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Bio-economic modelling for policy analysis of nitrate pollution reduction in irrigated agriculture

The study of a region in Southern Italy

Josephine Semaan

Série "Master of Science" n°53
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Bio-economic modelling for policy analysis of nitrate pollution reduction in irrigated agriculture. The study of a region in Southern Italy

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Abstract. Many forms of environmental pollution result from irrigation and intensive agriculture. In this work, a method of coupling agronomic and economic models is used to analyse the effect of different agricultural policies on nitrate pollution. The area of study is a 100-ha farm in Southern Italy, with five field crops: wheat, sunflower, tomato, sorghum and sugar beet. Different methods, techniques and efficiency levels of irrigation were introduced. The agronomic model EPIC was used to simulate yield and nitrate leaching. These outputs, together with production costs, were used as inputs in a non-linear optimisation model, written in GAMS language. The objective was to maximise the farmer's income.

A multi-criterion approach was used to analyse the impacts of three possible policies on the reduction of nitrate pollution: increasing water prices, management subsidies for high irrigation efficiency and application of taxes on N-fertilisers.

The results indicate that pollution could be reduced by about 40% with an associated social cost of 600 000 lires.ha^{-1} in water pricing, 285 000 lire.ha^{-1} in taxes and 170 000 lire.ha^{-1} in subsidies for efficiency.

Keywords. modelling, irrigation, nitrate pollution, water pricing, subsidies, taxes.

Résumé. *L'irrigation et l'agriculture intensive sont à l'origine de plusieurs formes de pollution environnementale. Dans ce travail, une méthode de couplage entre un modèle agronomique et un modèle économique est utilisée pour analyser les effets des différentes politiques agricoles, sur la réduction de la pollution en nitrate.*

L'aire d'étude est une exploitation de 100 ha au sud de l'Italie, avec 5 cultures: blé, tournesol, sorgho, tomate et betterave à sucre. Différents méthodes, techniques et niveaux d'efficacité de l'irrigation ont été introduits. Le modèle agronomique EPIC a été utilisé pour simuler les rendements et le niveau de nitrates lessivés.

Ces données, en plus des différents coûts opérationnels, ont fait l'objet d'un modèle d'optimisation non linéaire écrit en langage GAMS. La fonction objectif était de maximiser le revenu.

Une approche multicritère a été utilisée pour analyser l'impact de trois politiques agricoles possibles pour la réduction de la pollution en nitrates: l'augmentation du prix de l'eau, les primes sur l'utilisation des niveaux élevés de gestion de l'irrigation et les taxes sur les fertilisants. Les résultats de ce travail ont montré qu'il est possible de réduire la pollution en nitrate de 40% avec un coût social associé de 333 000 lires.ha^{-1} pour la politique du prix de l'eau, de 285 000 lires.ha^{-1} pour les taxes et de 170 000 lires.ha^{-1} pour les primes à l'efficacité.

Mots clés. *modélisation, irrigation, pollution en nitrate, prix de l'eau, primes, taxes.*

Cette thèse a obtenu le prix de la meilleure thèse du CIHEAM-IAMM en 2001

The Committee emphasized the importance of this Master Thesis focused on merging economic and agronomic models to analyze the effects of different agricultural policies on environmental hazards. This is an area of uppermost importance in current Mediterranean agriculture associated to crop intensification, which will undoubtedly play a key role for decision-makers in the near future. The Committee highlighted that this thesis was carried out through an integrated Mediterranean Agronomic Institutes postgraduate program, under the direction of scientists from Montpellier and Bari

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Bio-economic modelling for policy analysis of nitrate pollution reduction in irrigated agriculture: The study of a region in Southern Italy

Josephine Semaan

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Introduction

This work is the fruit of collaborative research by the Mediterranean Agronomic Institute of Bari (IAMB) and the Mediterranean Agronomic Institute of Montpellier (IAMM) within the framework of the research project on “Sustainable Agriculture in the Mediterranean Region”.

The aim is that of aiding decision making in irrigated agriculture by linking agronomic and economic models. A methodological approach is used to define water pricing policies, taking the environmental impact into consideration. This involves analysis of the impact of water price policies and agricultural policies on both farmers' incomes and the environment.

Water is an essential input in various economic sectors and especially in agriculture, with irrigation accounting for between 70% and 80% of total water consumption (Hamdy and Lacirignola, 1997). Excessive or inadequate use of water in irrigation causes serious deterioration of the environment. One of the negative externalities of irrigated land is nitrate leaching leading to the pollution of ground and surface water, with danger to human life when drinking water is affected. The quantity of nitrate fertilizers applied is not always in a linear relation with the quantity leached causing pollution. As the leaching of nitrate from fields is linked to irrigation and agricultural practices, the impact of water pricing and agricultural policies on nitrate leaching and pollution can be appraised.

This concerns the role of water price policies encouraging farmer to use irrigation resources efficiently by stimulating improvements in water management practices. The goal of policy intervention is the encouragement of farmers to modify their choices of inputs and outputs to coincide with socially optimal decisions (Wichelns, D., 1997). The underpricing of water leads on the one hand to the inefficient use of water and on the other income transfer from non-irrigated to irrigated areas. Furthermore, there is usually no cost or penalty for polluting of water through wastes and fertilizers or chemicals and neither is there a penalty for causing environmental damage through the misuse of this valuable resource. (Kasmakoglu, H., and Çakmak, E.H., 1997).

The "standard approach" in environmental economics considers that if a negative externality exists (such as nitrate pollution), this is because a social cost is not included in the costs of the economic agents that cause this pollution. This leads to considering environmental impacts in the cost-benefit analysis of farms

The coupling of biophysical models with economic models to develop a bio-economic model enables the integrated analysis of agronomic and environmental issues (Flichman *et al*, 1995, Boussemart *et al*, 1996). This approach helps to attain the following objectives:

- a decision support tool for the better definition of agro-environmental and rural policies;
- a tool for evaluating alternative policies, i.e. to define the level of subsidies required for the use of environmentally friendly agricultural practices, it is necessary to evaluate the trade-off between environmental gains (or losses) and farmers' possible economic losses (or gains);
- measuring the impact on income associated with achieving specific environmental targets, i.e. how changes in water pricing will affect the level of nitrate pollution and crop production, affecting farmers' incomes.

Chapter I: Literature review

I – Nitrate pollution

Nitrates are a natural part of our biosphere. A vital element for living things, nitrogen may exist as N_2 (nitrogen), NO_2^- (nitrite), NO_3^- (nitrate), NH_3^+(ammonia) or NH_4^+(ammonium), which is constantly recycled in the atmosphere. Nitrates are found naturally in freshwater sources, vegetables, meat and decomposing organic matter.

To increase the productivity of agriculture, it is essential to use plant nutrients such as nitrogen, phosphorus and potassium as fertilisers. But these can pollute surface and groundwater elements when they are applied in excess of plant needs (Devinder *et al.,* 2000).

Global industrial production of nitrogen fertilisers has increased steeply from nearly zero in the 1940s to roughly 80 million metric tonnes per year. In the US and Europe, only 18% of the nitrogen inputs in fertilisers is recovered by farm crops, meaning that an average 174 $kg.ha^{-1}$ of surplus N is left behind in croplands each year (Carpenter, 1998).

1. Accumulation and leaching of nitrates

Many farmers apply nitrogen as fertilisers or manure to their crops. Nitrogen applied through fertilisers or manure is converted to plant—available—nitrate by bacteria living in the soil. The growing plants consume part of these nitrates. Growing bacteria also consume nitrates. When sufficient decomposable organic matter is present, soil bacteria can remove a significant amount of nitrate-nitrogen through a process called immobilisation. Another group of bacteria converts the nitrates to the gaseous form when oxygen is limited; this is called denitrification. The nitrates taken up by crops, immobilised in organic matter or converted to atmospheric gases by denitrification can leach out of the root zone and possibly reach groundwater (Devinder *et al.*, 2000).

2. Nitrate levels and negative effects

Current public health standards for safe drinking water require that the maximum contamination level (MCL) should not exceed nitrate concentrations of 10 ppm nitrate-nitrogen or 45 ppm nitrate. High nitrate levels may have a significant impact on human life as well as on the environment:

- blue baby disease (methemoglobinemia), which affects children under the age of 6 months,
- gastro-intestinal cancer,
- eutrophication of fresh water, leading to loss of aquatic diversity (aquatic plants, fishes, etc.).

3. Pollution of groundwater and surface water

A climate with rainfall exceeding evapotranspiration often leads to the movement of rain water to groundwater. A proportion of the water received through precipitation becomes surface runoff and is lost from the land through rivers and streams. Because nitrates are highly soluble salts, when water moves on the surface of the soil, it dissolves some nitrates are present in the surface layers of the soil.

Another part of precipitation seeps into the soil and recharges the groundwater. This seeping water dissolves nitrates and carries them to the groundwater. Most of the flow in a mountain streams is from groundwater. Thus nitrates that were initially lost through leaching to groundwater can contribute to the nitrate pollution of surface water such as streams, rivers and lakes.

4. Factors affecting nitrate leaching

A. Fertilisers

Nitrate leaching from fertiliser use depends upon the fertiliser type (ammoniacal, nitrate or organic), application methods and climatic conditions. Nitrate leaching may be greater when a fertiliser contains nitrate in comparison to situations in which ammoniacal nitrogen is the major component of the fertiliser. Nitrate losses are likely to be greater when all the nitrogen is applied in one application rather than in split applications. Full application of fertilisers or manure will cause high nitrate losses in early spring. Nitrate losses from fertilisers can be reduced by matching fertiliser application to crop nitrogen requirements.

B. Soil types

Nitrogen fertilisers or manure used on a sandy soil are more vulnerable to leaching to groundwater than on clayey soil because water moves rapidly through sandy or other coarse-textured soils, carrying nitrates.

Soil thickness and the distance between the root zone and the groundwater also determine the vulnerability of an aquifer to pollution. The closer the plant's roots to the water table, the more readily nitrates enter groundwater.

Nitrate leaching from shallow soils on fractured rocks such as limestone can cause extensive contamination of groundwater.

C. Crop types

Crops that are likely to increase nitrate leaching are those that have high N requirements, have a high economic value and tend to be inefficient in N use. High-value crops such as nursery crops, greenhouse crops, orchards and vegetable crops are more likely to receive high application rates of N fertilisers. Any excess N that is not used by the plants may become a source of pollution.

D. Irrigation

Water applied in excess of evapotranspiration often leads to runoff or deep percolation. As nitrates are highly soluble salts, moving water dissolves some of the nitrates present. This will lead to the contamination of surface and groundwater. The use of irrigation therefore increases the chance of nitrate pollution. A study conducted by Burkart and Kolpin (1993) showed that the frequency of excess nitrate in a well was higher when irrigation was performed within 3.2 km of the well (41%), than when no irrigation was performed (24%). Furthermore, nitrate pollution is also linked to the amounts and times of irrigation operations and to application efficiency.

