A DSS For An Integrated Analysis Of Irrigation At Farm And Catchment Level: DSIRR

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Abstract: The definition of a suitable policy for water in agriculture assumes an increasing relevance in the context of growing scarcity and competing uses of water. Simulation models and DSS can play an important role in the definition of a Basin Plan that is a bargaining process with stakeholders requiring a lot of information that must be easily accessible to all actors. In this context the support of DSIRR "Decision Support System for Agricultural Irrigation" could be valuable to conduct an economic-environmental assessment of agricultural activity that focuses on irrigation. The program operates at catchment level and simulates farmer's decision process. A multicriteria approach is adopted to reach a better representation of farmer's behaviour. Different types of farms can be integrated at basin scale. An explicit consideration of agronomic aspects, like water-yield functions and rotations permits accurate description of irrigation in terms of technology, irrigation needs by crop, type of soil, with explicit consideration of climate. Short and long term analysis could be conducted. Mathematical programming techniques are applied to find solutions. Scenario analysis could be implemented to explore alternative states of the environment and policy options and sensitivity analysis of key parameters conducted. A user-friendly interface permits the user to define and control the simulation to run. The results of an application to an Italian case study that considers innovation in irrigation technology are presented.

Keywords: *Decision Support System, Multicriteria modelling, Agriculture, Water, Irrigation, Agriculture policy, Water policy*

1. INTRODUCTION

Agriculture in most Southern European countries, uses a high percentage of water (from 50% to 80%). The definition of a suitable policy takes on an increasing relevance in the context of growing scarcity and competing uses of the resource. To comply with existing water laws basin plans, key documents for water planning at catchment scale, must be implemented. Their definition should be conducted in a bargaining process that involves stakeholders and requires a lot of information that must be easily accessible to all actors. Simulation models and Decision Support System (DSS) could play an important role in this context.

Mathematical models can be applied to a wide range of technical, structural and institutional conditions that describe the regional differentiation existing in the agricultural sector. This variety of situations will in turn be of use as a guideline for discussing the related policy implications.

This paper describes a DSS that is aimed at conducting an economic-environmental assessment of agricultural activity focusing on irrigation. The program operates at catchment level and simulates farmer's decision process at farm level. In the first section the DSS is described; in the second an application is presented that refers to Northern Italian Agriculture.

2. DSIRR

2.1. Description

DSIRR "Decision Support System for Agricultural Irrigation" is a scenario manager to run agro-economic models implemented in GAMS (General Algebraic Modelling System) Brooke et al. (1992). The program permits the final user to run a chosen simulation in real time, without having a specific knowledge about Mathematical Programming Techniques (MPT) and modelling, but only of the agricultural and irrigation problem at hand.

DSIRR includes all the relevant aspects of irrigated agriculture: farming conditions, producti-ve potential, crop diversification, technological packages, water availability, patterns of water use and management, irrigation methods, labour, financial capital and environmental aspects. Production costs, market prices, agricultural and environmental policies are also considered.

Great care has been taken to create a flexible system where the user can define the level of detail and aggregation.

Farms can be very diversified ranging from small-scale family farms to large commercial farms, from intensive fruit and horticulture productions to extensive cereals and industrial crops. Different systems of water delivery can be present: private wells and basins, cooperative water distribution systems, the latter diversified according to the network (open canal, pipes, etc.). Environmental aspects linked to water-soil relations, climate effect, i.e. rain, negative and positive impacts are included through ad hoc indexes and parameters.

DSIRR is written in Visual Basic and C++. The program operates as a 32-bit Windows application on a PC with at least 32 MB of RAM. More is recommended to run complex problems. The GAMS model works behind a User Interface (UI), which is the only part accessible to the user. All steps, like set definition, parameter implementation, equation writing, model resolution, are controlled by the main menu, the toolbar and the dialog windows of the UI.

The creation and storage of archives of data for a specific farm condition and scenario analysed enriches the DSS databases which can be reused and distributed.

Different analyses can be performed. A basic option determines the optimum cultivation plan on the basis of the parameters levels. Demand curves can be derived via parametric analysis on water allocation or price. Risk analysis can be included.

