A Multi-Criteria Approach for Irrigation Water Management

João Paulo Saraiva and António Cipriano Pinheiro[*]

Abstract

The major implications that the European Union (EU) Water Framework Directive (WFD) may have in irrigated agriculture were analysed using alternative water policy measures. The consequences of policy change were evaluated in a case study (Baixo Alentejo, Portugal), using a Multi-Criteria Decision Making (MCDM) model that simulates farmers' preferred behaviour. The study compares the effects of water pricing (volumetric and flat tariffs) and consumption quotas, in farmer's income, water agency revenues, agricultural employment and water demand for irrigation. Model results indicate that the adjustments in farmer's responses are dependent on the policy strategy enforced and on the policy level.

Key Words: *Water Framework Directive; Flat Pricing; Volumetric Pricing; Multi-Objective Programming; Water Management; Portugal.*

Introduction

Water is a resource that is becoming increasingly scarce, requiring careful economic and environmental management to deal with increasing pressures (World Bank 1993). Water is not always in the right place or at the right time (OECD 1999a). In fact, under Mediterranean conditions, the availability of water resources is unequally distributed both in time and in space, causing strong discrepancies across regions and seasons.

Irrigation water is a productive factor without any substitutes (OECD 1999a;OECD 1999b); in European Mediterranean countries and in Portugal, the water use for agriculture represents 70% (EEA 2003) and 74.8% (INAG 2002) of the total water consumption, respectively. In these conditions, the successful management of water resources is primarily influenced by policies affecting irrigated agriculture. In this sense, within the European Union (EU), the Common Agricultural Policy (CAP) and the Water Framework Directive (WFD) are the most important policies.

The EU Water Framework Directive (Directive 2000/60/EC 2000), was enacted in the first half of 2000 and establishes a framework for Community action in the field of water policy. In the light of this Directive, EU Member States are obliged to put into practice a cost recovery strategy and to implement a water pricing policy. In practice, this means that farmers of most irrigation schemes will have to adjust their production

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practices or their cropping patterns to either higher water prices or to tighter water controls. This study aims to quantify the dimensions and implications of these adjustments.

Recent research with identical objectives and closely related methodologies has been conducted in other European countries under the EU funded research Project WADI – *Sustainability of European Irrigated Agriculture under the Water Directive and Agenda 2000*. WADI focused on the impacts of various policy instruments for irrigation water management and on the combined effects of the WFD and CAP scenarios (see for instance, Bazzani et al. 2002;Bazzani et al. 2004;Berbel & Gomez-Limon 2000;Berbel, López, & Gutiérrez 2005;Gallerani et al. 2005;Gómez-Limón & Riesgo 2005;Gomez-Limon & Berbel 2000;Gomez-Limon, Arriaza, & Riesgo 2003;Gomez-Limon & Riesgo 2004;Manos, Bournais, & Kamruzzaman 2005;Manos, Bournaris, & Kamruzzaman 2003;Morris et al. 2005;Pinheiro & Saraiva 2005;Saraiva & Pinheiro 2003). In a similar study carried out in Spain, Varela-Ortega et al. (1998) using a dynamic profit maximizing model and administered pricing scenarios, revealed the different implications of adopting alternative volumetric pricing instruments. Michailidis et al. (2003) evaluated the demand of water for irrigated agriculture in the Western region of Macedonia, using a sequential stochastic programming model and accounting for deficit irrigation.

Although models based on mathematical programming are widely applied for agricultural economic policy analysis (Hazell & Norton 1986;Howitt 1995), most of them assume that the farmer behaves as a pure profit maximizer. However, it is demonstrated that, in reality, the decision maker seeks a compromise solution between several objectives (Hazell & Norton 1986;Romero & Rehman 1989). To overcome this problem, the modelling approach adopted in this study is based on a multi-objective mathematical programming model, supported by Multi-Criteria Decision Making (MCDM) and using the Multi-Attribute Utility Theory (MAUT) (see Bazzani et al. 2005;McCarl & Spreen 1997;Romero, Amador, & Barco 1987;Sumpsi, Amador, & Romero 1996;Varela-Ortega et al. 1998). This permits to incorporate farmers' decision-making behaviour and responses into policy analysis. In this paper, the farmer's objectives of maximizing farm income, minimizing risk, employment and operative capital were considered as attributes of the utility function.

