocation combinations taking into account those multiple goals and principles of good water governance. Results show that multiple water uses do constrain full economic impact for agriculture and suggest that integrated management frameworks and policies are needed at regional territorial level to reach a compromise between competing economic, social and environmental goals and achieve project global development benefits.

Keywords: Water Management; Multiple Criteria Decision Making; Interactive Decision Maps; Feasible Goal Method.

Résumé

Le barrage d'Alqueva dans la Région de l'Alentejo a été construit pour résoudre les problèmes de pénurie d'eau dans le sud du Portugal et assurer une disponibilité permanente de l'eau dans les secteurs, domestique, industriel, agricole, de la production d'énergie électrique et pour des raisons écologiques et environnementales. La compétition entre ces divers usages implique l'élaboration d'un cadre de gestion intégrée. Dans le présent travail, la technique de la Cartographie Décisionnelle Interactive a été utilisée pour explorer et mettre au point des solutions efficientes et équitables pour l'allocation de l'eau, en prenant en compte les différents objectifs et principes sur lesquels devrait reposer une bonne gouvernance de l'eau. Les résultats ont montré que les divers usages de l'eau constituent une contrainte majeure en termes d'impact économique pour le secteur agricole et ont mis en évidence la nécessité d'adopter des cadres de gestion et des politiques intégrées à l'échelle régionale afin d'atteindre un compromis entre les objectifs économiques, environnementaux et sociaux concurrentiels et, de générer des bénéfices sur le plan du développement global.

***Mots-clé**: gestion de l'eau; prise de décision multicritère; cartographie décisionnelle interactive; objectifs réalisables.*

Introduction

At the International Conference on Water in 1992 it was proposed that integrated water resources management must be based on ecological, institutional and economic principles. The ecological principle integrates land and water governance for a better environmental management. The institutional principle considers that all stakeholders must participate in water decisions. The economic principle tries to introduce market criteria to improve the use efficiency of water resources. Water should be treated as a single environmental resource and allocated among main groups of water users, namely agriculture, industry and households. The ecological restrictions make that the environment has to be treated as a user in its own right (UNO, 2006). This is aligned with the objective of integrated water resources management, adopted by the World Summit on Sustainable Development in Johannesburg in 2002.

Molden (2000) suggested that in the management and development of a river basin, a development phase of water resources, a utilization period and a phase of reallocation should be considered, once the competition by the resource is high.

Essentially, the discussion about integrated water management tries to achieve equilibrium between equity and efficiency criteria on the water allocation process under sustainable conditions. The equity in allocation means that all users should have the equal opportunity to access to water resources. The efficient and beneficial water use must include the optimal economic as well as the social gains. The sustainability can be understood as a capacity to conserve the environmental system for the future generations (Lévite and Sally, 2002).

The Alentejo region, situated in the south of Portugal between the Tejo river and the Algarve region, represents one third of the territory of Portugal and 5% of its population. The Alentejo's economic indicators are below of the country averages, the population density is relatively low and the population is aged. Agriculture is important to the regional economy and employment but available water resources are scarce and the rainfall has a significant spatial and temporal variability (Fragoso and Lucas, 2009).

To solve water scarcity and to stimulate the economic development in the Alentejo region, the Portuguese Government has been developing, since 1995, the Alqueva Project on the Guadiana river. The Alqueva Dam is the main infrastructure of the project, with 3350 hm^3 of useful storage capacity and a full storage level at 152 m. It allows to increase considerably the water availability and to reduce its vari-

* University of Évora, Department of Management, ICAM/CEFAGE, Évora, Portugal.
** University of Évora, Department of Mathematics, CIMA, Évora, Portugal.
*** University of Évora, Department of Management, CEFAGE, Évora, Portugal.

ability in the Alentejo region. The project also includes a hydroelectric plant with a power of 240 GW (EDIA, 2006), the Pedrogão Dam, an inlet system for water supply and an irrigation system. The water supply includes household and industrial needs, and more than 200 thousand people in the Alentejo region and in other areas (Setúbal, Andaluzia in Spain, etc.) could benefit from it. In the agricultural context, the project will ensure irrigation of more than 110 thousand hectares (Hidrotécnica Portuguesa, 1995).

The Alqueva project has also very significant negative environmental and social impacts, mostly due to the submersion of a very large area that includes important ecological values and habitat, local villages as well as an important paper industry (Portucel Recicla). Other important impacts are related to the Guadiana estuary and the quality of water for irrigation.

The multiple purposes of the Alqueva project put the problem of reasonable water allocation among different users (agriculture, energy production, household and industrial consumptions, etc.) while maintaining good environmental conditions in the region.

The objective of this paper is to study all possible water allocation strategies and to determine efficient water allocations for the multipurpose Alqueva project applying the Feasible Goals Method/Interactive Decision Maps (FGM/IDM) technique (Lotov et al., 2004). To apply this technique, one simple linear multi-criterion model of the Alqueva region was proposed. The FGM/IDM technique allows to construct (or approximate) all Pareto optimal solutions in multi-dimensional criteria space and provides a fast and easy way to display them in graphic form and understand efficient trade-offs between conflicting objectives.

The paper is organized as follows. We briefly sketch the FGM/IDM technique in Section 2. The mathematical model of multipurpose water uses in the Alqueva region is given in Section 3. In Section 4, the study of this model by means of the FGM/IDM technique is described and the resulting solution is formulated. Finally, in Section 5, the resulting solution is discussed.