5. Water treatment

Nitrate is present in water as highly soluble salts. Standard water treatments such as sedimentation, filtration, chlorination or pH adjustment with lime application do not affect nitrate concentration in the water.

Nitrates can be removed from water by specialised water treatment technologies such as ion exchange, biochemical denitrification and reverse osmosis. Incorporation of these nitrate removal technologies in a water treatment system could substantially increase the cost of water treatment.

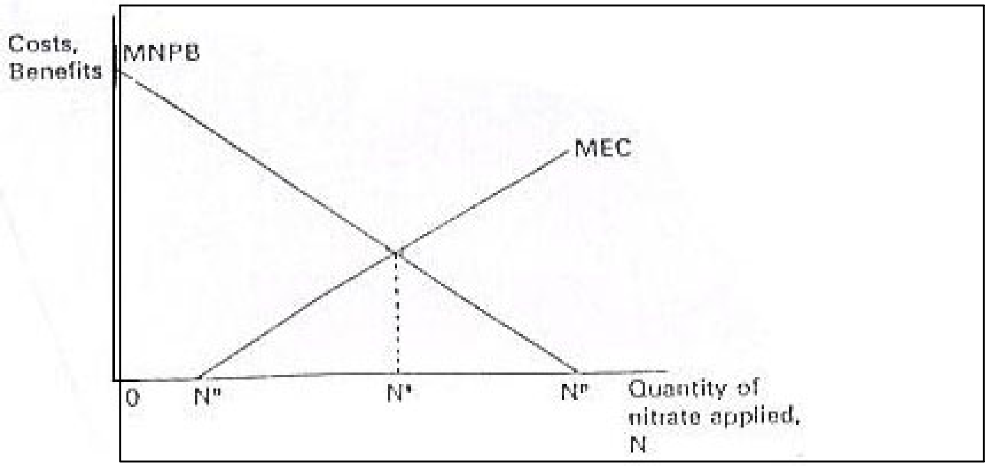
One California water district estimated that wellhead nitrate-N treatment costs $375 per million gallons. Thus, once an aquifer is contaminated with nitrate, it will cost a large amount of money to use that aquifer as a source of drinking water (Devinder *et al.,* 2000).

The European Community suggested that land application of livestock manure should be limited to 170 kg N. ha^{-1}. $year^{-1}$ from the end of 2002 (and 210 kg N. ha^{-1}. $year^{-1}$ from the end of 1998).

6. Nitrate as an externality problem

Given the response of a plants to nitrogen input, the use of nitrogen fertilisers has increased in agriculture. At the same time, some side-effects are observed that are harmful for the physical environment and human health, and nitrate pollution is considered a non point-source externality. An externality is a process that occurs when, in addition to normal production (e.g. agricultural production), someone simultaneously produces other products that can be advantages or disadvantages for other groups in society (e.g. nitrate leaching). These externalities are not generally considered in market transactions (Stiglitz, 2000). This externality side of nitrates is shown in Figure 1 according to Hanley (1990). The marginal external cost (MEC), which is the cost of this side effect of the production activity, paid by the victim or society, shows that pollution increases as the level of nitrate applied rises. As pollution increases, low nitrate waters become increasingly scarce, thus raising the cost of each additional emission unit.

Figure 1. The nitrate externality. (Hanley, 1990)



The MEC function originates at point N°. Below this point, nitrates are assimilated by the ecosystem. As nitrogen inputs rise, then, *ceteris paribus*, the crop output level will also increase. These output increases will decline in marginal terms as a result of diminishing returns. The marginal net private benefit (MNPB) is constructed assuming "price-taking behaviour" by the farmers. It is what is referred to in the next sections as the net revenue of farmers. Given a constant output price and a fixed amount of all other inputs, the MNPB falls as nitrogen input rises [(*)]. Market inefficiency then occurs, as farmers choose input N^p maximising short-term profits whereas society would prefer input use N^s, which maximises net social benefit (assuming that all other conditions for allocation efficiency hold).

However, this approach is complicated by the dynamic nature of the problem. Nitrates may take up to forty years to travel from the soil to groundwater, depending on the nature of the intervening rock layers. Given the large conceptual and methodological problems associated with estimating contemporaneous external costs, this is, for all practical purposes, an impossible task (Hanley, 1990). This means that policies aiming at reducing nitrate pollution may have no direct impact on water quality; the results may take many years to appear.

II – Crop-water production function

A production function is commonly referred to as the relationship between inputs to and the outputs of a production process. Crop growth and production are the results of complex processes relating plants to their physical environment, in which energy, water, CO_2 and[1] nutrients play a fundamental role. Plants typically grow to the level that is allowed by the component provided in the least amount. Water is one of the most important inputs to the crop production process. Classical agronomic approaches to crop response to water were largely based on experiments in which yield was related to water (or other inputs) applied as an independent variable.

Two approaches to estimating crop-water production functions are generally found in the literature (Letey, 1991). One approach synthesises production from theoretical and empirical models of individual components of the crop-water process. The second approach estimates production functions by statistical inference from observations of alternative levels of crop yield, water applications, soil salinity and other variables.

The crop modelling approach is aimed at the quantitative integration of the physiological processes for understanding and predicting crop response to environmental resources. Since water (in terms of both quantity and quality) is the greatest limiting factor for agriculture in the Mediterranean Basin, an optimisation approach is required in order to make the best use of it according to the final objective (Steduto, 1997). When the total quantity per season is considered, this is called the "macro" production function. The "micro" production functions are obtained when optimal timing and depth of irrigation are considered. In fact, in agricultural technology, modelling is an essential tool for planning, management, and environmental impact assessment at farm or regional levels.

The relation between crop productivity and water is taken into account here, but it should always be borne in mind that the plant growth and production processes interact in a complex manner.

7. Physiological aspects of crop-water relations

The time dependence of events must be taken into account in the addressing of crop performance in relation to water. Water stress has different effects on crop growth according to the severity, duration and timing of the occurrence. The main physiological processes treated in crop modelling are as follows

A. Transpiration

The water status of the canopy is governed by the balance between water loss through transpiration and water supply by the roots. The crop transpiration rate is obtained by adding the transpiration rates of successive leaf layers with a given leaf area index (LAI) (de Wit, 1978). The foliage characteristics involved in this process are the leaf area index, leaf width and canopy architecture, the extinction of visible, short-wave and the net radiation and the extinction of wind and exchange coefficients (de Wit, 1978).

B. Water uptake by the root system

Uptake of water from the soil is governed by the difference in water potential in the crop and in the soil and by the resistance to water flow in the soil-plant system. Most crop models where no water stress is studied assume that the water potential in the soil is maintained at field capacity (-0.1 bar). The water

(*) In certain situations, an increase in the amount of fertilizer and production may be associated with a decrease in the level of pollution (Flichman and Jacquet, *personal communication*) status of the canopy is characterised by its relative water content and its total water potential. The total resistance to liquid flow through the plant is primarily concentrated in the root system, where the water must traverse the protoplast as cell walls are suberised (de Wit, 1978).

The temperature of the medium has a distinct influence on the uptake of water by the root system. First, temperature may influence the structure of cell membranes, thus changing the conductance of the roots. On the other hand, increasing temperatures causes decreasing water viscosity and facilitates transport through the roots.

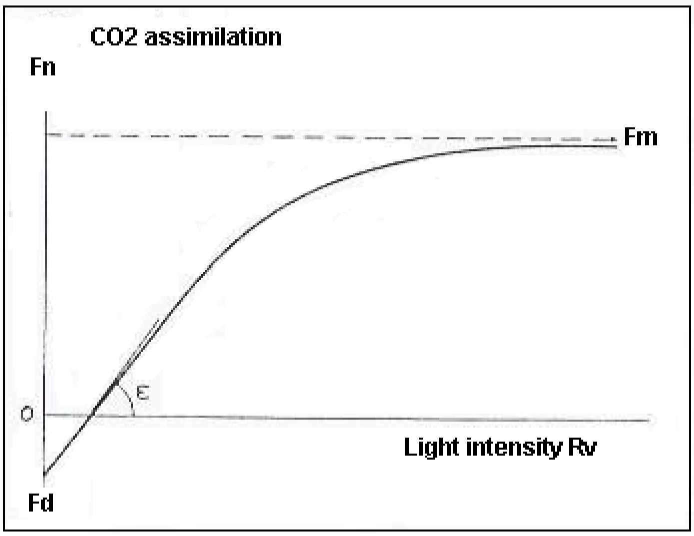
C. Leaf area development

This is the process that is most sensitive to water stress. During crop development, when leaf area is reduced, light interception is also reduced, leading to a decrease in the assimilation process. The area reduction may be quite strong even at mild water stress and with no effect at all on stomatal closure. If water stress is severe enough to induce stomatal closure, the source intensity for assimilates which is the photosynthetic rate will also be reduced and consequently the resulting biomass will be reduced as well. In consequence, the maturity and the senescence phases are accelerated by moderate water stress.

D. Carbon dioxide assimilation and stomatal resistance

More than 90-95% of plant dry matter and almost any process involved in crop growth and productivity depend on the assimilates derived from photosynthesis. CO_2 assimilation is the most important photosynthetic process. It is very dependent on light as shown in Figure 2 (de Wit, 1978).

Figure 2. A typical light response curve of the net assimilation of carbon dioxide for an individual leaf



F_d stands for the dark respiration, ε for the slope (or efficiency) at low light and F_m for the net assimilation rate at light saturation.

Maximum assimilation F_m depends much more on temperature than initial efficiency does.

This assimilation phenomenon differs between plants in C_3 and in C_4 according to differences in light response. CO_2 assimilation is affected by different resistances: the boundary layer, stomatal resistance, and metabolic resistance to CO_2.

In field conditions, water stress plays a dominant role in affecting stomatal resistance and metabolic resistance and the resulting accumulation of biomass dwindles.

E. Reproduction and partitioning of assimilates

When water stress occurs during the reproductive stage, the number of grains or fruits per plant or/and the biomass per plant grain or fruit can be reduced in a more complex manner than expansive growth (Steduto, 1997). In general, the number of flowers is linked to plant size. The pollination stage is very sensitive to water stress (Hsiao, 1993). Fertilisation is likely to be inhibited when water stress is sufficiently severe at pollination (Hsiao, 1982).

The harvest index (HI) is set by the amount of biomass in the reproductive organs, or harvestable parts of the crops, of economic interest. When water deficits occur early on or are slight and evenly distributed over the crop cycle, HI is generally unaffected, but can be reduced substantially when the deficit is concentrated around the flowering and fruit filling stages (Steduto, 1997). The sharing of assimilates among plant parts is of fundamental importance in determining crop productivity. Water stress may lead to and increase in the root:shoot ratio, decreasing the above ground biomass and thus the yield.