The predictable implications that implementing the WFD may have in an irrigated cereal crop farming system in Baixo Alentejo (Portugal) are quantified when volumetric and flat tariffs and consumption quotas are applied. The WFD effects reported in this paper are analysed in the context of the Agenda 2000 agricultural policy measures (for a detailed discussion of the combined effects of the WFD and post-Agenda 2000 policy scenarios see Berbel and Gutiérrez (2005)).

Farmers' adjustments to alternative water policies were analysed considering farmer's income, water agency revenues, agricultural employment and water demand for irrigation.

Simulation results indicate that a Multi-Objective Decision Making model approach constitutes a powerful tool to better understand the processes related to natural resources use in agriculture and to assess the policy effects that influence them. The study shows that farmer's responses to policy change (measured by income, employment and resources use) are dependent on the policy strategy enforced and on the policy level set by the WFD.

Methodology

Modelling Agricultural Decisions

One of the vulnerabilities of agricultural economic programming models is often derived from an over-simplification of reality. Since the pioneering works of Heady (1954) and King (1953), which first reported the use of Linear Programming (LP) in farm planning, mathematical programming models have been widely used in agricultural economics (Hazell & Norton 1986), particularly for policy analysis (Howitt 1995). Since these early uses of LP, several methodological advances have been incorporated in the field of mathematical modelling in order to provide a "potentially more realistic portrayal of agricultural reality" (Hazell & Norton 1986). Some of these improvements particularly related with this research are the advances in the areas of modelling risk and risk aversion, on the role of instruments of economic policy and on the ability to model farm decisions (Hazell & Norton 1986).

In agricultural economics models the modelling of producer' responses has always been a fundamental concern. In fact, "the producers' behavioural question is always present" in every model, and it has been the principal focus of applied agricultural modelling research (Hazell & Norton 1986). In other words, the implications of policy actions cannot be fully evaluated until the farmers' responses are well understood (Hazell & Norton 1986).

Until recently, most agricultural economics studies considered farmers to behave in a profit maximising way. Nevertheless, numerous studies have proven that farmers behave in a risk-adverse way (Hazell & Norton 1986) or that are other goals to which the farmers reacts to (Romero & Rehman 1989). The results of ignoring these other goals often bear little relation to the farmers decisions (Hazell & Norton 1986) and lead to excessively constrained models improper for policy analysis (Howitt 2005).

In this line of thought, the traditional optimisation of one single objective (for instance, income maximisation) may not entirely reflect the farmers' behaviour. In practical terms, this means that the *ex-ante* analysis of agricultural or agri-environmental policies would be biased, and that policy measures could be mis-targeted and fail to achieve their purposes.

The most well established decision theory in economics to deal with the problem of multiple objectives is the expected utility theory, developed by von Neuman and Morgenstern in 1944 (Hazell & Norton 1986;McCarl & Spreen 1997) and, as such, it is the principal theoretical basis for choice under uncertainty (McCarl & Spreen 1997). The MAUT used in this research is derived from the expected utility theory. The figure below provides a schematic illustration of the model use to explore farmers' behaviour.

To overcome this problem, the analysis of policy effects in this study uses a behavioural model, based on Multi-Criteria Decision Making Theory (MCDMT) and Multi-Attribute Utility Theory (MAUT). In the MAUT formulations the objective function to optimise is a utility function composed by the multiple attributes that the farmer wishes to optimise. The composite optimisation of these partial utilities, each one associated to each considered attribute (objective), maximizes the farmers' total utility.

Using this methodology, the farmers' utility is not singularly conditioned by profit or gross margin maximisation; there are other objectives to which the decision maker reacts, such as risk, hired labour dependency, capital investments, fixed costs, leisure time or indebtedness (Hazell & Norton 1986;Romero & Rehman 1989). The objectives considered to be the most relevant for the farmers' in these case studies are the maximisation of farm income (RFE), and the minimisation of risk (Risk), employment (TL) and operative capital (K).