DSIRR can export the results to Microsoft EXCEL in table and graphical form or maintain them in text form according to the user's preference. In this way most of the output is made accessible to other programs.

2.2. The mathematical model

Simulation models based on MPT are widely applied in agriculture and irrigation systems. Berbel J. et al. (1998), Varela-Ortega et al. (1998), Amir et al. (1999), Gómez-Limón et al. (2000).

Mono and multicriteria approaches are both available to represent the farmer's decision process. In the former case, founded in the neoclassical economic theory, the farmer acts as a profit maximizer. In the latter case the farmer's objective function is composed of different components according to Multi Attribute Utility Theory (MAUT) paradigm, which Ballestrero et al. (1988) demonstrated that is closely linked to a multicriteria problem. The aggregate utility function assumed linear[1] (1) requires normalization since different units are involved:

$$U=\sum_{o} w_o * \frac{Z_o^+ - Z_o}{Z_o^+ - Z_o^-} \quad (1)$$

where: U represents the utility index, Z, Z^+, Z^- objectives values, ideal and nadir (*ideal* and *nadir* are respectively the best and worst case), w weights, o objectives.

The selection of objectives and the estimate of the related weights can be conducted in a non-interactive approach. This follows the methodology proposed by Sumpsi et al. (1996) and improved by Amador et al. (1998), that minimizes the model results distance from observed farmers' choices in a weighted goal programming. Alternatively, the objectives could be derived via an interactive procedure with the decision maker.

Income (Table 1), risk, labour, technical difficulty can all be considered as possible attributes.

Table 1. Income definition.

A) Gross output
Income
Subsidy
Other
B) Expenses [intermediate consumption]
Variable costs
Inputs
Services
Salary
Rent
C) A-B GROSS MARGIN
D) Fixed costs
Asset Depreciation
Existing
New investments
Irrigation Fees
E) C-D NET INCOME
F) Remuneration
Own labour
Interest on financial capital
Interest on asset
Own land
G) E-F PROFIT

In general the farmer's problem is cast as a constraint maximization and in the simpler case can be formalized as[2]:

[1] Hwang (1981) showed that it represents a close approximation to more complicated non linear forms remaining easier to use and understand.

[2] This simplified formulation permits to appreciate the logic of the model. For a more complete presentation of the program see Bazzani (2003), IBIMET - Technical paper, in progress.

$$\max_{\{X,W\}} \text{INC}= \sum_{c}\sum_{i}\sum_{s}\left\{\mathrm{X}_{c,i,s}\left[\mathrm{p}_{c,i}\,\mathrm{q}_{c,i,s}\left(\mathrm{wr}_{c,i,s}\right)+\mathrm{su}_{c}-\mathrm{vc}_{c,i,s}\right]\right\} -\sum_{k}\sum_{l}\sum_{p}\mathrm{W}_{k,l,p}\mathrm{wp}_{k,l,p} \qquad (1)$$

subject to:

…

$$\sum_{s}\sum_{c}\sum_{i}\mathrm{X}_{c,i,s}\mathrm{ir}_{c,i,s} \le \sum_{l}\mathrm{W}_{k,l,p} \quad \forall k,p \qquad (2)$$

…

where the indices represent: *c* crop, *i* irrigation level, *s* type of soil, *k* water source, *l* water provision level[3], *p* period. To distinguish between variables (endogenously determined) and parameters (exogenously fixed) the former are written in capital letters: *INC* income (€), $X_{c,i,s}$ activities[4] (ha), $p_{c,i}$ crop market price (€/t), $q_{c,i,s}(wr_{c,i,s})$ crop production as function of water (t), $wr_{c,i,s}$ crop water requirements (m^3), su_c subsidies (€), $vc_{c,i,s}$ variable costs (€), $W_{k,l,p}$ water consumption (m^3), $wp_{k,l,p}$ water price (€/m^3), $ir_{c,i,s}$ crop irrigation requirements (m^3).