F. Biomass production

Many quantitative studies relating plant growth to transpiration have been performed at different times in agricultural research and work on the relationships between crop yield and water use has been conducted since the beginning of the twentieth century. The linear relationship between total dry matter production and ET has frequently been reported in the literature.

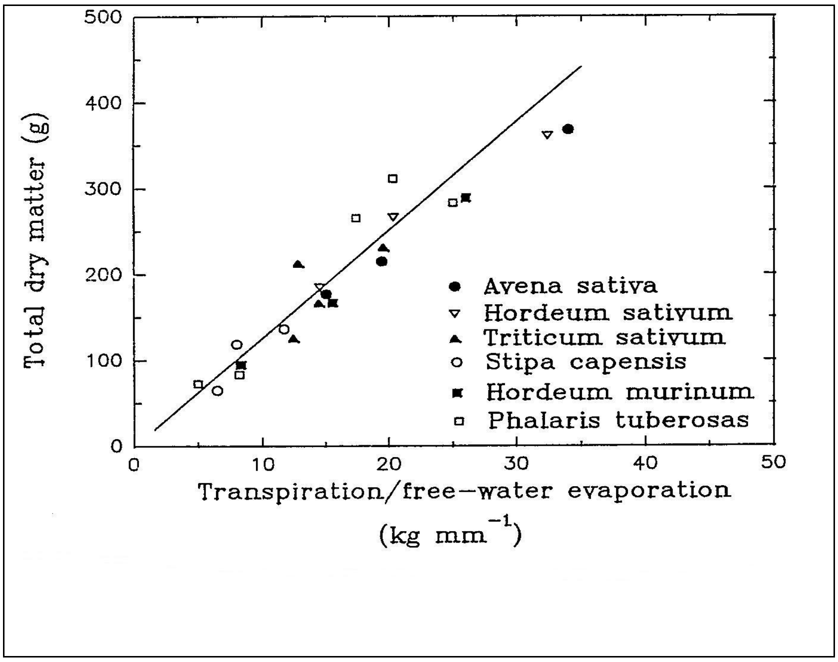
The "growth engine" of many crop models relies on the energy:biomass conversion ratio, a term that includes many efficiencies (efficiency related to optical properties of the foliage, efficiency due to the radiation intercepted by foliage, efficiency of the conversion of radiation to carbohydrates, etc.). This method gives good results for non-limiting field conditions, but is very hard to calibrate and validate for water or nutrient stresses. Thus, when water is limiting source, it might be more appropriate to address the relationship between crop productivity and transpiration (Steduto, 1997).

De Wit (1958) performed a study on the transpiration ratio investigated world-wide, including field studies, concluding that the relationship between dry matter (DM) and transpiration (T) for arid and semi-arid regions was linear as follows:

$$DM = m * (T/E_o) \qquad (1)$$

Where m is a coefficient (the slope) accounting for crop difference, and E_o represents the evaporative demand of a given environment, introduced to normalise for the different locations. DM generally refers to above-ground biomass. Figure 3 shows the linear relation between total dry matter and transpiration.

Figure 3. The relation between dry matter and transpiration according to de Wit, 1958



The commercial yield of a field crop (Y) can be expressed as:

$$Y = HI * m_N \int_e^h Tdt \qquad (2)$$

Where HI is the harvest index,

m_N is the value of m normalised for the saturation deficit of the atmosphere,
e and h are the emergence and harvest time,
t is the time (days).

Two major problems arise in this approach. The first is the difficulty of considering the root biomass in the calculation of dry matter, mainly affecting the simulation of root crops such as sugar beet and potato. The second problem is the difficulty of the separation of soil evaporation (E) and crop transpiration (T) in order to use evapotranspiration (ET), which is much easier.

In addition to these physiological processes, other physiological processes exist such as osmotic regulation, a mechanism adopted by plants for tolerating water stress. This osmotic adjustment varies according to species, genotype and the rate and degree of stress. Another process is respiration, which is responsible for the use of assimilated carbon and thus affects the carbon balance. The most important aspect of plant-water relationships is the sensitivity of each of them to increasing stress.

8. Water–yield relationship

Like any system, crop yield response to water is the response of production to one of the inputs. In addition to climatic requirements, nutrients and management, the production of a crop is strongly linked to the available water, and this differs from crop to crop. In general, the response of the yield to the quantity of water used is characterised by a logarithmic curve (Figure 4). In the first part of the curve, the response has a sharp slope, corresponding to an increasing yield rate for every unit of water applied. However, at a certain point, this increase of the yield will have a gentler slope, a decreasing rate, because crop response to input decreases.

From an economic point of view, the optimal level is reached when the value of the marginal productivity of the last unit of input is equal to its cost. In many cases, this optimal point does not correspond to the maximum yield of the crop, especially if the crop water requirements are high and the price of water is also high.

Figure 4. General shape of a production function (Salvatore, 1979)

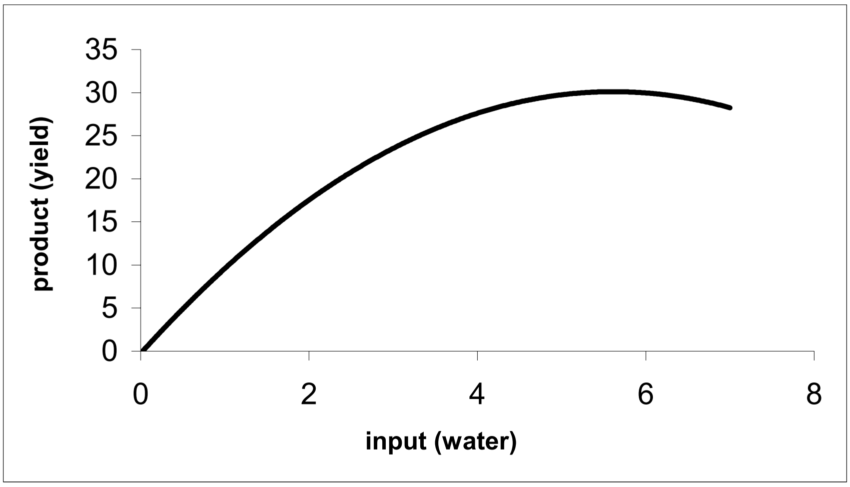
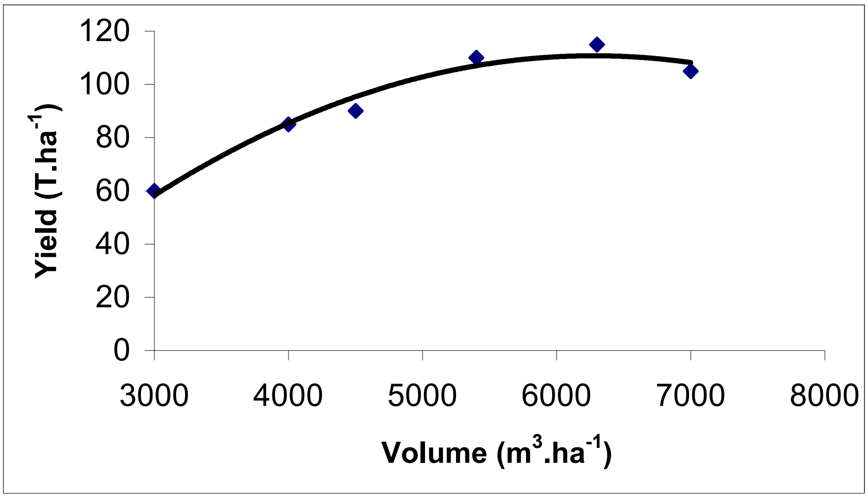


Figure 5 shows the response curve of tomato to water applied, from experiments conducted in the study region, the Capitanata (Lamaddalena *et al.,* 1999).

Figure 5. Yield response curve of tomato to volume of water applied in the Capitanata



III – Relation between water policies and environmental impacts

A number of natural resources and environmental problems are associated with irrigation and drainage. Farmers are not generally faced with the costs resulting from nitrate leaching and the resulting damages or/and treatment costs are likely to be very high. The point-source pollution problem can be solved by direct taxing of pollution emitted. However, it is difficult to monitor the actual volume of pollution caused by non point-source pollution In this case, it is necessary to devise alternative policies for inducing socially acceptable levels of pollutants.

Many studies had shown the potential role of water price incentive in modifying farm-level irrigation decisions to coincide with environmentally optimal choices. These studies (e.g. Gardner and Young, 1988; Dinar *et al.,* 1989; Mimouni *et al.,* 2000) came up with the results that the use of economic incentives, which modifies the price of inputs (like water), generate or reduce effluent from non-point sources like the nitrate pollution.

A study performed in a California irrigation district (Wichelns, 1999) showed that a block-rate pricing programme leads to significant reductions in applied water for some crops (especially melons) and reductions in the total volume of drain-water. Another study performed in San Joaquin Valley (USA) (Weinberg, 1999) showed that an increase in water price led to a 30% reduction in drainage and percolation.

As nitrate pollution is directly related to the cultivated crop, to rainfall intensity and timing and to the irrigation schedule (volume of water applied, irrigation method, timing, etc.), and as the irrigation policy can be affected by water policies, water prices might be a way of achieving a certain modification of environmental impacts. Water pricing policies may create an incentive to conserve water in agriculture, thus creating a large new water supply and providing a flexible complement to a pollution reduction policy. This is related to the concept of "the polluter pays".

Different water policies compensate for cost of implementation of irrigation, maintenance and operation costs and, indirectly, the cost of environmental damage which is generally paid for by society.

IV – Irrigation water policies

Some argue that water should be treated as an "economic good", thus improving its allotment. But others argue that water is a "social good" because it is crucial to human survival.

In any case, water pricing is a key way of improving water allotment and encouraging conservation of the environment. The price of water should be considered as a component of integrated water management.

Countries implement water pricing schemes to meet short-term and long-term policy goals in cost recovery, the encouraging of water saving protection of the environment (Dinar and Subramanian, 1997). Here we see the concept of full cost recovery, which is the process of directly or indirectly capturing and directing to public agencies some portion of revenue resulting from government actions to provide irrigation services, regardless of whether or not the funds are used to pay for any construction or operation and maintenance costs. In practice, the criterion for successful recovery can vary from a small fraction of operation and maintenance costs only to more than 100% of the total costs of construction and operation and maintenance (Abu Zeid, 1995).

In order to enhance irrigation and improve agricultural production, most Mediterranean countries subsidise irrigation water, supplying cheap water mainly through public sector financing of irrigation infrastructure. Studies performed by the World Bank (1994) showed that in proportion to other sectors, irrigation is the largest component of water subsidies in developing countries, totalling $20-25 billion annually based on cost recovery of 20-25%.

