Ecological versus Economic Objectives: A Public Decision Making Problem in Agricultural Water Management

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Abstract: The planning of a new irrigated area is a complex problem where a multiplicity of very different criteria (economic, ecological, social, etc.) have to be taken into account. A lexicographic goal programming model capable of handling this multiplicity is formulated. The methodology is applied to the planning of the irrigated lands of the village of Tauste in Aragón (Spain). An important result generated by the model is the conflict between economic criteria and environmental effects such as "salt-load," which affects the water quality in the basin. This matter is thoroughly analysed by determining the transformation curve between "salt-load" and the investment outlay in the irrigation systems discussed.

Introduction

In many geographical areas, water is the main limiting factor for agricultural development. Consequently, the transformation of large rain-fed areas into irrigated lands has been and will continue to be a common practice to increase regional wealth in many parts of the world. The positive effects of irrigation in agricultural production, primarily in terms of increased profitability and employment, are well known.

However, the massive use of water for irrigation is not exempt from negative effects. Water is a multi-purpose natural resource essential for agriculture, industry, human consumption, recreational activities, etc.; hence, its intensive use in a single activity (e.g., agriculture) can generate an important opportunity cost in the other activities. Moreover, intensive irrigation practices are also one of the main causes of salinization of soils and river basins, as well as an important source of energy consumption (Aragüés *et al.*, 1985; and Golley *et al.*, 1990). For these reasons, the use of water for irrigation must be carefully planned, thus avoiding the very common practice of over-irrigation.

This paper has a twofold aim. First, a methodology is proposed that simultaneously determines the allocation of agricultural enterprises and irrigation systems in a newly irrigated area. Traditional criteria regarding private profitability, as well as social (e.g., employment levels) and ecological criteria (e.g., degradation of water quality due to "salt-loading" effects), are taken into account. The methodology demonstrates how a lexicographic goal programming (LGP) model is a suitable approach to these multi-criteria problems. Second, the proposed methodology is applied to a water management problem in the irrigated lands of the village of Tauste in Aragón (Spain). The irrigation efficiency level (65 percent) in this micro-region of more than 11,000 ha was found to be inadequate, generating important salinity problems for the waters of the Arba river.

Irrigation Systems

To improve irrigation efficiency in the micro-region of Tauste, five feasible alternative systems were considered. The first system (hereafter System A) consisted of improvement of the existing infrastructure by covering the ditches with cement and levelling the land using laser techniques. This method leads to an irrigation efficiency of 72 percent (i.e., an increase of 7 percent over current efficiency). The second, third, and fourth systems (hereafter Systems B, C, and D) involved three different sprinkler systems with an irrigation efficiency of 81 percent. The differences between these three systems lie in the amount of energy and labour required. The fifth system (hereafter System E) consisted of a trickle irrigation system with an irrigation efficiency of 93 percent. Table 1 shows the characteristics of each of the five irrigation systems considered.

Table 1—Technical and Economic Characteristics of the Five Irrigation Systems Considered

Characteristics	Improvement of the Current Infrastructure	Sprinkler Irrigation			Trickle Irrigation
	System A	System B	System C	System D	System E
Validity	All crops	All crops	All crops	Not for maize and sunflower	Only maize, vegetables, and fruit trees
Labour use (hours/ha/year)	Depends on crop	6	3	60	8
Energy (ptas/ha/year)	0	4,628	7,518	4,630	4,420
Cost (ptas/ha)	138,800	371,510	260,160	136,850	228,010
Planning horizon (years)	15	25	15	15	20
Annual maintenance and operational costs (ptas/ha)	200	3,530	2,416	1,775	4,189
Irrigation efficiency (percent)	72	81	81	81	93

Table 2—Sensitivity Analysis Results

Criteria	Scenario 1	Scenario 2	Scenario 3
Water consumption (Hm^3/year)	59.5	59.5	62.8
Energy use (million ptas/year)	17.5	17.5	12.2
NPV (million ptas)	81	372	609
Employment (work units/year)	565	565	565
Seasonal labour (work units/year)	283	283	304
Salt-load (t/year)	20,619	20,619	30,584
Loan (million ptas)	1341	1099	2081
Irrigation system (percent of whole area)	SA = 55, SF = 45	SA = 55, SF = 45	SA = 70, SF = 30

Currently, the whole area (approximately 11,000 ha) is irrigated by a furrow system. The five other systems have been successfully tested in the area. The irrigation scheduling system was not considered as it is a sophisticated system requiring an accurate data base and highly qualified manpower, not available in the region (Dudek *et al.*, 1981). Another method not considered consists of the establishment of a progressive water consumption levy, a policy that cannot be implemented because the current infrastructure of the area does not allow the measurement of individual water consumption. Consequently, farmers pay a fixed amount per hectare regardless of the water they use.