2. Feasible Goal Method and Interactive Decision Maps

The multipurpose integrated water resources management is a decision making problem with a large number of feasible solutions. The traditional approach to the decision making process (see Simon, 1960) consists of two main steps:

1. designing a relatively small number of decision alternatives (screening of decision alternatives), and
2. final choice of a decision alternative from a small list.

In the first step, the screening of decision alternatives requires analysing millions of options; it is a very difficult task and for this reason experts usually are asked to do this selection. In the second step, modern computational tools (simulation, multimedia and geographic information systems) support decision making process and provide decision makers with opportunities of rapid graphic assessment of one or more management strategies.

One computational tool designed to support the two steps of the multiple criteria decision making is the Feasible Goals Method and Interactive Decision Maps (FGM/IDM) technique (Lotov et al., 2001, 2004). The FGM/IDM technique is in line with the new information technologies and applies modern interactive visualization. This technique displays information on the outcomes of all possible decision strategies in a graphic form and helps to select a small number of strategies, which are a subject of further detailed exploration in simulation analysis.

The goal method is a well known approach to decision making with multiple criteria (Charnes and Cooper, 1961; Steur, 1986). In this method the decision maker identifies one desirable goal related to an efficient strategy, which could be unfeasible in reality. The computed decision can be distant from what was expected with the identified goal.

If we display all feasible goals, this problem can be avoided. When knowing the Pareto frontier, the decision maker can choose one feasible goal as his desirable goal. The idea to display the non-dominated frontier in decision problems with two criteria was introduced by Gass and Saaty as soon as in the 50s (Gass and Saaty, 1955). They showed that, in the case of two criteria, the non-dominated frontier of a linear model could be computed and displayed using standard parametric linear programming. Application of the parametric linear programming, however, is not so simple if the number of criteria is larger than two. In the book (Cohon, 1978), the idea of Gass and Saaty was transformed into one of the main groups of the Multiple Criteria Decision Making methods named «non-inferior (i.e., non-dominated) frontier generating methods». The linear multiple-criterion methods, which develop the idea of Gass and Saaty in a straightforward way, usually construct the list of all non-dominated vertices and provide it to user (see Zeleny, 1974; Steuer, 1986). However, it is extremely complicated to utilize this information. Visualization of such information is very complicated, even in the case of three criteria.

In the frame of the FGM/IDM technique, the generation of efficient frontiers of feasible sets in the criterion space (FSCS) and the screening of feasible decisions are based on the algorithms of a universal mathematical approach called the Generalized Reachable Sets method (Lotov, 1973). These algorithms (Bushenkov et al., 1982; Bushenkov, 1985; Chernykh, 1988) are able to approximate FSCSs in the space till 5-7 dimensions. The Pareto frontiers of the FSCSs are visualized in the form of Decision Maps. The decision maker has the opportunity to investigate these maps in an interactive way and to select an appropriate criteria combination (feasible goal) directly in computer screen. When the preferable goal is identified, the computer automatically calculates the decision variables of the model corresponding to the preferable goal. The history of the development and applications of the FGM/IDM technique can be found in some

books (Lotov et al., 2001, 2004).

The main steps of the IDM/FGM technique are presented in Figure 1 and include:

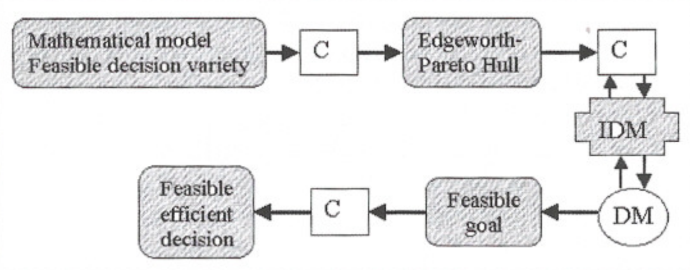
1) construction (or approximation) of the Pareto frontier on the base of the Edgeworth-Pareto Hull (EPH);

2) interactive display of decision maps;

3) identification of a preferable feasible goal; and

4) computation of the decision corresponding to the preferable goal.

Figure 1 – *The main steps of FGM/IDM technique (source: Lotov et al., 2001). «C» denotes the computer processing and «DM» denotes the decision maker.*



Now, let's give a formalized description of the FGM/IDM technique. A mathematical model with the decision variables vectors x belonging to the linear space R^n can be represented in the general form as

$$x \in X,\ X \subset R^n,$$

where X is a variety of feasible decisions of the model. Let the criteria vector y be an element of linear finite-dimensional space R^m. In this case the criterion vectors y are related to decisions by a given mapping $f : R^n \rightarrow R^m$. A variety of objective vectors y that are attainable if all the feasible decisions are used (i.e. a feasible set in the criteria space – FSCS) can be defined as

$$Y = \{y \in R^m : y = f(x),\ x \in X\}$$

Let us suppose that a decision maker is interested in decreasing the objective values y. An objective point y' dominates another objective point y'', if and only if $y' \leq y''$ and $y' \neq y''$. The set of all non-dominated points $y \in Y$ is known as Pareto-optimal frontier of Y and defined as:

$$P(Y) = \{y \in Y : \{y' \in Y : y' \leq y, y' \neq y\} = \varnothing\}.$$

Usually, the decision maker is interested only in analysing Pareto frontier $P(Y)$. In this case, the construction of the Edgeworth-Pareto Hull (EPH) of the FSCS can be useful. In accordance to Stadler (1986), the Edgeworth-Pareto Hull of FSCS is the broadest variety $Y^* \subset R^m$ with the same Pareto frontier $P(Y)$. In the case of decreasing the criterion values y, a point y' dominates all y such that $y \geq y'$. Therefore, Y^* can be defined as