The costs of supplying irrigation water consist of the variable costs of processing and delivering water to end users and the fixed costs of capital operation and maintenance (O and M). Variable costs depend on the amount of water delivered, while fixed costs do not (Tsur and Dinar, 1997).

According to Tsur and Dinar (1997), the most frequently used criteria for pricing irrigation water around the world are as follows.

1. Volumetric pricing

This method consists of using a direct measurement of the volume of water consumed. The water price may be set as equal to the marginal cost of water supply.

2. Output pricing and input pricing

Output pricing methods charge irrigators a water fee for each unit of output they produce. Input pricing methods charge for water use by taxing inputs (e.g. fertilisers).

3. Area pricing

Area pricing charges for water used per irrigated area, depending on the kind and extent of the crop irrigated, the irrigation method, the season of the year and other factors.

4. Tiered pricing and two-tariff pricing

With tiered pricing—a multi-volumetric method—water rates vary as the amount of water consumed exceeds certain threshold values. Two-part tariff pricing methods involve charging irrigators a constant marginal price per unit of water purchased (volumetric marginal cost pricing) and a fixed annual amount.

5. Betterment levy pricing

Betterment levy pricing methods charge water fees per unit area based on the increase in land value occurring from the provision of irrigators.

6. Water markets

Water markets may be formal or informal, organised or spontaneous, and they differ throughout the world in industrial and developing countries alike.

The preferred pricing method is the one that yields to highest social benefit. In the absence of implementation costs, and according to Dinar (1997), the volumetric method (or one of its related methods—tiered or two-part tariff pricing) is optimal in terms of social gains in comparison with all the other methods. Other methods may perform better for implementation costs.

Bos and Wolters (1990) investigated farmers representing 12.2 million hectares of irrigated farms world-wide and found that 60% of the irrigation projects charge on a per unit area basis and less than 15% of the irrigation projects charge for water using a combination of area and volumetric methods. About 25% of the projects charge using the volumetric method (Tsur, 1997).

Efficiency and equity are the two fundamental economic objectives to be defined when designing economic policies (Mergos, 1997). It is of great importance that the existing water resources should be allocated efficiently. In an economically efficient allocation, the marginal benefit of water use should be equal for all users. Efficiency is short-run, when the net benefit to be maximised involves variable costs and abstracts from annual capital and other fixed costs. A useful means of achieving efficient water allocation is to put the right price tag on it. Efficiency of water use is attainable whenever the pricing method affects the demand for irrigation water. The volumetric, output, input tiered and two-part tariff schemes all satisfy this condition. In addition to efficiency, resource allocation may also be based on equity. Equity objectives are particularly concerned with fairness of allocation in economically disparate groups and may or may not be consistent with efficiency objectives. Table 1 shows a comparison between these different methods (Dinar and Tsur, 1997).

Table 1. Comparison of various pricing methods (Dinar and Tsur, 1997)

Pricing Scheme	Implementation	Time horizon of efficiency	Ability to control demand
Volumetric	Complicated	Short-run	Easy
Output	Relatively easy	Short-run	Relatively easy
Input	Easy	Short-run	Relatively easy
Per area	Easiest	unknown	Hard
Tiered	Relatively complicated	Short-run	Relatively easy
Two-part	Relatively complicated	Long-run	Relatively easy
Water markets	Difficult	Short-run	unknown

Pricing and cost recovery issues should, as a principle, be part of project economic analysis. However, a number of issues arise when the actual implementation of pricing policies is concerned. However, cost recovery and the charging of water is not an end in itself but serves the objectives of efficiency and equity within the national economy. On the other hand, water price determination is influenced by a number of other case-specific natural factors (physical, hydrological, environmental, etc.) as well as social and institutional factors.

Water price ranges for different countries for the sector of agriculture are shown in Table 2 (Dinar and Subramanian, 1997).

Table 2. The price of agricultural water in different countries (1997)

Country	Water price	
	fixed $/ha/year	variable $/m³
Industrialised countries		
Australia	0.75-2.27[1]	0.0195
New Zealand	6.77-16.63	
Canada	6.62-36.65	0.0017-0.0019
United States		0.0124-0.0438
Israel		0.16-0.26
France		0.11-0.39
Italy	20.98-78.16	0.07-0.14[7]
Portugal		0.0095-0.0193
Spain	0.96-164.48	0.0001-0.028
Africa		
Algeria	3.79-7.95[2]	0.019-0.22
Madagascar	6.25-11.25[3]	
Namibia	53.14	0.0038-0.028
Sudan	4.72-11.22[4]	
Tanzania		0.26-0.398[5]
Tunisia		0.02-0.078[5]
LA and Asia		
Brazil	3.5	0.0042-0.032[6]
India	0.164-27.47[6]	
Pakistan	1.49-5.8	
Taiwan	23.3-213.64	

Per unit of water entitlement
Per litre per second per ha
Depending on scale of irrigation perimeter
Depending on crop and irrigation scheme
Depending on location
Depending on state and crop
The price was not reported, this is the price for a region in Southern Italy.

Chapter II: Material and methods

I – Study area

The study area is in San Severo in the Capitanata area in the province of Foggia, in the Puglia region of southern Italy. The province of Foggia covers 600,000 ha, forming 6% of the agricultural land of Puglia and therefore plays an important role in regional agriculture.

As in the whole of southern Italy, rainfall distribution is irregular during the year in the Capitanata, with a relatively long dry period in spring and summer. The average rainfall of about 460 mm is mainly concentrated from autumn to spring (October to May), when precipitation totals about 400 mm. This is why irrigation is one of the most important factors in the improvement of agricultural production.

In the province of Foggia, 13 % of the labour works in agriculture. Most farms have an area of 60-80 ha, with others having an area of 5-10 ha or 150-200 ha. In addition to olives and grapevines, durum wheat is still a major crop, with the recent expansion of industrial tomato. The other major field crops are sugar beet, sunflower, asparagus, melon, maize, sorghum and soybean. The region is characterised by more or less evolved deep, calcareous soils with fine texture and moderate to poor drainage.

1. Irrigation

The Capitanata irrigated area totals about 250,000 ha with a minimum supply of water of 2,000-2,500m3/ha. The irrigation network is designed for on-demand operation with a discharge at the hydrants of 10 l.s-1 and a minimum head of 20m. The system was designed in 1975 for sprinkler irrigation but most of the farms are now equipped for trickle irrigation.

Present water pricing consists of fixed and variable costs. The fixed costs depend on the area irrigated with the rate being Lit 30,000.ha-1, and variable costs are changed according to the volume of water used with a block-rate tariff as shown in Table 3.

Table 3. Capitanata consortium criteria for water pricing (Lamaddalena et al, 1999)

Volume range (m^3 ha^{-1})	Cost of water (Lit.m^3)
0 - 2000	170
2000 - 2500	205
2500 - 3000	240
> 3000	340

2. The farm studied

The study addressed a typical 100-ha farm growing tomato, wheat, sugar beet, sunflower and sorghum. This is a typical field crop farm for the region with a common rotation. Tree crops were not included in this study, due to the difficulty in simulating response in an agronomic model approach. It is specified here that the size of the farm and the crops cultivated may affect the prices and the costs of each component. The size of the farm may also have different response and elasticity to the changes in the methods of irrigation and levels of irrigation efficiency management.

The water supply for this farm consists of the collective network of the consortium, with farmers paying for the water according to a certain tariff. Although the hydrant discharge (10 $l.s^{-1}$) is not suitable for surface irrigation, surface, sprinkler and drip irrigation are considered, assuming that there are no water supply constraints. Surface irrigation is included for methodological purposes. The tendency in the region is for trickle irrigation because of its high efficiency. Sprinklers are used where trickle irrigation is not possible technically.

II – Methodology

The methodological approach used combines a biophysical model and a mathematical programming model at farm level, leading to “bio-economic” modelling of the entire farming system, including environmental parameters associated with different agricultural techniques, such as nitrate pollution.

The first step is the use of an agronomic simulation model considering the interaction of crop growth with climate, soil and agricultural practices (including irrigation). This makes possible the estimation of crop production and nitrate leaching. This research orientation has been developed during the past decade in several countries (Europe, the USA and Australia).

The second step is the use of economic models that use information from biophysical models. The outputs of the agronomic model are the inputs for the economic model and other economic inputs such as the prices of products, production costs, irrigation water, labour, fertilisers, irrigation, etc. The economic model generates the farmers' income and the level of nitrate leaching for each scenario.

The methodology consists of a multi-scenario analysis that, by changing water price or applying subsidies and taxes, shows the effect of the latter on farmers' incomes and nitrate pollution. This makes it possible to identify a set of water policies and corresponding levels of nitrate losses and farmers' incomes.

This type of methodological approach has been already applied with success to studies on erosion and agricultural externalities and is focused on irrigation efficiency for the first time in the present work (Deybe, 1994, Flichman *et al*, 1995, Donaldson *et al*, 1995, Boussemart *et al*, 1996, Blanco, 1996, Dalton and Masters, 1997, Louhichi *et al*, 1999, Mimouni, *et al*, 2000). The methodology used was the coupling of an agronomic simulation model (EPIC) and a multi-objective programming model (MOPM).

1. The agronomic model

The biophysical model used is the EPIC model (Erosion-Productivity Impact Calculator). This model was developed in the early 1980s by USDA-ARS, Soil Conservation Service (SCS), and Economic Research Service (ERS) teams. EPIC is a mechanistic simulation model used initially to examine the long-term effects of various components of soil erosion on crop production (Williams *et al*, 1984).

EPIC is designed to be:

- capable of simulating the relevant biophysical process,
- capable of simulating cropping systems for hundreds of years because erosion can be a relatively slow process,
- applicable to a wide range of soils, climates and crops,efficient, convenient to use, and capable of simulating the particular effects of management on soil erosion and productivity in specific environments.

EPIC is designed to help decision makers to analyse alternative cropping systems and project their socio-economic and environmental sustainability.