It should be noted that in equation 1, representing the farmers' objective function, production *q* is expressed as a function of water and irrigation costs are kept apart. This approach permits the derivation from equation 1 of *water demand function* (3) via parametrization of price or quantity.

$$W = f\left(wp;Q\right) \qquad (3)$$

This function determines the quantity of water *W* demanded by a farmer in a given district in a certain period as an inverse function of its price *wp,* given the farm production possibilities and characteristics *Q*:

Short (ST) and long term (LT) analysis can be conducted that differ in terms of decision variables, objectives and constraints. Among the latter crop rotations, commercial and policy aspects, as well as land, labour, financial capital, and water availability are considered. Models are static but can include seasonality.

Table 2 identifies the decisions variables which the user can select in the different time horizons.

ST models allow only for the choice of the annual crop mix and irrigation level, given the existing irrigation devices, while new plantation and farm size variation are not possible. Seasonal labour represents another decisional variable while permanent labour is fixed.

In the LT analysis new orchards can be planted and the choice of irrigation technologies is endogenously determined. Integer programming is needed to cope with this type of models. Irrigation, requiring ad hoc investments, adds a fixed component to the total costs. The number of equipments is distinctly quantified for the fixed ones (like drip irrigation) and the moveable ones (like sprinklers), which can be used in many plots.

Table 2. Decisions variables for time horizon

			Time horizon	
			Short	Long
Objective	1	Mono-objective	x	x
	> 1	MAUT	x	x
Decision variables	Farm	Enlargement/reduction	no	yes
	Crop	Annuals change mix	yes	yes
		Plantation abatement	yes	yes
		New plantation	no	yes
	Irrigation	Level change	yes	yes
		Techniques change among existing	yes	yes
		New techniques	no	yes
	Labour	Seasonal	yes	yes
		Permanent	no	yes
	Financial	Indebtment	yes	yes

An upper limit is imposed on *W* to control water availability. A constraint on total water availability per year is also included. In separate equations labour requirements for irrigation, diversified among technologies, enter the model respecting the seasonality. Further details are in Bazzani et al. (2002a).

2.3. Data requirements

The quantity of data required to run the model depends on the level of detail chosen by the user.

For each type of farm considered soil and labour availability, distinguished by owned/family and hired/external, are compulsory. Optionally more types of soil can be included. Reclamation fees and financial data covering capital availability, fixed costs and remuneration are linked with specific constraints and equations which are under the user control.

[3] Water provision levels permit to simulate an increasing pricing scheme, via blocked tariffs.

[4] An activity is a crop characterized by its production process, i.e. fertilization, irrigation, …; the same crop determines distinct activities if more production possibilities are considered.

Another set of data describes crops and production process. These data can be stored in files which can be differentiated by regions and farms. Water yield functions are stored in a discrete form, data are reported only for the irrigation levels adopted by the user. Irrigation requirements consider rain and soil contribution and water loss due to technical irrigation inefficiency (ranging from about 50% for furrow irrigation to 5% for drip irrigation). The selling price of crops and subsidies are explicitly considered, to allow exploration of different scenario. Agronomic information describing possible rotations, commercial relations and political constraints are also present.

Irrigation data include: type (fixed/moving), irrigation volume per hour, efficiency, engine and power requirement. This permits the quantification of energy consumption which represents a variable cost. Labour requirement is expressed as a percentage of the irrigation time[5]. Economic data include annual quota for restoration, maintenance and insurance and the cost per hour if the irrigation technique can be applied using an external contractor.

Other coefficients describe water provision and price by type and level, rain by periods, setaside[6] requirements, and optionally remuneration for internal factors (land, labour and capitals).

Distinct data quantify the sustainability indicators, the methodology adopted is derived from OECD (2001), but their inclusion is optional.

3. A CASE STUDY

3.1. Simulation of annual crop system

DSIRR was applied to study the impact of the EU Water Framework Directive (WFD) (EU Dir. 60/2000) on the Italian agriculture. WFD suggests the adoption of economic instruments, including pricing, to meet two main goals: “good environmental quality” and “cost recovery”. In this paper the analysis of the annual crop system of the Italian Po Basin is presented, see Bazzani et al. (2002b) for further results.