The fundamental methodological components of this mathematical programming model are well reported elsewhere (see Bazzani, Viaggi, Berbel, López, & Gutiérrez 2005;Sumpsi, Amador, & Romero 1996), and therefore only a short summary is presented here to avoid unnecessary and overlapping sections. An additive MAUT utility function for these objectives can be written as:

$$U_i(u_1+u_2+u_3+...+u_n)=f\left[w_1.f_1(u_1)+w_2.f_2(u_2)+w_3.f_3(u_3)+...+w_n.f_n(u_n)\right] \qquad (1)$$

being f_i , $\mathrm{i}=1,2,...,\mathrm{n}$ exclusive functions of the attribute u_i, and w_i the weights attached to the attribute u_i.

The problem is now centred on the values of the weights (w) attached to each attribute. These weights are responsible for simulating "the decision-making plan as close as possible to the farmers' real-life decision plan" (Gomez-Limon & Berbel 2000), and were derived by goal programming (see McCarl & Spreen 1997 Chapter XI), confronting model outputs with farmers observed behaviour.

As the contribution of each objective has different measurement units, the function must be rewritten normalising all objectives units, allowing additivity and enabling it to translate a meaningful value (Gomez-Limon & Riesgo 2004). The normalising step allows to express the relative importance of each objective to the farmers' utility, and consequently to the decision making process. This normalised equation can be rewritten as:

$$U = w_{RFE}\frac{RFE(\vec{X})-RFE_*}{RFE^*-RFE_*}+w_{RISK}\frac{RISK_*-RISK(\vec{X})}{RISK_*-RISK^*}+w_{TL}\frac{TL_*-TL(\vec{X})}{TL_*-TL^*}+w_K\frac{K_*-K(\vec{X})}{K_*-K^*} \qquad (2)$$

in which the symbols [$_*$] and [*] indicate the anti-ideal and ideal values for the corresponding objective and $\vec{X}$ indicates the vector of possible activities.

The use of simulation models based on mathematic programming is an instrument often mentioned in the literature to explore irrigation and water problems, and multi-objective models with MAUT formulations have been successfully used in the past to simulate the implications of water policy in the irrigated agriculture sector (see, for example, Arriaza & Gomez-Limon 2003;Arriaza, Gómez-Limón, & Upton 2002;Gómez-Limón, Arriaza, & Berbel 2002;Sumpsi, Amador, & Romero 1996;Varela-Ortega, Sumpsi, Garrido, Blanco, & Iglesias 1998).

Data Requirements

Whenever possible, the data used to feed the model came from official sources within the Ministry of Agriculture and the Institute of Statistics. Crop yields, producer prices and subsidies respect to a time series from 1997 to 1999 (GPPAA 2001a; GPPAA 2001b; INE 2001a; INE 2001b; INE 2001c; INE 2001d; INGA 2002). To validate and run the model the data were updated to the campaigns of 1999/2000 and 2002/2003.

Model Objectives

The mathematical formulation and some particular comments are separately presented for each objective.

- **Land and Entrepreneurial Revenue (RFE) maximization** – This income indicator accounts for all variable costs plus devaluation costs, but it does not deduct land and entrepreneurial remunerations and private capital interests.

$$\text{Max TRFE} = \sum_{i} \text{RFE}_i \text{X}_i \tag{3}$$

where (X_i) RFE contributions of selected individual crops are added.

- **Risk minimization (RISK)** – The variance of RFE was used to assess risk.

$$\text{Min VAR} = \vec{X}'.[Cov].\vec{X} \tag{4}$$

where, $[\text{Cov}]$ represents the upper triangular variance-covariance matrix of the RFE, $\vec{\text{X}}$ is the column vector of all possible activities (crops) and $\vec{X}'$ is its transposed row vector. It accounts for both prices and production levels for the selected crops in the considered period.

- **Total Labour minimization (TL)** – This indicator considers the labour used in general; that is, hired labour as well as family labour.

$$\text{Min TL} = \sum_{i} \text{L}_i \text{X}_i \tag{5}$$

where (L_i) is the unit crop labour requirements, and Xi is the activity dimension.