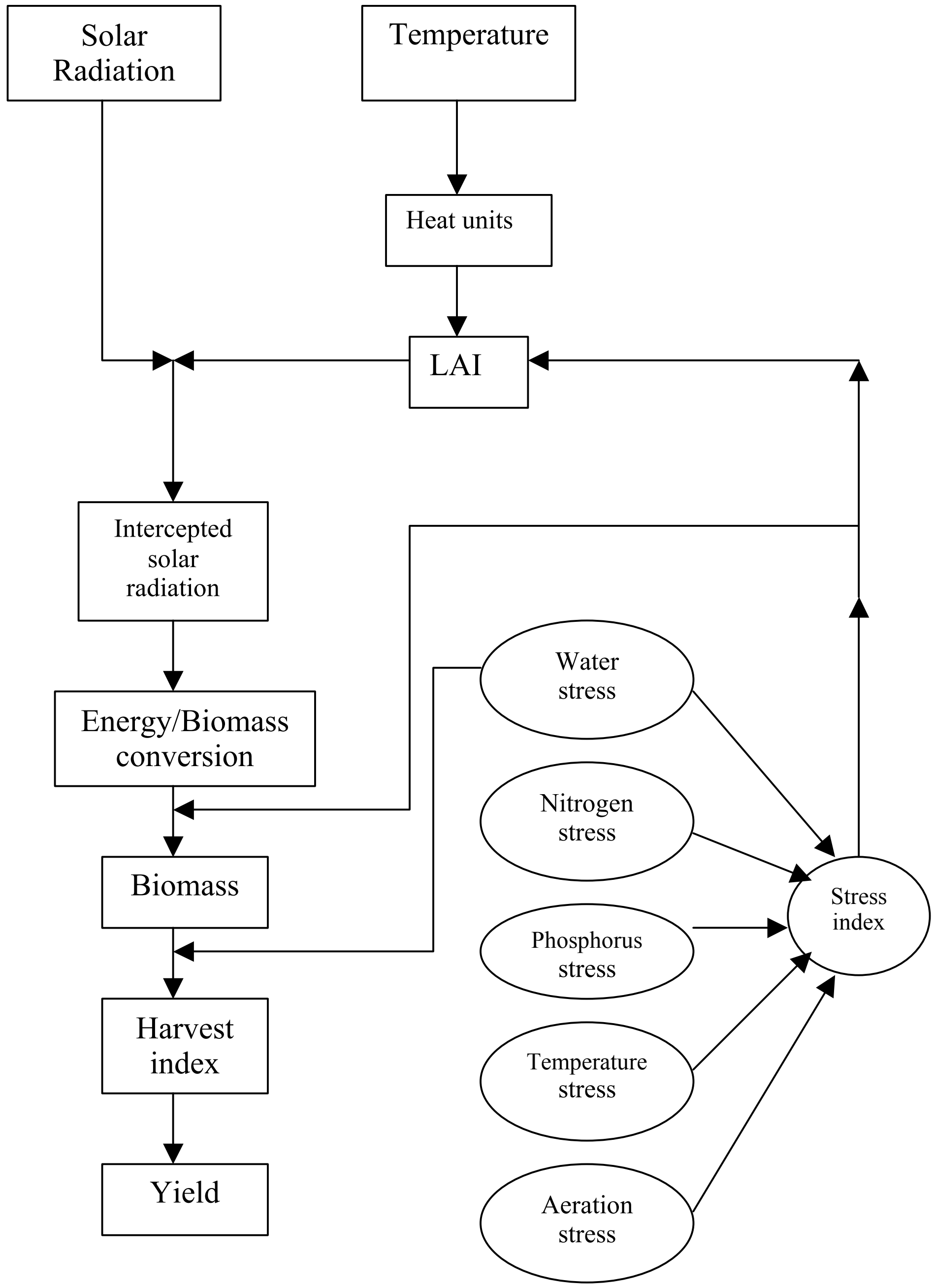
The model uses a daily time step to simulate weather, hydrology, soil temperature, erosion sedimentation, nutrient cycling, tillage, crop management and growth, pesticide and nutrient movement with water and sediment and field-scale costs and returns. Among all the uses of EPIC, focus here is on crop productivity and nitrate leaching.

The version used is EPICPHAS real time (EWQTPR) that was developed in Toulouse (France) from the original version of EPIC (Cabelguenne *et al.*, 1990). This version has been adapted for irrigation management. The crop growth module takes into account the effect of water stress on crop yield considering different phenological phases. The module was thus adapted to water stress phases by introducing additional parameters making it possible to:

- divide the crop vegetative cycle into four phases,
- simulate a rooting system adapted to different species (e.g. conical, cylindrical forms) able to extract water from different depths,
- simulate the effect of water stress on the variation of the harvest index,
- change biomass-radiation relationships according to biomass composition (e.g. proteins, oils, etc.)
- simulate adaptation to drought.

A schematic diagram of the relationships among the variables influencing crop growth and productivity in EPIC is provided in Figure 6.

Figure 6. Schematic diagram of the relationships among the variables influencing growth and productivity in EPIC (Steduto, 1997)



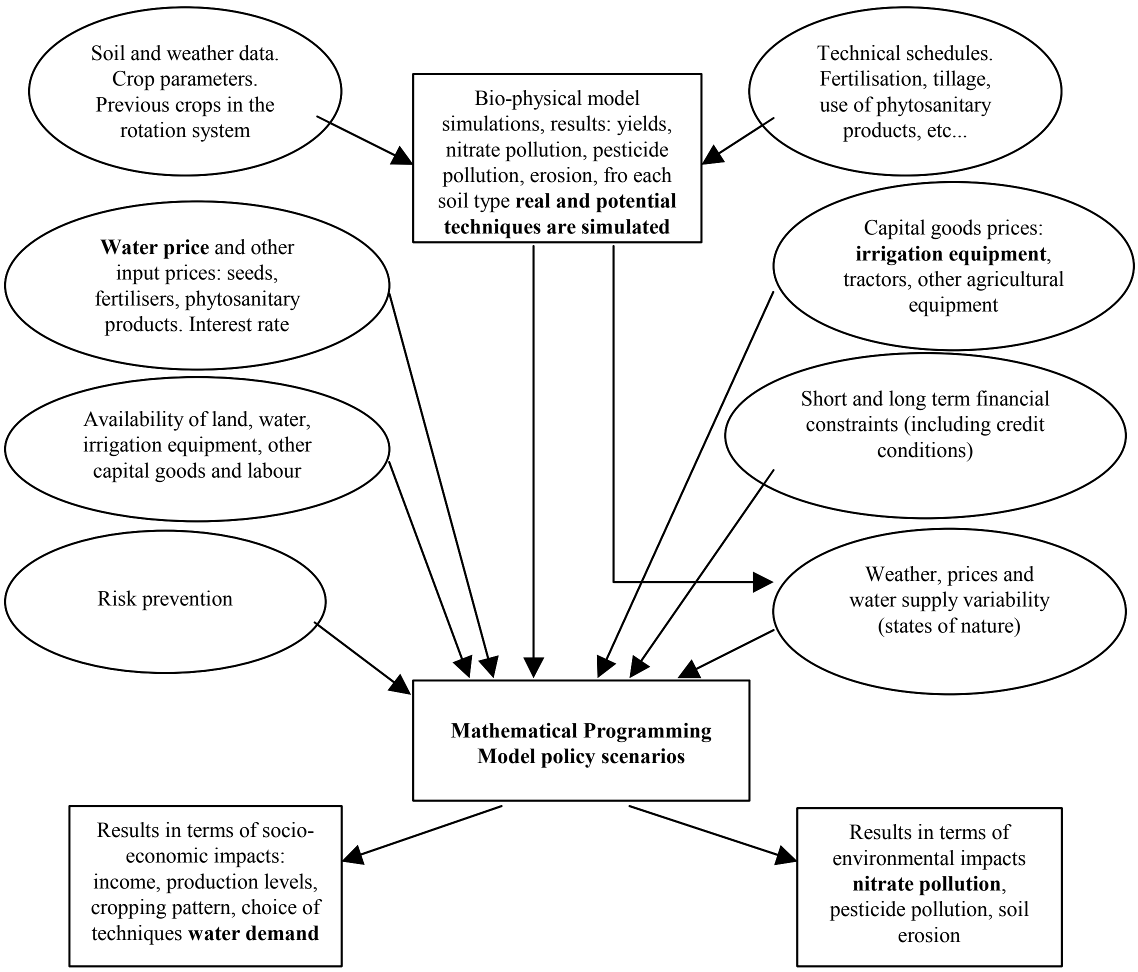
2. The economic model

If we can satisfactorily reproduce the technical and economic universe of agricultural production and assume a reasonably good utility function to be maximised or minimised, we may then build a "positive" model that can be used not for advising on the best way to use its resources but to simulate scenarios (Flichman, 1997).

In other words, a mathematical programming model (MPM) can be developed for forecasting and not for direct advice for decision centres. This is why the model requires calibration and validation as it should be able to reproduce the behaviour of a real system so that certain parameters can be changed (policy parameters such as prices, taxes, tariffs, subsidies, etc.) and forecasting analysis performed on the impact of these changes on the system. A positive model of this type can be used to help decision making in an indirect way. A mathematical multi-criteria economic model is used with linear combination of revenue (positive) and risk (negative). The risk is represented by the standard deviation of income in different states of nature. The model chooses the optimum solution with the highest net revenue and with low risk with regard to climatic and market price variability.

A positive bio-economic model is shown diagrammatically in Figure 7.

Figure 7. Diagram of a positive bio-economic model (Flichman, 1995)



3. The data considered

A. Agronomic inputs

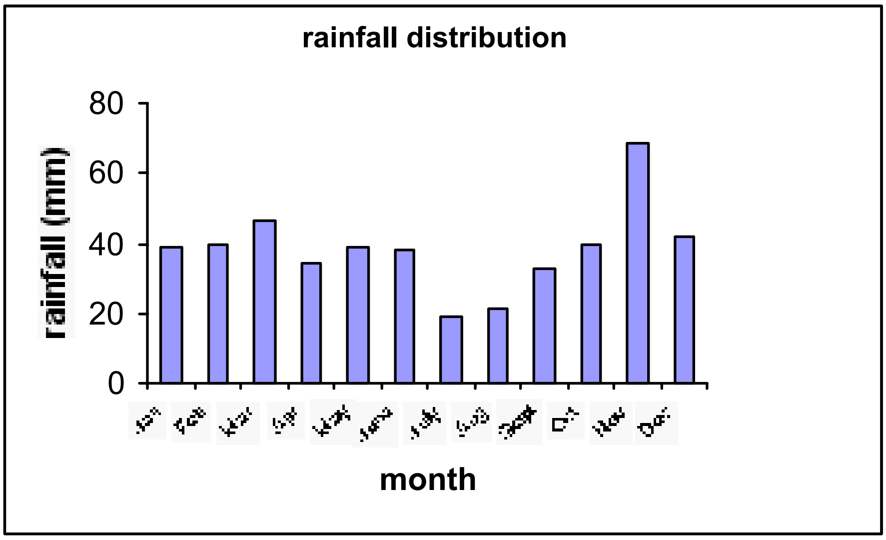
Climatic inputs

Both climatic and soil data were considered for the bio-physical model EPIC, in addition to crop parameters to calibrate the model and the management scheduling to run it.

The climatic file consists of a set of 6 years of daily data comprising temperatures (minimal and maximal) and rainfall. This is a representative set of data for a 50-year period. Due to the absence of reliable radiation data, Hargraves' method was used to calculate evapotranspiration.