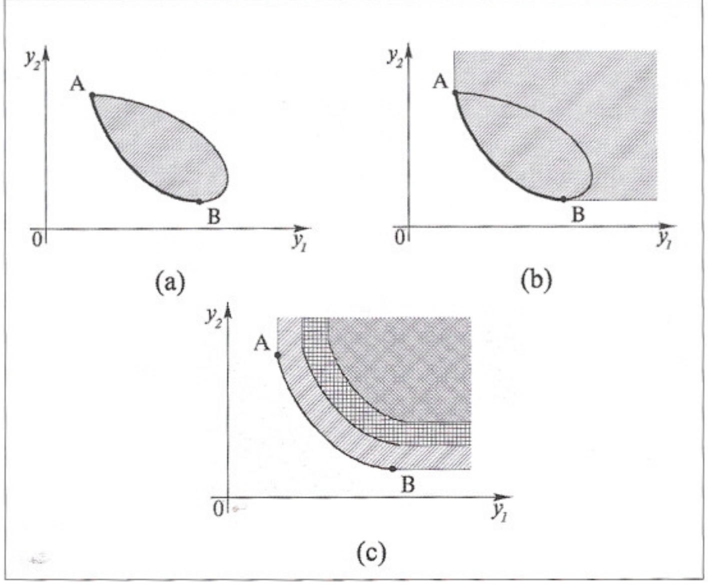
$$Y^* = \{y \in R^m : y \geq y',\ y' \in Y\}$$

or briefly

$$Y^* = Y + R^m_+$$

where R^m_+ is the non-negative cone of R^m. Figures 2(a) and 2(b) illustrate the Y and Y^* varieties with the same $P(Y)$.

Figure 2 – *(a) – FSCS, AB – Pareto frontier; (b) – EPH of the FSCS; (c) – a series of superimposed bi-criteria EPH (three-dimensional decision map).*



It is clear that the dominated frontier of the variety of the feasible objectives disappears in the EPH and the EPH has a simpler structure than the FSCS.

Display of the EPH instead of the original variety plays a minor role in the case of two criteria, but it is extremely important in the case of a larger number of criteria. Let us consider the third criterion y_3 of the problem. To display the Pareto frontier for all three criteria, one can consider several bi-criteria EPHs while several constraints are imposed on the value of the third criterion y_3 (y_3 is not greater than...) and superimpose these pictures (slices). Figure 2(c) provides an example of three-dimensional decision map. It informs the decision maker on the Pareto frontier for all the three criteria.

Generally speaking, decision maps are calculated as series of bi-dimensional (bi-criteria) slices (cross-sections) of the EPH. Let u denote the values of two selected criteria and z^* denote the fixed values of the remaining criteria. Then, a bi-dimensional slice of the set Y^* related to z^* is defined as

$$G(Y^*, z^*) = \{u : (u, z^*) \in Y^*\}$$

It is important to note that a slice of the EPH contains all combinations of the values of the two criteria that are feasible if the values of the remaining criteria are not worse than z*.

So, decision maps are fairly similar to topographic maps. The decision maps can be easily generalized for the case of four, five and more criteria. The approximating EPH of F-SCS instead of the direct approximation Pareto frontier is the main feature of the IDM technique.

The decision maps help to identify a preferable feasible goal. Once identified, is regarded as the «reference point» (Wierzbicki, 1981), that is, an efficient decision is obtained by solving the following optimization problem:

$$(1)\quad \left[\min_{1\le j\le m}(y_j - y') + \sum_{j=1}^{m}\{\varepsilon_j(y_j - y'_j)\}\right] \Rightarrow max$$

for $y = f(x),\ x \in X,$

where $\varepsilon_1, \ldots, \varepsilon_m$ are small positive parameters. Since the goal is close to the Pareto frontier, the efficient decision results in criterion values that are close to the goal.

3. Multiple criteria model of the Alqueva region

There are different types of mathematical programming models that are used in natural resources economics. Hazell and Norton (1986) and Boussard and Daudin (1988) described several applications to the agricultural sector and Zekri (1991) and Millan and Berbel (1994) utilised the goal programming for study multiple criteria decision problems in irrigation in southern Spain.

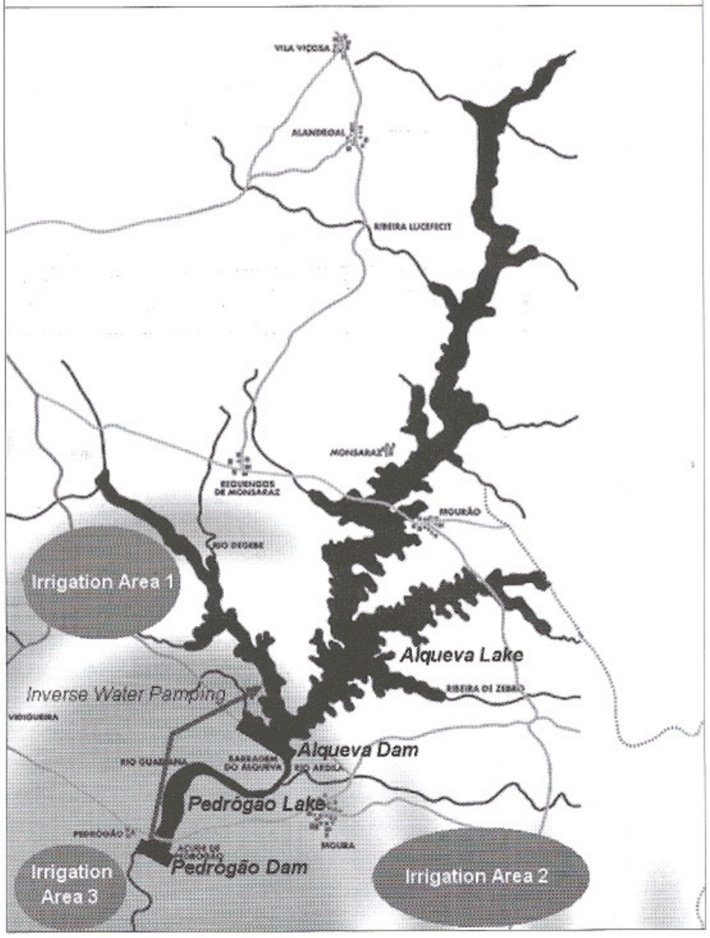
The mathematical programming model proposed in this study includes the main characteristics of Alqueva project at an aggregated level as water availability, irrigating systems capacity, hydroelectric power production and flows in Alqueva water system. The model describes the objectives of different water users and the available resources. Exploring the Pareto frontier with the IDM/FGM technique allows to find a preferable efficient water allocation respecting equity criteria of the integrated water management strategy.