- **Operative Capital (K) minimization** – K is the maximum level of indebtedness that the farmer is willing to face. The working capital in each month (WKN_m) is obtained by the product of the necessary working capital in each activity ($WKM_{m,i}$) and the extent in which they are produced, added to previous months' capital requirements (WKN_{m-1}).

$$\begin{aligned} &\textstyle\sum_i \text{WKMm,i} * \text{Xi} + \text{WKNm} - 1 < \text{WKNm} \\ &\text{K} > \text{WKNm} \end{aligned} \tag{6}$$

Model Constraints

The trade-off between the model predictive power and model reality adherence is highlighted in Howitt (2005). If too constrained, the model shows a high adherence to reality, but its predictive power is diminished. A less constrained model does not exhibit such fine adherence, but its predictive capacities are further enhanced.

Some main restrictions were imposed to the model:

- **Land constraints.** The total area for crops and set-aside must be inferior to the availability of land. A representative cereal farm of 100 hectares was considered.
- **CAP constraints**. The CAP compulsory and voluntary set-aside measures were modelled, at the 10 and 50 per cent value of COP crops (Cereals, Oilseeds and Protein

crops), respectively; Activities subject to CAP quotas were constrained to their present levels (case of durum wheat, sugar beet and industry tomatoes).

- **Rotational constraints.** The area occupied by traditional Autumn/Winter crops (winter cereals) is identical to that occupied by Spring/Summer crop ones (maize and sunflower); rice production is also upper bounded to simulate real conditions.

Model Validation

The model is validated by comparing the activities which maximize the utility function, and those actually produced by farmers. This step enables to determine if existing deviations are small enough to consider the model as being representative of reality (adherent) or, on the contrary, if the model does not reproduce farmers' behaviour.

From the analysis of Table 1, one must conclude that the model reproduces farmers' crop selection with high accuracy. Therefore, the model is considered to be adherent to reality.

Table 1. Baixo Alentejo – model validation for a cereal farm (100 ha)

Activities	Observed Value (ha)	Multi-Objective Model		
		Obtained Value (ha)	Deviation (%)	Deviation (ABS acum.)
Wheat	21,7	26,2	-4,5	4,5
Durum Wheat	10,9	10,9	0,0	4,5
Maize	16,8	18,6	-1,8	6,3
Rice	3,4	3,4	0,0	6,3
Sugar Beet	3,9	3,9	0,0	6,3
Sunflower	17,0	18,6	-1,6	7,8
Ind. Tomatoes	5,8	5,8	0,0	7,8
Vegetables	5,2	5,2	0,0	7,9
Olive Groves	8,6	-	8,6	16,5
Set-aside	6,6	7,4	-0,8	17,3
Total	100,0	100,0	-	17,3

Results

Water demand curves

The water demand is determined by parameterisation of its price(s) or quota levels; as a result, the model outputs the amount of water demanded at a particular water price, or determines a shadow price, in the case of water quota simulation. The water demand curve associated with the quota regulation estimates the willingness to pay and the marginal utility.

Figure 1 shows for all policy instruments a negative price-quantity relationship – that is, water pricing and quotas vary in an opposite direction to water consumption. All irrigated crops respond to water pricing and quota regulations with the diminishment of their areas; the evolution of irrigated areas (Figure 2) evolves similarly to their respective water demand curves. It is notable that the greatest efficiency of policy instruments is achieved under the volumetric pricing and quota regulation situations.

The flat pricing situation curve is characterized by extensive inelastic segments, without any response to price increases. Indirect policy instruments, such as flat tariffs, are independent of the volume consumed and do not promote to more efficient uses (Tsur & Dinar 1995) or more use-efficient crops.