Average rainfall is approximately 460 mm per year, maximum temperature is 31°C in July and minimum temperature is 5°C in January and February. Rainfall distribution is shown in Figure 8.

Figure 8. Monthly average rainfall distribution for the climatic series



Soil inputs

The soil data inputs used for the different soil layers are layer thickness, texture, bulk density, field capacity and wilting point, H, cation exchange capacity, organic matter and organic carbon. The soil is sandy-clay, with characteristics shown in Table 4.

Table 4. Physical and chemical soil characteristics

soil layer (cm)	pH	Organic carbon	Sand (%)	Clay (%)	silt (%)	CEC	OM (%)	PWP (%)	FC (%)	Bulk density ($g.cm^3$)
0-120	8.5	1.21	45	42	13	29	1.24	21	39	1.3

B. Crops and management

Five crops were used: wheat, sorghum, sunflower, tomato and sugar beet. Different irrigation levels were considered for each crop with 3 different levels of management according to the method used: low efficiency management (M1), medium efficiency management (M2) and high efficiency management (M3). Each management level defines an efficiency in irrigation water application for each method of irrigation. The values of these efficiencies are shown in Table 5.

Table 5. Different efficiencies of water application

	Management		
Method	M1	M2	M3
surface	0.50	0.65	0.80
sprinkler	0.65	0.75	0.85
drip	0.70	0.85	0.95

With, M1: low efficiency management, M2: medium efficiency management and M3: high efficiency management.

The different levels are defined according to certain operations and equipment used in each case as follows:

- land levelling
- expert consultation
- tensiometers
- pressure regulators
- volumetric valves
- manometers
- water meters
- water markers
- electronic programmers
- surge flow equipment
- partial flumes
- agro-meteorological stations.

The operations and equipment for each crop, irrigation level and method and management efficiency are reported in detail in Table 1 of Annex 1.

Even though efficiency could change with the amount of irrigation water applied, it is assumed that it is the same whatever the volume because the model accounts for the water balance and reliance is placed on management skills. It is also considered that the efficiency in deep percolation of the first irrigation (when crops are at critical stages) represents water potentially available for later use by the crop until the maximum root depth is reached. One of the most critical assumptions is that the equipment and skills associated with a given level of irrigation efficiency are really sufficient for achieving such efficiency.

C. EPIC calibration and validation

EPIC yield response to water was calibrated and validated under different conditions of irrigation and climate using experimental data and records provided by the “consorzio per la bonifica della Capitanata” for the study area. The calibration and the validation procedures could be operated only for yield response of the different crops and no data were available for nitrate leaching. Nevertheless, since nitrate leaching is strongly related to the oil-water balance, the EPIC results can be considered valid in terms of leaching on a relative rather than absolute basis (Sharpley and Williams, 1990).

D. Scenario simulation

After calibration and validation, three amounts of water applied (or techniques) with the associated schedules and applications were defined: T1 is the first level of deficit irrigation, T2 is the level of deficit irrigation, and T3 is the “full irrigation” technique. In addition, technique level T0 is the “rainfed” condition and is only used for wheat, sorghum and sunflower.

The three techniques represent the attitude of the farmer and the irrigation schedules of irrigation that the farmer may use and are shown in Table 6. The nitrogen fertilizers applied to each crop and technique are shown in Table 7.

Table 6. Water applied for each crop and technique

	Water depth (mm)		
Crops	T1	T2	T3
tomato	180	330	500
sugar beet	250	450	700
wheat	90	160	300
sunflower	210	350	600
sorghum	180	250	400

Table 7. Nitrogen fertilisers applied for each crop and technique

	N fertilisers ($kg.ha^{-1}$)			
Crops	**T0**	**T1**	**T2**	**T3**
tomato		150	200	200
sugar beet		150	200	200
wheat	120	120	120	120
sunflower	70	80	100	100
sorghum	100	200	200	200

The irrigation methods associated with each technique were: no irrigation (R0), surface irrigation (R1), sprinkler irrigation (R2) and drip irrigation (R3).

E. Economic inputs

The economic model is constructed using the GAMS (General Algebraic Mathematical System) language. “Activity” in GAMS is defined by all combinations of the four different sets: crop, irrigation method, technique used and management efficiency level.

Yields

The yields were estimated from EPIC and the 5-year average yields were used to calculate the farmer's profit. Two variabilities in yields were also considered:

1. variability resulting from the area under the crop (10%): considering that the yield varies from a minimum when all of the surface allowed is cultivated to a maximum value when the minimum area is cultivated;
2. variability due to climatic changes: considering five different climatic years, EPIC will generate five different yield levels for each activity, with the different sets representing “good”, “bad” and “average” years.

Nitrate percolation

Nitrate percolation was estimated by EPIC according to the crop, techniques and the management efficiency level. It is expressed as $kg.ha^{-1}$ of N passing beyond the maximum root depth.

Crop rotations

A rotation coefficient was used for each crop in order to respect the real situation. As a result of problems of nutrition and resistance to certain pathogens, some crops that could not be present on the same piece of land in the following year. These rotation coefficients are shown in Table 8. The rotation coefficient of 0.2 means that the tomato should not be grown on more than 20% of the total land because it cannot return to the same position for 5 years.

Table 8. Crop rotation coefficients

Crop	rotation coefficient
wheat	1.0
tomato	0.2
sugar beet	0.2
sunflower	0.3
sorghum	0.5

Costs and prices

The costs were calculated according to data from the region and from the Foggia consortium reported in the last five years, together with consultation of experts in the region when certain data were not available.

The costs used are:

- production costs for each crop excluding irrigation (water, labour and equipment) and fertiliser costs,
- the cost of irrigation equipment defined for each crop and irrigation method,
- the cost of labour for the irrigation of each crop, method and technique,
- the cost of fertiliser,
- the cost of irrigation water
- the cost of management, differing from one efficiency level to another. This includes the cost of different equipment and the time of experts used to increase the efficiency of water use. It is calculated according to the operations and equipment used to reach each level. This cost is defined for each crop, technique and irrigation method.

These costs were calculated in the light of consultations of experts in the study region and of the Capitanata consortium and according to market prices of equipment and inputs.

The crop prices used are the average for a 5-year period (from 1996 to 2000), taking into account the percentage variation of these prices and considering this variability in 20 different states of market (Annex 3). These prices are considered as exogenous and not affected by the production level.

A multi-criteria model constructed using these inputs. It has two objectives:

1. maximising farmers' profits,
2. minimising risk.

The variables observed are:

- the quantity of water used,
- nitrate percolation and pollution.

A detailed diagram of the economic model written in GAMS language is provided in Annex 2.
The objective function (U) of the model that is maximised, is:

$$\mathbf{Z - \varphi^* S_v = U,} \qquad \textbf{(3)}$$

With Z being the total net revenue of the farmer (Lit)

φ id the coefficient for the risk prevention parameter (taken as 1.65, assuming a normal distribution of revenue for all the states of the system, this value gives the probability of revenue higher than U as ≥ 95%),

S_v, is the standard deviation of the variance of the random revenue calculated using the variability of the yield according to states of nature, and the variability of the price according to states of the market;

Z is the average revenue calculated using the following equation:

$$Z = \sum (Y^*P + S_b) - \sum (C_O + C_m + H_L{}^*C_L + F_N{}^*C_N + C_e) - T^*A - P_w{}^*V_w \quad (4)$$

With Y being the average yield of the crops for each technique (tonnes/ha), varying according to the area used:

$$Y = Ymax - ((Ymax - Ymin)/R_{coef}{}^*A)\ ^*X \qquad (5)$$

With Ymax being the maximum yield reached when the area used is minimal (tonnes.ha^{-1}),
Ymin is the minimum yield reached when the area used is at maximum (tonnes.ha^{-1}),
R_{coef} is the rotation coefficient for each crop (%),
A is the total area (ha),
X is the actual area used (ha),
P, the average price of the crops (Lit.tonne^{-1}),
S_b, the subsidies awarded for certain crops (Lit.ha^{-1}),
C_O, the crop production cost (Lit.ha^{-1})
C_m, the cost of management for each level and crop (Lit.ha^{-1})
H_L, the hours of labour needed for each technique,
C_L, the price of labour per hour (Lit),
F_N, the amount of nitrogen fertiliser (kg urea .ha^{-1}),
C_N, the cost of the nitrogen fertiliser (Lit.kg^{-1}),
C_e, the cost of irrigation equipment (Lit.ha^{-1}),
T, the fixed tariff for irrigation (Lit.ha^{-1}),
P_w, the price per m^3 water (Lit.m^{-3}),
V_w, the total quantity of water applied (m^3).

The standard deviation of the random revenue was calculated as:

$$\mathbf{S_v} = \sqrt{DEV^2 / N * M} \qquad (6)$$

With,

N = the number of states of nature (5 different climatic years)
M = the number of market states (20 different market prices)
and,

$$DEV = Z - Z1, \qquad (7)$$

with

$$Z1 = \sum (Y_v * P_m * P_i + S_b) - \sum (C_O + C_m + H_L * C_L + F_N * C_N + C_e) - T * A - P_w * V_w \qquad (8)$$

in which Y_v is the yield, varying according to area and climate

$$Y_v = Y_n * Y / Y_m \qquad (9)$$

With Yn being the yield varying with the climatic year and given by the output of EPIC (tonnes.ha^{-1}),
Y_m is the average yield between Ymax and the Ymin (tonnes.ha^{-1}),
P_m is the average price of the 20 different market states for crops (Lit.tonne^{-1})
P_i is the variability of P_m.

Chapter III: Results and discussion

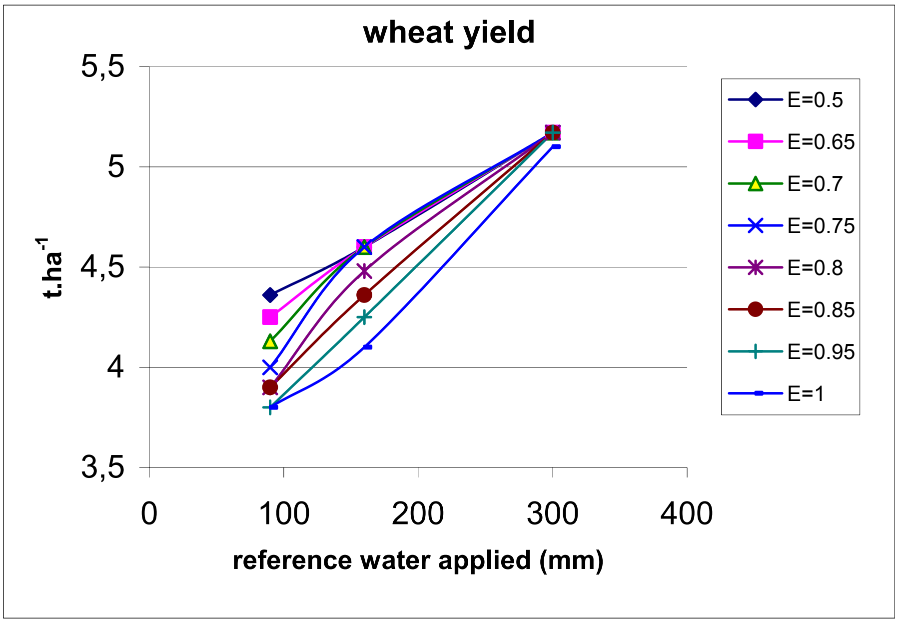
I – Results of the agronomic model

The results for the four techniques (rainfed, first level of deficit irrigation, second level of deficit irrigation and full irrigation) in terms of yield response to water and nitrate leaching are as follows for all the five crops concerned and for the efficiencies considered.