The scheme of the Alqueva water system is presented in Figure 3. In the model, the water use was aggregated in annual terms in function of needs and storage capacity of the two main dams of the Alqueva project, which are the Alqueva and the Pedrógão dams.

Availability of water was established individually on the basis of water flows from the Guadiana river to the Alqueva lake, considering initial volumes stored in the main two lakes and in other small secondary lakes.

Endogenous variables of the model estimate the level of agricultural production and income, nitrates leaching and percolation, household and industrial consumption and the water volume in the Alqueva lake at the end of annual period. The model also includes water transfers between the two main dams to maintain the Guadiana river's flows (due to ecological restrictions), the production of electric energy

Figure 3 – *Scheme of the Alqueva water system.*



at the Alqueva dam and the inverse water pumping from the Pedrógão lake to the Alqueva lake.

The simplified model can be represented by the following linear relations:

$$(2)\quad F_1 = \sum_j \sum_i g_i^j X_i^j$$

$$(3)\quad F_2 = \sum_j \sum_i p_i^j X_i^j$$

$$(4)\quad F_3 = E$$

$$(5)\quad F_4 = H$$

$$(6)\quad F_5 = a_0 + fi - \sum_i \frac{w_i^1}{\eta} X_i^1 - w_e E - H - r - T + I$$

$$(7)\quad P = p_0 + T + w_e E - \sum_i \frac{w_i^2}{\eta} X_i^2 - \sum_i \frac{w_i^3}{\eta} X_i^3 - fo - I$$

$$(8)\quad \frac{1}{0{,}68 w_e}\, T \le E$$

$$(9)\quad \sum_i X_i^j \le a_j,\ \forall j$$

$$(10)\quad X_i^j \le d_i^j,\ \forall i,j$$

The multiple objectives (criteria) are expressed by variables F_1 to F_5 in equations (2) to (6). They are:

maximize total agricultural income F_1 (in million euros);

minimize agricultural pollution from nitrates leaching and percolation F_2 (in 10^2 tonnes);

maximize production of electric energy F_3 (in GWh);

maximize household and industrial consumption F_4 (in hm^3);

maximize water volume accumulated in the Alqueva lake F_5 (in hm^3).

Agricultural income is given by the sum of the product of unitary gross margin (g_i^j) and area (x_i^j) of each crop i in irrigation zone j. Gross margin values are exogenous and are obtained by considering values of gross agricultural revenue, operational costs with goods and services, and water costs. These lasts were calculated on the basis of water pricing and agricultural water consumption for each crop and irrigation area. For water pricing it was considered 0,050 million euros by each hm^3 of water.

Agricultural pollution with respect to nitrates leaching and percolation in the soil in each irrigation area is evaluated through the exogenous unitary pollution parameters (p_i^j) and crop areas (x_i^j).

Electric energy production is represented by the variable E and is upward limited to 240 GWh (Hidrotécnica Portuguesa, 1992).

Household consumption H is limited to 87.6 hm^3. According to Hidrotécnica Portuguesa (1995), this value includes foreseen household and industrial consumption for the Alentejo region (27.6 hm^3), for the industrial park of Sines (40 hm^3) and for the zone of Setúbal (20 hm^3).

The variable F_5 is the water balance in the Alqueva lake. The exogenous parameter a_0 represents the water stored at the beginning of the annual period in the Alqueva lake and in small secondary lakes. The water inflows from the Guadiana river is given by the parameter fi. The water balance includes also current water uses for irrigation purposes, water for electric energy production, household and industrial consumption H, water needs associated with small secondary lakes r, water transfers T to the Pedrógão lake. It is still necessary to add the water delivered from the Pedrógão dam to the Alqueva lake through inverse pumping given by the variable I.

Water needed for irrigation in the first area depends on crop area variables (X_i^j), unitary water coefficients (w_i^j) and watering networks efficiency (η) which was fixed to 65%.

Water requested for electric energy production is calculated as a function of the variable E where w_e is a coefficient equal to 7,3 hm^3/GWh (Hidrotécnica Portuguesa, 1992).

In equation (7), the water balance in the Pedrógão lake is calculated. Its structure is similar to equation (6). The parameter p_0 means the initial volume of water stored in the lake. The variable fo, $fo \geq f^*$, represents the water releases from the lake to the Guadina river to maintain its good ecological conditions, where f^* is a constant. The water storage capacity P of the Pedrógão lake is limited by 515 hm^3 (Hidrotécnica Portuguesa, 1992).