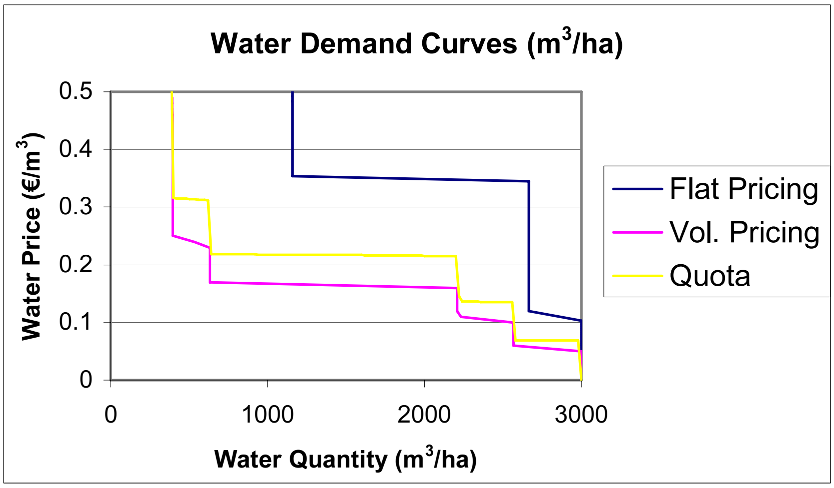

Figure 1. Water demand curves

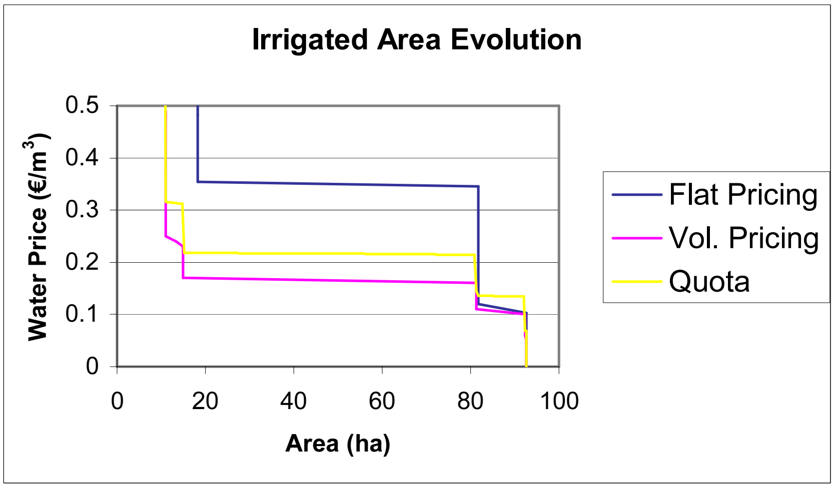

Figure 2. Irrigated area evolution

In the present situation, where the price charged per cubic meter is near zero, the average consumption per irrigated hectare is 2999 m^3. For a situation corresponding to a water price of 0.1€/m^3 the water consumption (average amount per hectare) decreases to 2566 cubic meters, in the volumetric pricing method, and to approximately 2570 m^3/ha in the quota simulation; this represents a 14% reduction in the water consumption. Under these situations, a 0.1€/m^3 price increase implies more than 10 per cent water consumption reduction. In the flat tariff simulation there is not any change in the water consumption, at this same level of water price.

Social implications

Figure 3 reveals that the analysed policy instruments systematically lead to the reduction of direct agricultural employment. If the simulated crop-technology relation is kept constant, the crop-mix change runs in parallel with a reduction of the demand for agricultural labour.

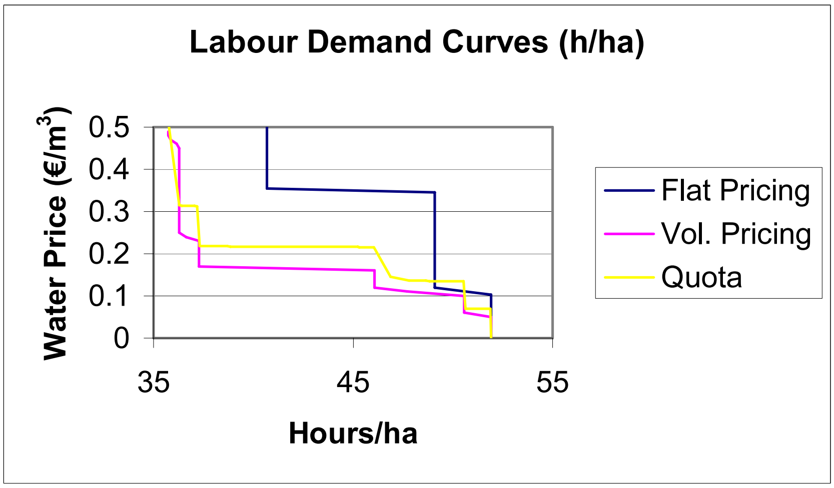

Figure 3. Labour demand curves

The flat-pricing method does not influence farmers' marginal decisions and therefore does not directly influence labour allocation decisions. In this situation farmers will demand labour for irrigated activities while the benefits of each activity surplus the flat tariff, beyond this point irrigation ceases and labour needs are diminished.