Methodology

The following attributes are essential for policy-making purposes in the context of the decision-making problem under consideration and consequently endogenously introduced into the model (Zekri and Romero, 1990).

Water consumption. The reduction in water consumption for irrigation allows an increase in the use of water for other purposes, the irrigation of new areas, and the reduction of "salt-load" effects in return flows, thus improving water quality.

Energy use for irrigation. Public decision makers are interested in efficient irrigation systems that minimize the use of energy.

Net present value (NPV). The NPV represents a measurement of private profitability in the allocation of agricultural enterprises and irrigation systems.

Employment. This is important because farming is virtually the only economic activity in Tauste and its current unemployment rate is very high.

Seasonal labour. For the reasons mentioned, it is important to obtain high employment in terms of both daily wages and permanent workers.

"Salt-load" has not been explicitly considered. It is, however, complementary to water consumption; that is, when water consumption is minimized, "salt-load" is also minimized. Consequently, "salt-load" is considered an exogenous variable that is calculated once water consumption is obtained using the hydrosalinity model proposed by Aragües *et al.* (1985) and adapted for Tauste.

Given the substantial number of attributes considered as well as the relative complexity of the constraint set, most of the potential benefits of some multi-criteria approaches such as multi-objective programming or compromise programming vanish. In fact, a problem of the size of the case presented in the paper is computationally almost intractable using multi-objective programming. However, such a problem can be easily treated through goal programming (Romero and Rehman, 1989, p. 102). Moreover, within the GP framework, the lexicographic variant is particularly relevant for decision making in the field of natural resource management where many attributes of a very different nature (economic, social, environmental, etc.) measured in different units have to be considered simultaneously (Romero, 1991, pp. 43–46).

In LGP, preemptive or absolute weights are attached to the achievement of various goals, which are grouped into a set of priorities. The problem corresponding to the highest priority level is solved first, and only then are the lower priorities considered. The structure of an LGP model can be summarized in the following way:

(1) Lex min $a = [g_1(n, p), ..., g_i(n, p) ..., g_k(n, p)]$,

subject to: $f_i(x) + n_i - p_i = b_i, \forall_i$, and $x \in F$,

where "Lex min" means a lexicographic optimization process; $g_i(n, p)$ is a function of the deviation variables; $f_i(x)$ is a mathematical expression for the ith attribute; b_i is the target for the ith attribute; n_i and p_i are negative and positive deviational variables measuring the under-achievement and over-achievement of attribute i with respect to its target; x is a vector of decisional variables; and F is the feasible set.[2]

In the problem under consideration, two priority levels were considered. In the first, the five attributes considered were included, attaching to them the following targets: 65 Hm^3/year for water consumption, 17.50 million ptas/year for use of energy, a zero value for the NPV (financial feasibility of the investment), 565 work units/year (1 work unit = 1920 hours) for the level of employment, and 565 work units/year for seasonal labour. For the attributes water consumption, energy use, and seasonal labour, the unwanted deviational variables are positive (i.e., over-achievements are not wanted), whereas for the attributes NPV and employment, the unwanted deviational variables are negative (i.e., under-achievements are not wanted).

The above vector of targets represents a situation that can be considered as an acceptable compromise for the policy maker and consequently should be satisfied in a Simonian sense, as far as possible. At the second priority level, the attributes water consumption, use of energy, and seasonal labour are again considered, although the targets are now set at more demanding levels: 54 Hm^3/year for water consumption, 5.5 million ptas/year for energy use, and 280 work units/year of seasonal labour. This second vector of targets represents what would satisfy the policy maker's needs as closely as possible once the achievement corresponding to the goals included in the first priority is maintained. The structure of the LGP model can be summarized as follows:

$$\text{(2)} \quad \text{Lex min } a = [(\propto_1 p_1 + \propto_2 p_2 + \propto_3 n_3 + \propto_4 n_4 + \propto_5 p_5), (\propto_6 p_6 + \propto_7 p_7 + \propto_8 p_8)]$$

subject to:

$$\begin{array}{ll}
\text{Water } (w) & + n_1 - p_1 = 65 \\
\text{Energy } (E) & + n_2 - p_2 = 17.5 \\
NPV & + n_3 - p_3 = 0 \\
\text{Employment } (EM) & + n_4 - p_4 = 565 \\
\text{Seasonality } (S) & + n_5 - p_5 = 565 \\
\text{Water } (w) & + n_6 - p_6 = 54 \\
\text{Energy } (E) & + n_7 - p_7 = 5.5 \\
\text{Seasonality } (S) & + n_8 - p_8 = 280
\end{array}$$

$$x \in F$$

The feasible set is formed for constraints related to land occupation, crop rotation, water requirements during the peak months, financial requirements, etc.[3] The weights $\propto_i$ play a double role: they represent the relative preferences of the decision maker and are also normalizing factors. Thus, for instance, $\propto_i = w_i / k_i$, measuring the relative importance attached by the decision maker to the ith goal with respect to the other goals included in that priority, and k_i is equal to the difference between the ideal and the anti-ideal for this attribute. In this way, all traditional normalizing problems are avoided.

In order to compute the model, a planning horizon of 25 years was considered. It is assumed that the autonomous government will subsidize 30 percent of the outlay on the project and that the rest of the investment will be financed through a loan at a subsidized interest rate of 4 percent payable over 10 years. The discount rate chosen was 11 percent. All prices and costs are expressed in constant pesetas for 1988.

Results

The LGP problem (2) was solved by resorting to the sequential linear method (Ignizio and Perlis, 1979) hybridized with the method proposed by Romero and Rehman (Romero, 1991, Chap. 2), thus avoiding the generation of inferior solutions. By attaching the same relative importance to the normalized goals placed in the same priority level, the following solution in the goal space was obtained:

> w = 65 Hm^3/year; E = 5.3 million ptas/year; NPV = 346 million ptas
>
> EM = 565 work units/year; S = 283 work units/year

The above solution permits a complete achievement of the goals included in the first priority. With respect to the goals included in the second priority, there is a slight discrepancy (with no real interest) for the goals energy and seasonal labour and an important deviation of 11 Hm^3/year in water consumption. The corresponding irrigation structure is: 85 percent for System A (i.e., an improvement of the current infrastructure) and 15 percent for System E (trickle irrigation).

The "salt-load" corresponding to the above solution was calculated with the help of the hydrosalinity model. In this way, a "salt-load" of 36,209 t/year was obtained. This figure is important from an ecological point of view and is caused by the high water consumption of 65 Hm^3/year.

As the project analysed is heavily financed with public funds, it is of great interest to investigate the possibility of reducing the high "salt-load" obtained by an increase in the outlay on the project. This task is accomplished by resorting to the Non-Inferior Set Estimation Method (NISE) (Cohon *et al.*, 1979), which permits the determination of the transformation curve between outlay on the project and "salt-load." The transformation curve between the outlay on the project and water consumption is obtained. The figures for water consumption are transformed into "salt-load" figures using the hydrosalinity model (Figure 1).

Point A corresponds to the current situation; i.e., no improvement in the irrigation system. The corresponding "salt-load" is of 142,781 t/year. As usually occurs with this kind of analysis, the slopes of the straight lines connecting the corresponding extreme efficient points measure the opportunity cost of one objective ("salt-load" or water consumption) in terms of the other objective (outlay on the project or government subsidy).

In the southwest part of the transformation curve, the opportunity costs are not too high (e.g., an increase of 15,100 ptas in the outlay on the project for one ton of salt mass reduction along segment AB). However, in the northwest of the transformation curve, they are very high (e.g., an increase of 38,280 ptas in the outlay on the project for one ton of salt mass reduction along segment EF). It is possible to obtain sensible compromises in the neighbourhood of point C (i.e., acceptable figures of salt mass and water consumption) without greatly increasing outlay or government subsidy.

Sensitivity Analysis

The uncertainty inherent in many of the parameters used makes it necessary to implement a sensitivity analysis to assess the impact of the uncertainty in the conclusions derived from the research. Several scenarios were built for this purpose, each of which attempts to reflect a realistic situation in terms of loan conditions, weights attached to the goals, costs of the irrigation systems, etc. The most significant results are shown in Table 2.[4]

To investigate the effects of a reduction in water consumption—and consequently a reduction in "salt-load"—in the three scenarios considered, the weight attached to the water consumption goal is 50 percent higher than the weights attached to the other goals.