The inverse water pumping needs an additional expense of energy. The inequality (8) relates the spent energy with the total energy E produced in the system.

The model parameters were set to their average annual values. The initial volumes of the Alqueva and Pedrógão lakes are equal to 2200 hm^3 and 338 hm^3 respectively. These values represent two thirds of the maximal storage capacity of the lakes. The inflows from the Guadiana river into the Alqueva lake are equal to 2710 hm^3, which is a weighted average of the annual water flows referenced in the Study of Global Assessment of the Alqueva Project (Hidrotécnica Portuguesa, 1992). To maintain good ecological conditions in the Guadiana river it was assumed that water outflows f^* from the Perdógão lake were equal to their water inflows to the Alqueva lake (2710 hm^3). Initial volume accumulated in small secondary lakes is equal to 360 hm^3. The water needs associated with small secondary lakes r were estimated as 166 hm^3.

Equations (9) to (10) describe linear relationships established in the model for agricultural production. Irrigation in the Alqueva project should reach up to 110 thousand hectares distributed through three irrigation areas. About 64% of that area belongs to an irrigation system with water coming from the Alqueva lake. The other two irrigation systems are supplied by the Pedrogão lake and represent 27% and 9% of irrigation land, respectively.

In these areas, it was considered i irrigated crop production possibilities for each irrigation system j. The area of each crop in each irrigation system is given by the variable X_i^j expressed in thousands hectares. We considered in the model the following most important irrigated crops for Alentejo: winter crops (soft wheat and durum wheat), summer crops (corn and sunflower), horticultural and industrial crops (tomato, bell pepper, melon, onion, potato and beet), fruits (pear, peach, plum and table grape), vineyard and olives for oil. Agricultural production is constrained by the irrigated areas of each irrigation system (a_j) which are approximately equal to 72 thousand hectares for the Alqueva irrigation system and 30 and 11 thousand hectares for the two irrigation systems with water supply from the Pedrógão lake.

The irrigated land and water allocated to each crop depends on their income return and the area of each irrigated crop was limited by an upper bound (d_i^j) due to their specific marketing and agronomic constraints.

The principal agricultural technical coefficients used in the model were based on works by Noéme et al. (2004), Fragoso and Marques (2007) and Lucas et al. (2002) and are presented in the Annex.

4. Results

Relation between agricultural income F_1 and electric energy production F_3. The bi-dimension decision map for criteria F_1 and F_3 is presented in Figure 4. It is easy to note that trade-off between these criteria is composed by only one point ***A*** which corresponds to their maximum possible values. This means that there is no conflict between F_1 and F_3. For this reason the value of electric energy production was fixed to maximum value 240 GWh in all following studies.

Relation between agricultural income F_1 and water volume accumulated in the Alqueva lake F_5. Figure 5 presents the decision map for the pair of the criteria F_1 and F_5. Here, in contrast, we can see an extensive trade-off.

In point ***D*** agricultural income has its maximum possible value (F_1 = 140 million euros) when F_5 is equal to 2000 hm3. The criterion F_5 reaches its maximum in point ***A*** (F_5 = 2728 hm3 and F_1 = 0). Among these two points agricultural income increases as water volume in the Alqueva lake diminishes.

Moving from point ***A*** to point ***B*** along the Pareto frontier, agricultural income rises up to 72 million euros and water level drops

Figure 4 – *Decision map for criteria F_1 and F_3.*

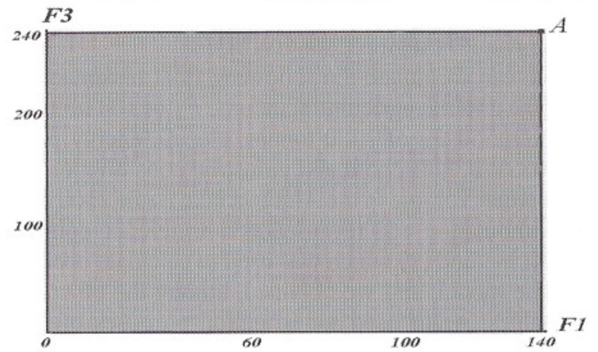


Figure 5 – *Decision map for criteria F_1 and F_5.*

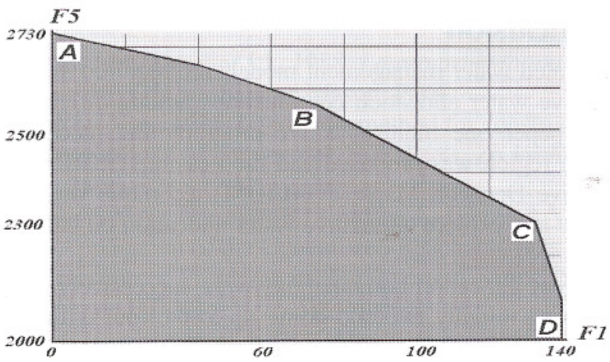
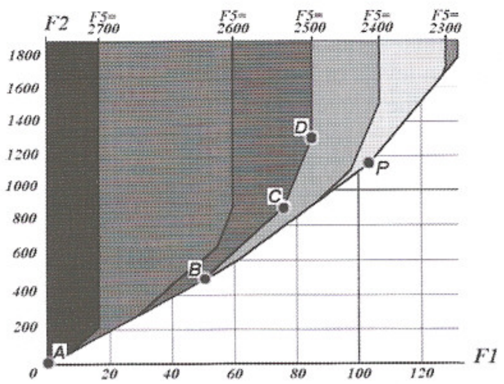


Figure 6 – *Three-dimensional decision map for criteria F_1, F_2 and F_5.*



from 2728 hm^3 to 2562 hm^3. Hence, half of maximum agricultural income can be achieved without a significant decrease on water volume in the Alqueva lake. Therefore, it is possible to promote agricultural production and to raise agricultural income without significant ecological or environmental losses. In this segment of the trade-off for each additional cubic meter delivered for irrigation the agricultural income increases by 0.43 euros.