Economic implications

Agricultural Income

Farmers' income varies in the opposite direction of water pricing or consumption quotas. Figures 4 and 5 show that reductions in water consumption led to points of lower income. Initial water price increases are responsible for quite significant income losses, while the following ones have lower repercussions, contributing to the abandonment of irrigated crops and bringing down the farming income to levels similar to those of rain fed extensive farming.

The most water consumptive crops (rice, maize and sugar beet), or with reduced profitability, are the most affected in the quota and volumetric pricing situations. In the former case, crops relative profitability vary with the water price, and crops less water demanding or rain fed crops progressively become more profitable alternatives. In the latter case, the water demand evolves by the necessity of better remunerating a gradually more scarce production factor, and as in the previous situation, crops which consume more water are put aside.

In the flat tariff situation there is no direct relation between water demand and pricing. All irrigated crops are equally influenced, in absolute values, in their profitability reduction. As a result, the less profitable crops are ones removed from production, instead of the more water consumptive.

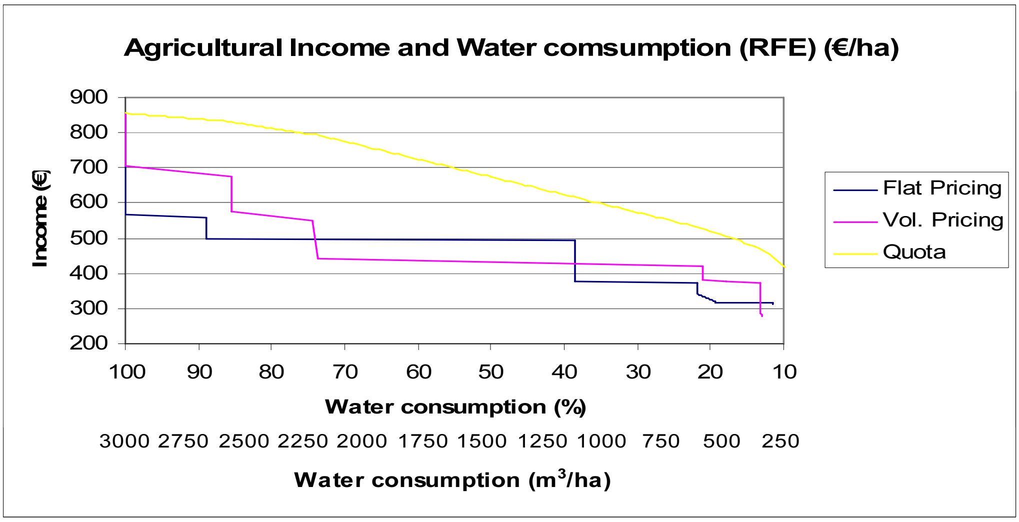

Figure 4. Relation between income and water consumption

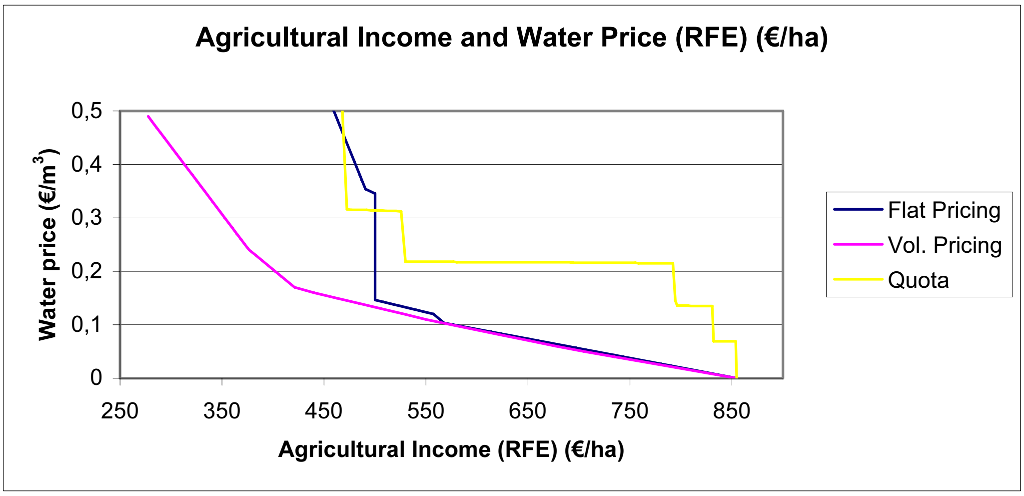

Figure 5. Relation between income and water price

Income transfers

This section analyses the capacity of policy instruments to generate revenues (farmer transfers to water agencies) and assesses government transfers to farmers in the form of direct payments.