The first scenario corresponds to the situation previously studied, with increased weight attached to the water consumption goal. The second scenario corresponds to an optimistic situation in which the cost of irrigation System A decreases 45 percent while the cash flow of the investment increases 2 percent per year. The third scenario corresponds to a pessimistic situation in which the cost of the different irrigation systems increases by 20 percent, no government subvention is considered, and the cash flow of the investment decreases by 2 percent per year.

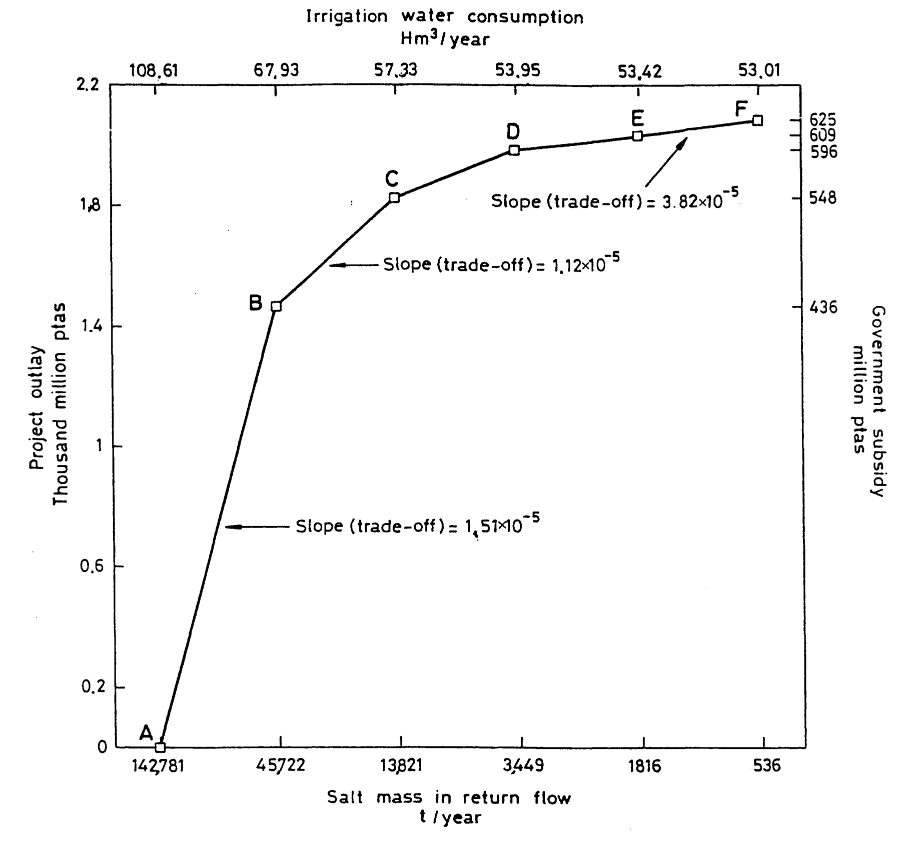

Figure 1

The results shown in Table 2 are instructive for the public decision maker as well as self-explanatory. However, the results in scenario 3 present some apparent oddities which should be clarified; e.g., without government subsidies, the NPV improves with respect to the other two scenarios. However, there is a simple explanation for this apparent anomaly. In scenario 3, the farmers must pay back the loans at an interest rate of 11 percent, which makes the financial constraints of the model more severe, so that cheaper combination irrigation systems are considered. These cheaper combinations generate higher NPV figures and at the same time considerably increase water consumption and hence "salt-load" figures.

Concluding Remarks

Most of the goals relevant to the problem analysed are fully achieved (employment, NPV, etc.). However, there is a significant deviation between the target fixed for water consumption and the level actually achieved. This deviation is important because water is a scarce resource necessary for many purposes and also because the "salt-load" affecting the water quality of the river basin is directly proportional to the level of water consumed. In this sense, one of the conclusions derived from the model is particularly relevant: government subsidies can considerably improve environmental goals such as water consumption (e.g., "salt-load" instead of private goals such as NPV).

Notes

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[2]For a more detailed description of the technical aspects of LGP, see Ignizio, 1976.
[3]For details, see Zekri 1991.
[4]For more details, see Zekri, 1991.

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Discussion Opening—*A.K. Kashuliza* (University of London)

The role of irrigation in agricultural development and the Green Revolution, especially in geographical areas where water is the main limiting factor to agricultural production, is very clear and needs no over-emphasizing.