1. Wheat

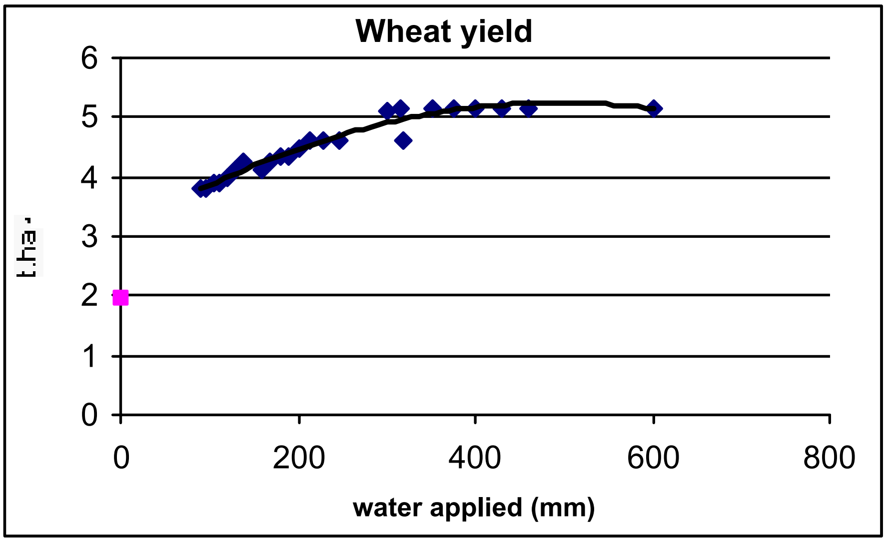
The yield response of wheat to water is shown in Figure 9 for each level of efficiency. The x-axis represents the reference amount of water applied equivalent to that for 100% efficiency. For example, the highest point corresponding to 100 mm reference water applied and to 0.5 efficiency of 0.5 is 200 mm. The y-axis reports yield responses obtained for each reference amount of water applied but allowing for different levels of efficiency. This way of expressing yield response to water highlights how at low amounts of reference water applied low efficiencies result in a greater water application and hence advantages for the crop. It is noted that 90 mm reference water applied at the lowest application efficiency (0.5) corresponds to the highest yield response (4.4 $t.ha^{-1}$) and the highest efficiency (1) corresponds with the lowest yield response (3.8 tons. ha^{-1}). All the other yield responses of the remaining efficiencies lie between the two. This type of response is expected because 90 mm is considered quite insufficient for satisfying the seasonal crop water requirements of wheat under the climatic conditions of the study area and the extra water received as a result of inefficiency is partially utilised by the crop. As the reference water amount increases, the advantage of the extra water resulting from inefficiency decreases to the point at which (Figure 9) crop water requirements are fully covered with 300 mm water and the advantage of receiving extra water by inefficient application is completely lost.

Figure 9. Wheat yield response to water at three levels of reference water applied and eight levels of application efficiency



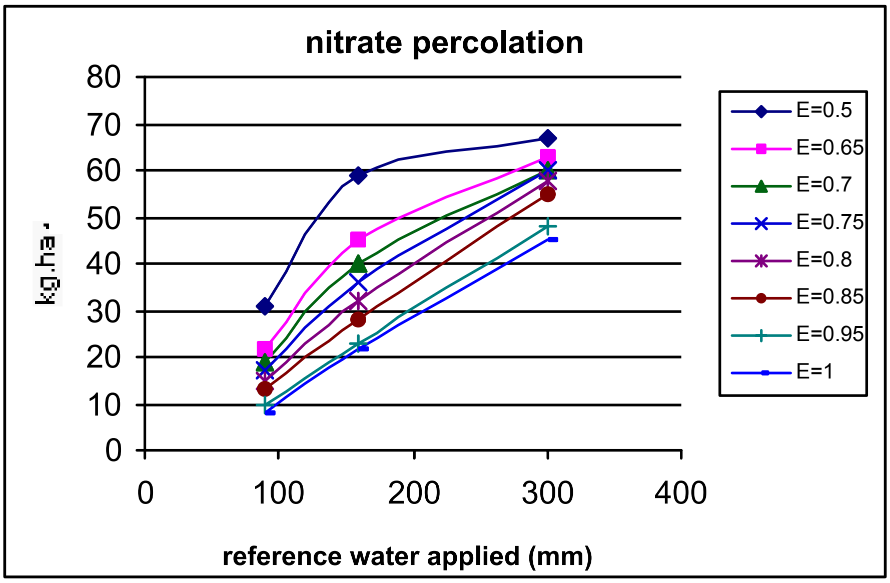
Plotting the yield response of wheat against the actual water applied gives the results shown in Figure 10. This is a typical response of wheat in the area under study, where the average yield under rainfed conditions is about 2 $t.ha^{-1}$ (corresponding to zero water application in Figure 10). When some 90 mm of water is applied as supplemental irrigation at critical stages, the highest increment in yield is obtained with a doubling of the yield. The highest wheat yield is obtained with about 300 mm water, giving about 5.2 $t.ha^{-1}$. Yield no longer increases with water application of 300 to 600 mm and a decrease can be expected at high applications (400-600 mm) because of possible lodging. However, this feature is not simulated by the crop-growth model and is therefore not shown in Figure 10.

Figure 10. Wheat yield response to actual water applied



Nitrate percolation corresponding to the different levels of water amounts and efficiencies is now observed in the similar manner to yield. Nitrate percolation at different water amounts applied is shown in Figure 11. This figure, in contrast with advantages obtained by the yield response in Figure 9, highlights the fact that inefficiencies are always disadvantageous for the environment.

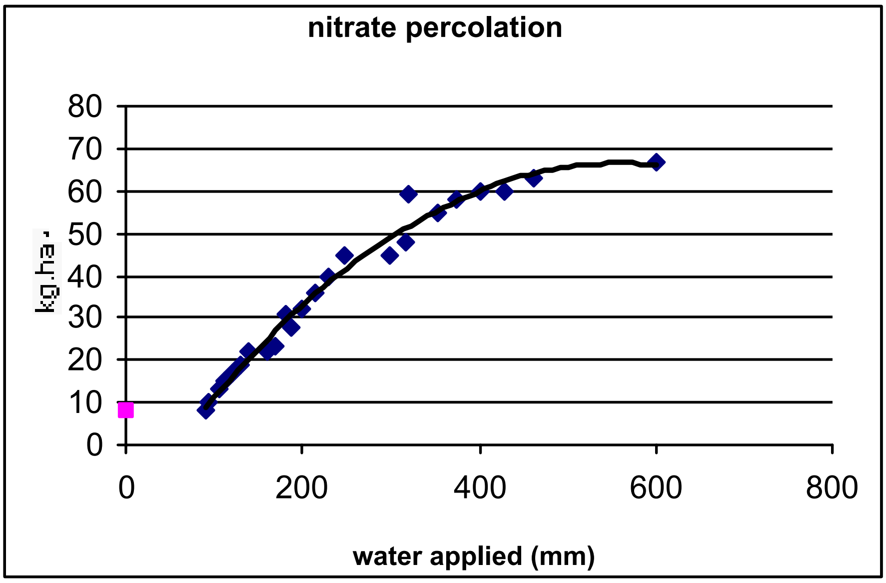
Figure 11 Nitrate percolation in response to reference water applied to wheat at three levels of water amounts and eight levels of application efficiency



In fact, nitrate percolation always increases with decreases in efficiency whatever the amount of reference water applied. The ranges of nitrate percolation obtained for the wheat crop varies from 8 to 31 $kg.ha^{-1}$ at 90 mm reference water applied, from 22 to 59 kg.ha-1 at 160 mm reference water applied and from 45 to 67 kg.ha-1 for 300 mm of reference water applied.

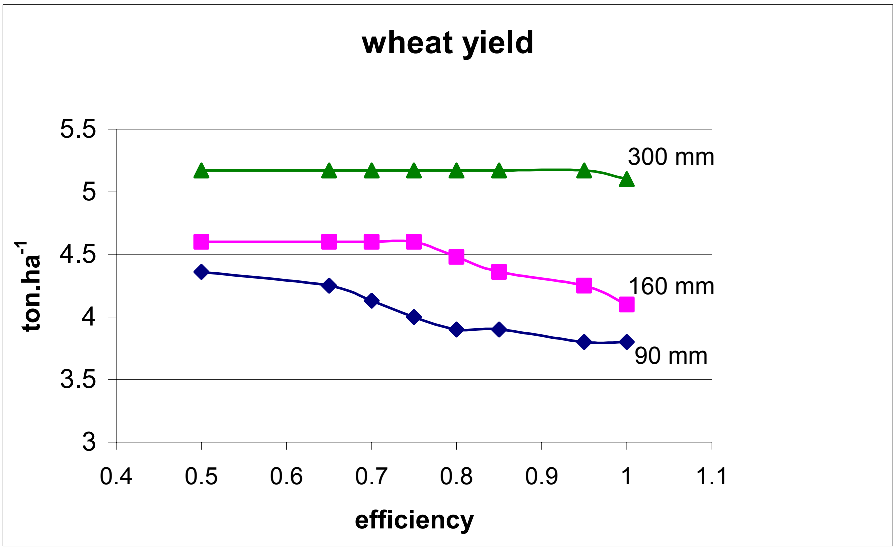
Plotting the overall nitrate percolation against the water applied gives the results shown in Figure 12. The rapid increase in nitrate percolation with increase in water use is clear. It is also noticed that the slope of the relationship between nitrate percolation and water applied is significantly steeper than the slope of the relationship between yield and water applied.