In the Italian Po Basin, maize and sugar beet represent the main irrigated annual crops[7]. The reference farm has about 28 Ha of cultivable land of good quality and labour requirements are covered by the family. The crops used in the simulation are sugar beet, maize, soya-bean, wheat and setaside. These crops present a decreasing complexity for farmers and in many cases this aspect becomes a relevant decision criteria.

Furrow irrigation (FUR), the traditional irrigation technique (50% efficiency), is progressively being replaced by self moving sprinkler (BMS) or guns, with an efficiency of about 75%. The effect of this technological shift which substitutes labour with capital is complex. Labour in a family farm is an internal resource and does not require additional cost, while sprinklers are durable assets, involving ad hoc investment with specific costs partly unrelated to use (fixed restoration quota) and partly depending on use (variable cost). The latter depends on pumping activity, which is energy consuming.

The higher irrigation efficiency permits saving of water, but only the trade off between labour and cost is relevant to farmers when water is a zero cost resource. In this regard, different farmers’ behaviours can be identified, but two situations represent well the total variability: a profit maximizing behaviour (MO), and a more balanced one (MC), with a utility function that depends on net income 57.50% (max), labour 40.44% (min), complexity 2.06% (min).

Five irrigation levels diversified by crops describe water-yield functions in four periods (May, June, July and August) (Figure 1).

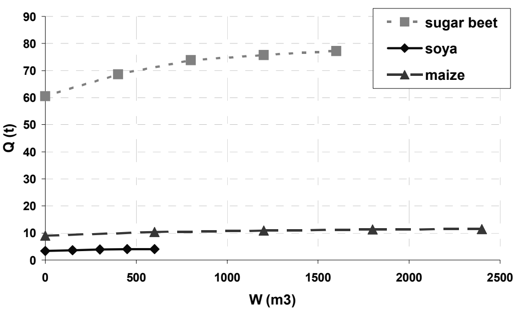

Figure 1. Water yield functions.

Figure 1 highlights the maize’ highest water needs, around 2400 m^3/season, followed by sugar beet with 1600[8].

[5] Irrigation time is calculated by the program as function of crop water requirement, rain and water tableau contribution, irrigation efficiency and flux.

[6] Setaside is the uncultivated area complying with agricultural regulations in various countries.

[7] In the Po basin, rice represents a specific water intensive production system which has been analyzed separately, like orchards and vegetables.

[8] Water response curves are derived by experimental activity in the Po valley conducted in recent years by “Consorzio di Bonifica del Canale Emiliano Romagnolo”.

In Italy water price currently is null or very low. The implementation of WFD will probably increase it. The possible impact of this policy is captured by the following Figures (2, 3, 4) which compare different irrigation technologies, FUR and BMS, and for the latter MO and MC behaviours. All data are referred to 1 Ha of surface.

Water demand curves are showed in Figure 2. The three curves present similar decreasing pattern but different shapes and intercepts.

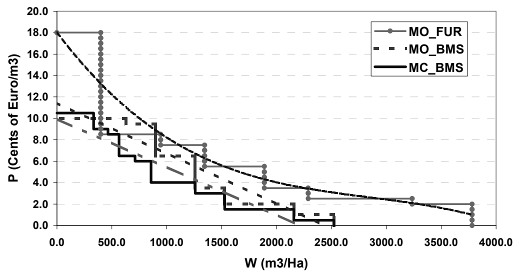

Figure 2. Water demand.

While FUR and BMS are approximated by linear and non linear curves of different shapes, the multicriteria objective function (MC) shifts the curve to the left.

In more detail, the external curve describes FUR: maximum water consumption is 3781 m^3/ha at zero price. Technological innovation represented by BMS drastically reduced water consumption to 2500 m^3/ha (-28.6%).

The intercept with the vertical axes, that identifies the point where irrigation stops, is also different: from 0.18 €/m^3 in the FUR, drops to around 0.10 €/m^3 when BMS is adopted.