However, for sustainable agriculture, the increase in production has to be considered not only against economic and social costs, but also the costs to the environment (e.g., levels of waterlogging, salinity, etc.). Also, as rightly pointed out by Zekri and Romero in their paper, as water is a multipurpose natural resource essential for agriculture, industry, human consumption, etc., its intensive use in a single activity (e.g., agriculture) can generate an important opportunity cost in the other activities.

There are thus important trade-offs (economic, social, environmental, etc.) in the planning of water management projects or programmes. The decision maker is faced with a complex problem, where a multiplicity of criteria of very different nature have to be taken into account.

The Multi Criteria Decision Making (MCDM) techniques, of which LGP is a part, which have also evolved over the last two decades, are virtually the only way of satisfactorily investigating the type of problem described above.

The capital outlay attribute is not considered in the basic analysis (LGP) along with other attributes; i.e., water consumption, energy, NPV, employment, and seasonal labour. Capital outlay is an important attribute because the analysis is comparing technical and economic characteristics of five irrigation systems. Although the authors mention this attribute in a later part of the paper (i.e., that the government will subsidize 30 percent of the outlay on the project and that the rest of the investment can be made through a loan), this does not eliminate the need to have this attribute in the base model to enable both economic (social) and private decisions to be made about the projects. It is therefore surprising that this important attribute is only considered in passing in the sensitivity section of the paper.

In the LGP model, preemptive or absolute weights are attached to the achievement of various goals on an *ex ante* basis, which are then grouped into a set of priorities. Is there a standard methodology of deciding which relative weight to give to which attribute? Otherwise the process is very subjective and results could vary considerably depending on who the decision maker is on any particular occasion.

The logical sequence of the LGP model is that higher priority goals are satisfied before the lower ones (hence the lexicographic order). Similarly, the priority sets will have different attributes, with the higher priority sets having the most preferable attributes. However, in the formulation of Zekri and Romero's LGP model, both the priority sets have the same attributes (at different levels). I therefore feel that the authors are conducting a sensitivity analysis of the first priority set of attributes rather than solving the classical LGP problem (which requires several sets of priorities).

It is clear from Zekri and Romero's paper that results of LGP analysis can be greatly enhanced if water pricing (in the form of a progressive water consumption levy or other method) is also considered. This was not possible in this case because the infrastructure in the area does not allow measurement of individual consumption. It would be interesting to hear from those who have worked in areas where the pricing criteria could or has been incorporated in the LGP model on how it could have influenced the results presented in Zekri and Romero's paper.

General Discussion—*Geert Thijssen, Rapporteur* (Wageningen Agricultural University)

In relation to a central element of Oskam's paper, the measurement of external effects of agricultural production, many questions were raised about how the shadow prices were calculated, given that several methods are available, such as contingent valuation, travel costs, hedonic prices, etc. Oskam's method is one of estimated costs per unit of measure to be taken for the future; for example, for ammonia, a list of marginal costs per unit reduction was calculated for the Netherlands. The question was raised of whether these prevention costs are a good basis for estimating damage costs resulting from agricultural pollution. The human health effects of pesticide residues and, for example, salmonella in manure, food, or water are important damage costs, which should be taken into account. In reply, Oskam pointed out that in the Netherlands, the government has set up standards for adverse externalities, so that the health effects are implicitly taken into account in measuring the damage costs. There was some concern as to exactly how the shadow prices are measured, an aspect which Oskam will be taking up in further work. Another comment referred to calculating the positive externalities of agriculture, even though it is very difficult to value the landscape, for example.

Some fundamental questions were raised concerning the limitations of the type of model used by Livingston and Witzke; for example, whether it can be used to analyse the exploitation of tropical woods, in the Amazon region, and whether the neoclassical approach, which is continuous, can be used to analyse the political process, which can be characterized by jumps.

In reply, Livingston said the model can handle different types of institutional agreements between countries. Both countries can gain by the agreement: win-win. One country can compensate another country for reducing its pollution (for example, Sweden pays to Poland to reduce the pollution of the Baltic Sea): win-win. One country pays another country for reasons of justice, for example the developed countries finance pollution reduction by developing countries. The cost of organizing political support is incorporated in a new version of the model, which is also estimated. However, future generations are not considered in the model and only a democratic society was considered as a political structure.

Participants in the discussion included T. Haniotis (Commission of the EC), T. Hasebe (Tohokan University), E. Rabinowicz (Swedish University of Agricultural Sciences), T. Roberts (US Department of Agriculture), K. Thomson (University of Aberdeen), E. van Ravenswaay (Michigan State University), U. Vasavada (Université Laval), and T. Veeman (University of Alberta).