From point ***B*** to point ***C***, agricultural income continues to rise but now at a lower rate and water releases in the Alqueva lake increase with consequent stronger negative environmental effects. At point ***C*** agricultural income is equal to 132 million euros and water volume in the Alqueva lake is 2275 hm^3 which means that the transformation rate of agricultural income to water volume in the Alqueva lake drops from 0.43 euros/ m^3 at point ***B*** to 0.21 euros/m^3 at point ***C***.

After point ***C***, small agricultural income increases are associated to strong decreases in water volume in the Alqueva lake. Here the transformation rate of agricultural income to water volume in the Alqueva lake is only 0.03 euros/ m^3. For this reason, in the following analysis the value of agricultural income F_1 was upper-bounded by 132 million euros.

Relation between agricultural income F_1, agricultural pollution F_2 and water volume accumulated in the Alqueva lake F_5. Figure 6 shows the three-dimensional decision map where agricultural income *(F_1)* is represented by the horizontal axis, agricultural pollution *(F_2)* is represented by the vertical axis and water volume in the Alqueva lake *(F_5)* is given by slices in different shades of grey. Each slice presents all possible combinations of the pairs (F_1, F_2) when F_5 is lower bounded by corresponding value shown in the top of the figure.

Let us consider the slice (bi-criterion EPH) corresponding to the restriction $F_5 \geq 2500$ hm^3. In its Pareto frontier (trade-off between F_1 and F_2), points ***A***, ***B***, ***C*** and ***D*** seem to be most interesting for analysis.

In point ***A*** agricultural pollution is minimal *($F_2 = 0$)* and agricultural income is also equal to zero. In point ***B*** agricultural income is 50 million euros and pollution is 500 tonnes, which means that for an additional Kg of nitrates percolation and leaching we must expect an increase of 100 euros on agricultural income.

From point ***B*** to point ***C*** agricultural income and pollution rise to 72 million euros and 930 tonnes, respectively. For this reason, one additional Kg of nitrates percolation and leaching increases agricultural income by 50 euros.

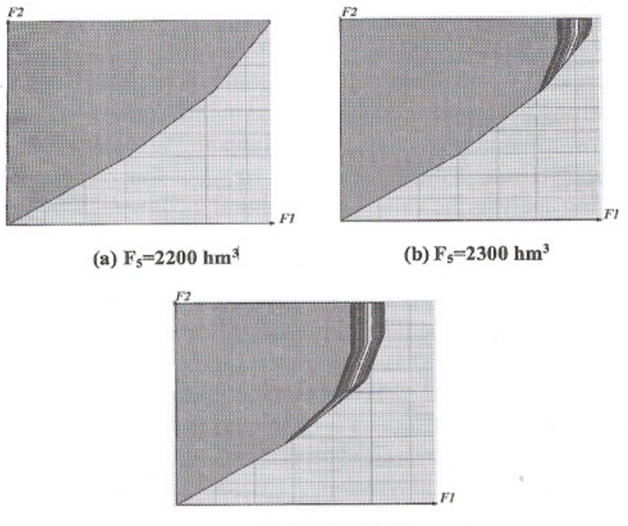
Starting from point ***C***, any increase in agricultural income gives significant effect in nitrates pollution. When we move from point ***C*** to point ***D***, one additional Kg of nitrate pollution rises the agricultural income only by 30 euros.

Similarly, we can analyse the other efficient frontiers on this decision map. For example, for the trade-off corresponding to the restriction $F_5 \geq 2300$ (i.e. for water volume in the Alqueva lake not less than 2300 hm^3), we concluded that the compromise values of the criteria F_1 and F_2 is close to point ***P***.

Relation between agricultural income F_1, agricultural pollution F_2, household and industrial consumption *(F_4)* and water volume accumulated in the Alqueva lake F_5. When we have four criteria to analyse we can use a sequence of three-dimensional decision maps constructed for different values of the fourth criterion. In Figure 7, agricultural income *(F_1)* is represented by the horizontal axis, agricultural pollution *(F_2)* is represented by the vertical axis and household and industrial consumption *(F_4)* is given by slices in different colours ($F_4 \geq 0$, 10, 20, …, 80 hm^3). The three-dimensional decision maps given in Figures 7a, 7b and 7c are constructed for the values of water volume in the Alqueva lake *(F_5)* not less than 2200, 2300 and 2400 hm^3 respectively.