At zero cost of water the optimum crop mix is always composed by maize and sugar beet full irrigated in a ratio 3/1, due to rotation, plus the setaside requirement (10%).

In all cases, response to water price increase is quite strong in a first phase which ends at a price of 0.06 €/m^3. This price level could reduce water demand to around 1000 m^3/Ha (-60%). Maize production is the first to leave the field to rain fed wheat. At higher prices the curves become steeper for the higher water marginal productivity on sugar beet at medium and low irrigation levels.

When MC is adopted at a water price of 0.04 €/m^3 soya-bean becomes profitable for the lower labour requirements.

The impact on farm income is sensible (Figure 3). A price of 0.06 €/m^3 decreases net income of –22% in FUR and of –19% with BMS, even if in absolute terms the latter is lower. As expected MC shows lower income levels than MO.

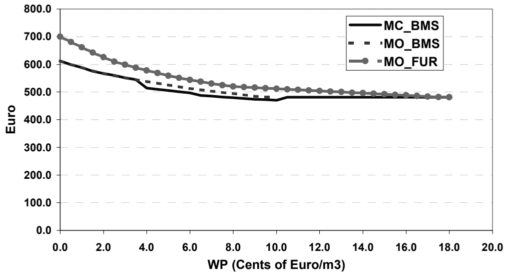

Figure 3. Farm Net Income.

Farm income reduction is partly due to a transfer from farmer to Water Authorities, which raises its revenue as depicted in Figure 4; partly to the adoption of less intensive production processes and a different crops mix. This latter effect is clearly captured by the labour requirements which shows a strong decreasing pattern in FUR and a much more stable one with BMS, until irrigation is abandoned and employment drops.

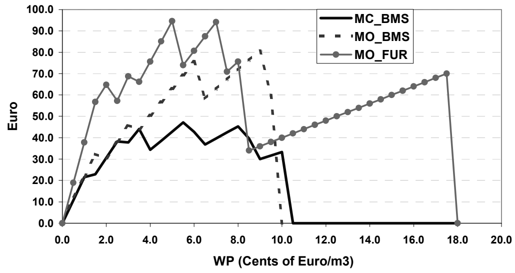

Figure 4. Water Authority Revenue.

The environmental indicators show that water price increase favours a less intensive agriculture with a reduced use of chemicals and possibly less negative impacts.

4. CONCLUSIONS

The application of DSIRR to differing production systems is generating valuable information on the impact of the EU WFD on irrigated agriculture in Italy. A clear trade off between agricultural profitability, employments, water saving and environmental impacts exists. Different systems present distinct responses, which are highly dependent on a multiplicity of exogenous factors. Product prices and input costs, subsidies and taxes play a decisive role in the farming process. Their influence can be easily checked with the DSS.

The research showed the relevance that innovation in irrigation technology, i.e. the shift from furrow to sprinkler on maize and sugar beet, can play to save water. Similar results appear in other production systems, moving for instance to drip irrigation or micro-irrigation in orchards and vegetables. This shift is anyhow costly for the farmers, therefore the adoption of sound interventions, which can be analysed *ex ante* with

DSIRR, can play a determinant role to move the system toward more sustainable patterns.

The modular approach adopted by DSIRR permits to easily integrate new modules focusing on specific aspects of interest or to link other programs. Among the main advantages of the present version are:

- richness of information covering socio, economic and environmental aspects related to irrigated agriculture;
- great flexibility which permits the definition of the level of detail of the analysis;
- applicability at farm and/or catchment level;
- a rich set of tested models aimed to apply mono and multicriterial MPT;
- good representation of farmers' behaviour;
- alternative techniques to deal with risk;
- short and long time horizons;
- easy derivation of water demand functions;
- the possibility to conduct scenario analysis;
- personalized database;
- a simple and well supported user interface;
- direct control of the simulation by the user;
- dramatic time saving;
- sensible reduction of cost and effort to conduct sound studies.

The results emerging from the research confirm the utility of the proposed approach to define environmentally, socially and economically sustainable policies for water and agriculture.

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