Figure 6 shows that the maximum receipt associated with flat tariffs has no impact on water demand or cropping patterns. This maximum receipt is approximately of 300 Euro per hectare, reached with an income sacrifice of 33.6%. Under the volumetric pricing system the maximum revenue is slightly superior to 350 €/ha, obtained at the water price of 0.16 €/m^3, sacrificing agricultural incomes by 48.5 %, and reducing water demands by 26.3 %.

Volumetric pricing and water demand quotas go almost together concerning the support given to farmers through direct payments (Figure 7). In the flat pricing method, the amount of granted support is maintained as long as there is no incentive to remove from production the crops object of subsidies.

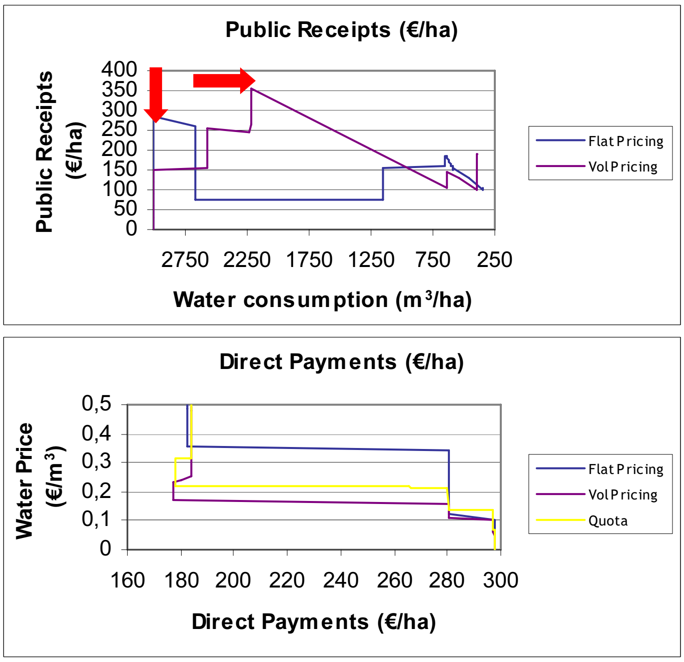

Figure 6 - 7. Income transfers

Final Comments

Water policies are often expected to achieve several and diverse objectives. Priority objectives to what is intended to be sustained must be clearly defined, as there is one particular policy instrument that best serves that particular objective. This study indicates that cost recovery, water pricing and water demand have little in common, and that different policy instruments should be chosen for each of these objectives.

If the objective is the protection of water bodies against excessive use, a regulatory instrument such a quota policy may be perfectly suited; if the priority is to promote the rational and efficient water use, the best policies to implement may consist in tradable rights or volumetric pricing policies; if the objective is to reflect the full cost of water services or to generate revenues, the adoption of flat pricing methods (cheaper than volumetric metering) may suffice to successfully reach this goal.

In the situation of Portuguese irrigated agriculture, in this study case contextualised by a representative cereal farm in the region of Baixo Alentejo, whatever the objectives may be, it is fundamental to have them accompanied by technical support measures, to create, develop, and reinforce technological adoption possibilities that promote water use efficiency and minimise negative environmental impacts.

Irrigation is expanding in Alentejo region due to Alqueva dam (it is anticipated that further 110000 hectares will be irrigated by 2025), so it is very important to make the objectives clearer in order to avoid any wrong decisions that could have negative effects in the medium and long terms.

Considering all that has been said, it is necessary to find a compromise solution, from the political point of view, that equates all these dimensions in the best interest of the future of agriculture, of the reinforcement of its competitiveness, without ceasing to consider the possible implication for human desertification, rural development, in this regional/local context where agriculture is often the unique economic activity propelling development.

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