The decision map in Figure 7a shows that all slices of household and industrial consumption criterion are close. That allows us to conclude that when water volume in the Alqueva lake is not

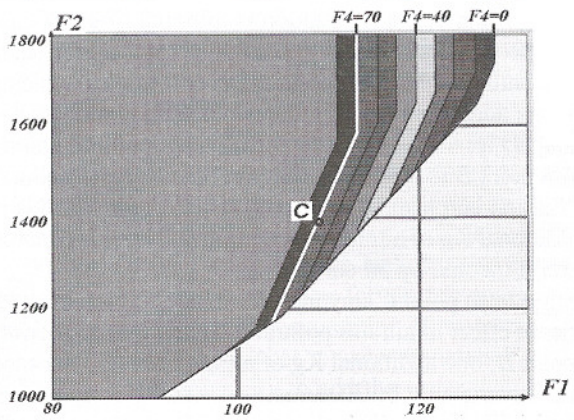
Figure 7 – *Decision maps for the criteria F_1, F_2, F_4 and F_5.*



(a) F_5=2200 hm^3 **(b) F_5=2300 hm^3**

(c) F_5=2400 hm^3

Figure 8 – *Fragment of figure 7b.*



less than 2200 hm^3 there is no conflict between household and industrial consumption F_4 and the first two criteria F_1 and F_2. In the decision map in Figure 7b it is possible to observe slices of different colours that reveals the existence of trade-offs between F_4 and the first two criteria. This means that these three criteria are in conflict. In the last decision map in Figure 7c the coloured area is larger, which means that this conflict increases.

The comparison of the three decision maps in Figure 7 leads us to opt for the feasible decision set represented in the decision map (b) related to water volume in the Alqueva lake not less than 2300 hm^3. It seems to be a reasonable choice because this combination represents near 70% of the maximum Alqueva lake capacity and it is slightly greater than the initial volume (2200 hm^3).

Figure 8 represents a fragment of the decision map from Figure 7b. We will consider here the trade-off between F_1 and F_2 corresponding to household and industrial consumption F_4 equal to 70 hm^3. This value gives about 80% of foreseen urban and industrial water needs for the Alqueva project. The point C on this trade-off shows a reasonable compromise between F_1 and F_2 (when F_4 =70 hm^3) which corresponds to the agricultural income F_1 of 108 million euros and nitrates pollution F_2 of 1400 tonnes. This is perfectly compatible with the maximum electric energy production in the Alqueva region (240 GWh).

Now we can formulate the following final reasonable combination of the criteria: agricultural income F_1 of 108 million euros, nitrates pollution F_2 of 1400 tonnes, electric energy production F_3 of 240 GWh, household and industrial consumption F_4 of 70 hm^3, and water volume in the Alqueva lake F_5 of 2300 hm^3. This criteria combination was regarded as a «reference point» in the Wierzbicki method (1) which was used to calculate decision variables of the model, and we obtained, among the others, the following values: water used for irrigation purposes of 363 hm^3, area occupied by fruits production of 30 thousands hectares, area occupied by vineyards of 30 thousands hectares, area occupied by olives for oil of 37 thousands hectares, water transfers from the Alqueva lake to the Pedrógão lake of 755 hm^3.

5. Conclusion

Integrated water management models are required to evaluate alternative water allocation combinations among different uses. In this paper one multi-objective programming model of the Alqueva region was proposed and the Feasible Goals Method / Interactive Decision Maps (FGM/IDM) technique was used to compute and explore alternative water allocation on base of this model.

Different allocation combinations were successively explored considering initially two and going up to the four criteria competing goals of agricultural income, final water levels in the dam, agricultural pollution and household and industrial consumption.

Final results show that an efficient and equitable combination of water allocation among competing uses is achieved when household and industrial consumption is equal to 70 hm^3, water use is equal 363 hm^3 for irrigation of 89 thousand hectares that generate an annual agricultural income of 108 million euros, allowing pollution levels of 1400 tonnes and maintaining the final water volume in the Alqueva lake at 2300 hm^3.

The electric energy production is not in conflict with other criteria, and it is possible to produce 240 GWh of electric energy, which is the maximum capacity of the electric plant at the Alqueva dam. The household and industrial consumption level represents 88% of the water needs foreseen by Hidrotécnica Portuguesa (1995) for the Alentejo region, for the industrial park of Sines and for the zone of Setúbal. The agricultural income corresponds to 77% of its maximum value of 140 million euros. This reduction has allowed lower pollution by 22% from its maximum of 1800 tonnes. The final water volume in the Alqueva lake is 70% of its maximum capacity and is larger than the initial volume by 5%. The irrigated crop area represents 80% of total irrigation area and the fruits, vineyards and olive trees are the agricultural activities which value most the water for the irrigation proposes.

These final results allow us to conclude that the achieved preferable point is a reasonable compromise among the considered criteria and its computable decisions seem to be coherent with the trends in the Alqueva region.

The multi-objective programming model proposed is a useful tool to support decision making in the Alqueva region, but it is still necessary to improve it including a hydrological model with dynamic equations, and disaggregating the decision strategies. It was proved that the Feasible Goals Method / Interactive Decision Maps (FGM/IDM) technique can be useful to explore trade-offs and to identify levels of different goals that require high trade-off rates among competing criteria exploring alternative efficient and equitable multiple goal interior solutions to support policy making process and decisions.

Results for policy purposes show that expected economic impact of structural agricultural policies of irrigation projects should be evaluated taking into account alternative uses for water resources. Proper allocations of water resources to alternative uses in scarcity areas must consider social and environmental needs. Multi-objective water allocation projects require integrated management frameworks and policies at regional territorial level to achieve reasonable compromise of competing economic, social and environmental goals, foster global project benefits and promote sustainable development.

References

Boussard, J.M., Daudin, J.J., 1988. *La programmation linéaire dans les modèles de production,* Mason, Paris.

Bushenkov, V.A., 1985. Interactive method for constructing orthogonal projections of convex polyhedral sets, *Zh Vychisl. Mat. Mat. Fiz.*, 25(9), 1285-1292.

Bushenkov, V.A., Ereshko, F., Kindler, J., Lotov, A.V., Maré, L., 1982. Application of the Generalized Reachable Sets Method to Water Resources Problems in Southwestern Skane, Sweden, *Working Paper WP-82-120, IIASA*, Áustria.

Charnes, A., Cooper, W., 1961. *Management Models and Industrial Applications of Linear Programming,* John Wiley, New York.

Chernykh, O.L., 1988. Constructing the convex hull of a finite set of points using non-precise computing. *Zh. Vychisl. Mat. Mat. Fiz.*, 28(9), 1386-1396.

Cohon, J., 1978. *Multi-objective Programming and Planning,* Academic Press, New York.

EDIA – Empresa de Desenvolvimento e Infra-estruturas de Alqueva, 2006. *Alqueva / Dez anos: Electricidade, regadio e 1.140 milhões de investimento*, Folha Informativa, 2006.

Fragoso, R., Lucas, M.R., 2009. Avaliação da competitividade da agricultura do Alentejo no âmbito do ecossistema Montado, *Revista de Economia e Sociologia Rural*, vol 27, nº 1, 9-26.

Fragoso, R., Marques, C., 2007. A Competitividade do Regadio em Portugal no Contexto da Nova Política Agrícola Comum: O caso de uma exploração agrícola no Alentejo, *Revista de Economia e Sociologia Rural*, vol. 45, nº1, 49-70.

Gass, S., Saaty, T., 1955. The Computational Algorithm for the Parametric Objective Function, *Naval Research Logistics Quarterly* 2,39.

Hazell, P.B.R., Norton, R.D, 1986. *Mathematical Programming for Economic Analysis in Agriculture,* Mac Millan Publishing Company, New York.

HP – Hidrotécnica Portuguesa, 1995. *Estudo prévio do sistema global de rega do Empreendimento de Fins Múltiplos de Alqueva*, Lisboa.

HP – Hidrotécnica Portuguesa, Tractebel and S.E.I.A., 1992. *Empreendimento de Fins Múltiplos de Alqueva: Estudo de avaliação global*, Lisboa.

Lévite, H., Sally, H., 2002. Linkages between productivity and equitable allocation of water, *Physics and Chemistry of the Earth* 27, 825-830

Lotov, A.; Bushenkov, V., Kamenev, G., 2004. *Interactive Decision Maps: Approximation and Visualization of Pareto Frontier,* Series: Applied Optimization, vol 89, Kluwer Academic Publishers, 310 p.

Lotov, A.; Bushenkov, V., Kamenev, G., 2001. *Feasible Goals Method: Search for Smart Decisions,* Computing Centre of Russian Academy of Sciences, Moscow, 240p.

Lotov, A., 1973. An Approach to Perspective Planning in the Case of Absence of Unique Objective, *in Proceedings of Conference on Systems Approach and Perspective Planning. Moscow,* Computing Center of the USSR Academy of Sciences.

Lucas, M.R., Godinho, M.L., Fragoso, R., 2002. The evolution of the agri-enviromental policies and sustainable agriculture, *in Proceedings of the X European Association of Agricultural Economist Congress: European Agri-Food System*, Saragoça, Espanha, Setembro, 2002.

Millan, J.S., Berbel, J., 1994. A Multicriteria Model for Irrigated Agriculture Planning under Economical and Technical Risk, *Agricultural Systems* 44, pp. 105-117.

Molden, D., 2000. *Irrigation and Water Resources Program Presentation to the IWMI Board of Governors,* International Water Management Institute, Colombo, Sri Lanka.

Noéme, C., Fragoso, R., 2004. Evaluation of Alternative Policies of Irrigation Water Price. Application to Large Farms in Alentejo Region, *Agricultural Engineering International – the CIGR Ejournal*, Manunscript LW 04006, vol VI.

ONU – Organização das Nações Unidas, 2006. *Human Development Report 2006 – Power, poverty and global water crisis,* Palgrave Macmillan, New York.

Simon, H., 1960. *Science of Management Decision*, Harper and Row, New York.

Stadler, W., 1986. Initiators of multicriteria optimization, in: J. Jahn and W. Krabs (eds) *Recent Advances and Historical Development of Vector Optimization*, Berlin: Springer-Verlag, 3-47.

Steuer, R., 1986. *Multiple Criteria Optimization,* John Wiley, New York.

Wierzbicki, A., 1981. A mathematical basis for satisfying decision making, in: J.Morse (ed) *Organizations: Multiple Agents with Multiple Criteria*, Berlin, Springer, 465-485.

Zekri, S., 1991. *Modelos decisionales multicriterio en planificación agraria: objetivos económicos versus objetivos ambientales,* PhD dissertation, Universidade de Córdoba, Córdoba.

Zeleny, M., 1974. *Linear multi-objective programming,* Springer, Berlin.

Appendix – Agricultural technical coefficients.

	Units	Summer Crops	Winter Crops	Horto Industrial	Fruits	Vineyard	Olives
Gross revenue	(10^6€/10^3 ha)	1,60	0,70	3,22	4,49	1,50	3,20
Operating Costs	(10^6€/10^3 ha)	1,05	0,85	2,08	2,62	0[illegible]	[illegible]4
Water needs	(hm^3/10^3ha)	6,0	1,5	4,9	4,9		
Nitrates pollution	(10^2Ton/10^3ha)	0,92	0,71	1,22	0,16		

Sources: Noéme et al., 2004; Fragoso and Marques, 2007; and Lucas et al., 2[illegible]

are