Figure 12. Nitrate percolation in response to water applied, in wheat



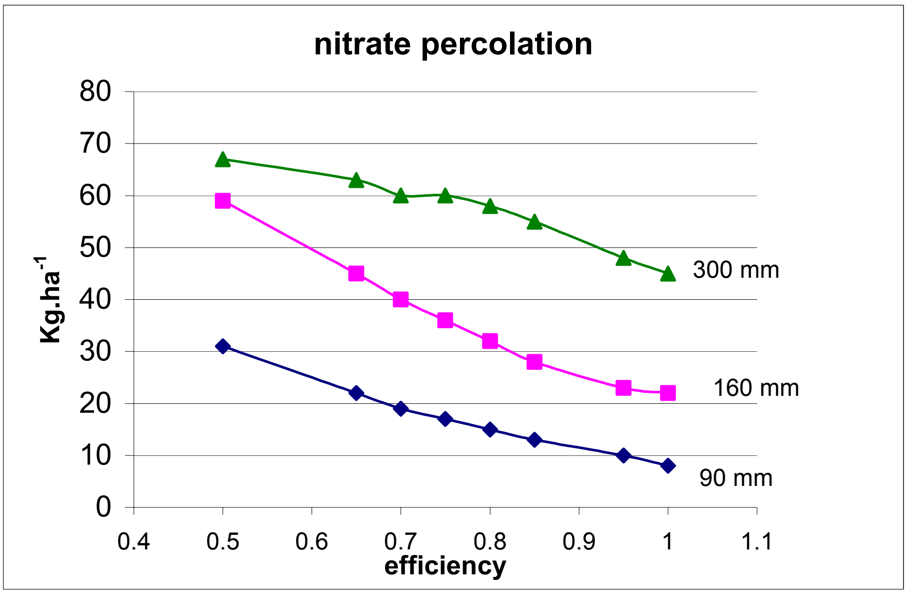
The links between yield and nitrate percolation and efficiency are deduced from these results and shown respectively in Figures 13 and 14. These relationships show that wheat yield decreases with an increase in application efficiency if the amount of water applied is insufficient to satisfy the seasonal water requirement of the crop (Figure 13). Moreover, the overall rate of such a yield decrease with increase in efficiency becomes more marked as the amount of reference water applied decreases.

Figure 13. Relationship between wheat yield and application efficiency at three levels of reference water applied



In contrast, nitrate percolation always decreases with an increase in efficiency and always decreases with an increase in the amount of water applied (Figure 14)

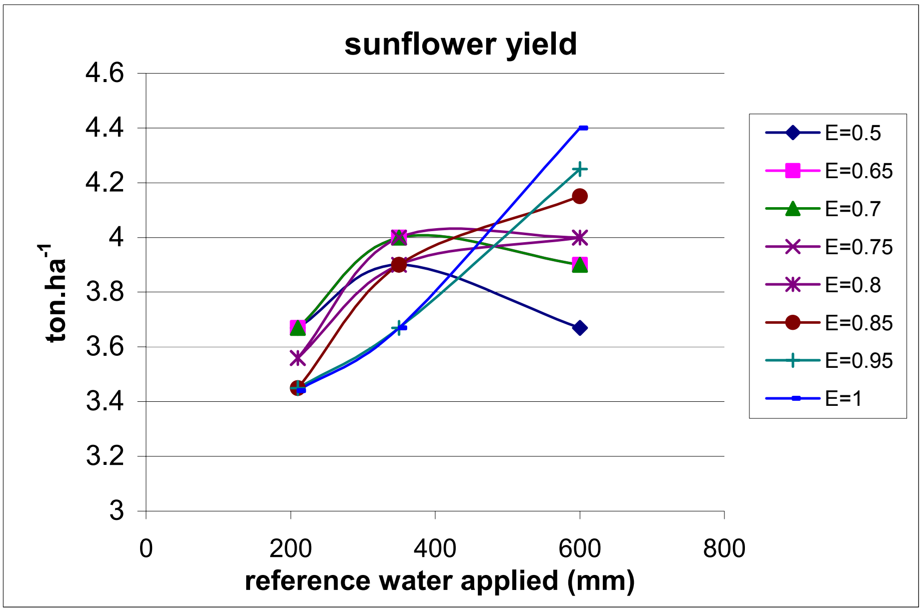
Figure 14. The relationship between nitrate percolation and application efficiency in wheat at three levels of reference water applied



2. Sunflower

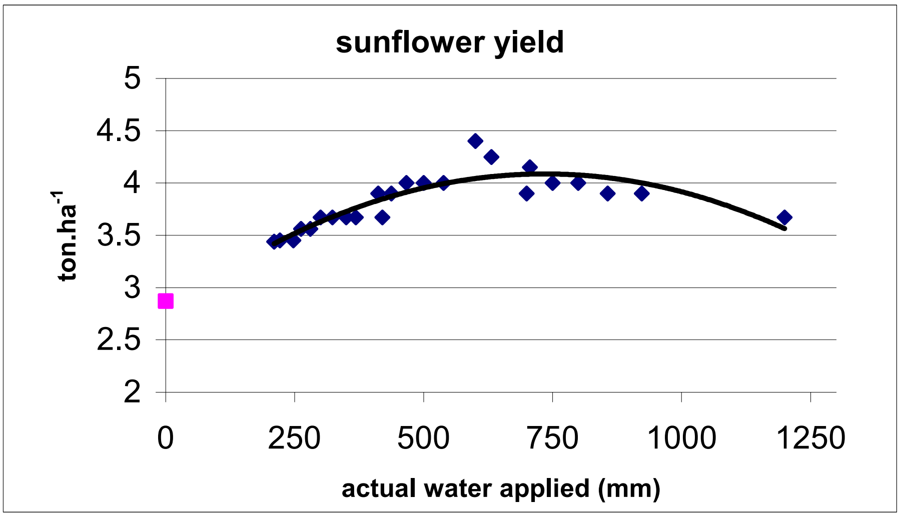
The yield response of sunflower to reference water applied for each level of application efficiency is shown in Figure 15. In this figure, for the reference water applied of 210 mm, and as for the response of wheat, low efficiencies result in higher yields than the higher efficiencies. In fact, the yield varies between 3.44 $t.ha^{-1}$ for 100% efficiency and 3.67 $t.ha^{-1}$ for 50% efficiency. Yield does not vary greatly with decreasing efficiency at the first level of deficit irrigation. Yield also increased with decreasing efficiency at the 350 mm reference water application, with the exception of response to the lowest efficiency (0.5) when the yield decreased in comparison with the other efficiencies. The yield response reversed totally with 600 mm water applied: the lowest efficiency gave the lowest yield (3.67 $t.ha^{-1}$) and the highest efficiency gave the highest yield (4.4 $t.ha^{-1}$) while the yields for other efficiencies were between the two values. In fact, this response shows that application amounts exceeding crop water requirements induce limitations to the crops and therefore decreases in yield.

Figure 15. Sunflower yield response to water at three levels of reference water applied and eight levels of application efficiency



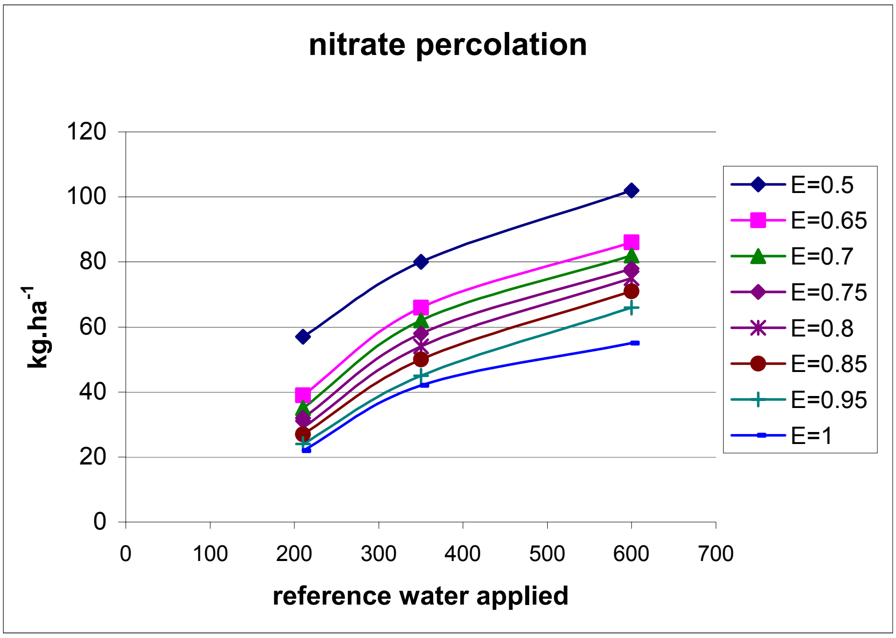
This decrease in response with very high water application is also shown in Figure 16, where the yield is plotted against the water applied. It is seen that the yield increases (4.4 t.ha^{-1}) until 600 mm water and than begins to decrease with increasing application amounts. The yield under rainfed conditions is 2.87 t.ha^{-1}, which is not particularly low in comparison with the first sub-optimal irrigation (210 mm) that begins with 3.44 t.ha^{-1}.

Figure 16. sunflower yield response to actual water applied



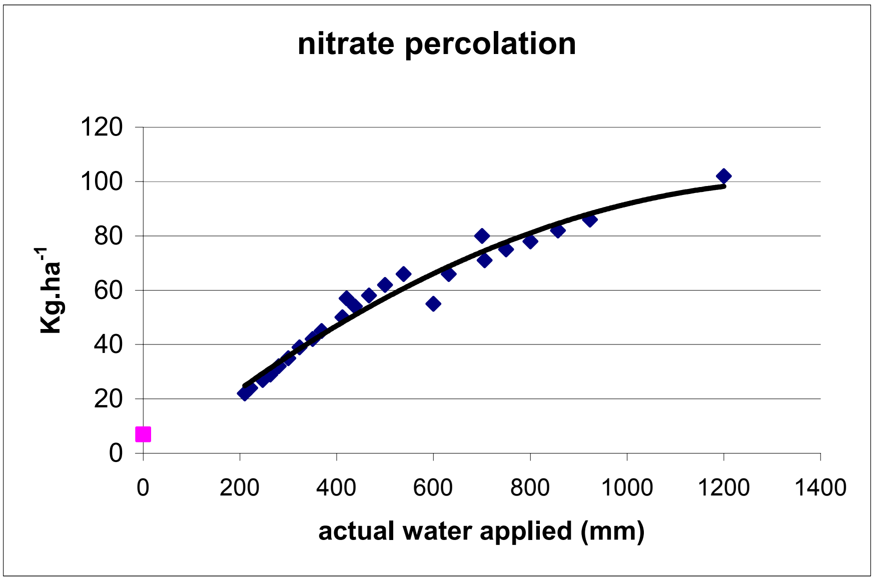
Nitrate percolation with sunflower is shown in Figure 17 for the different levels of reference water applied and the eight application efficiencies. In this figure, nitrate percolation always increases with the decrease in application efficiency and the increase in reference water depth. Nitrate leaching with sunflower varies from 22 to 57 kg.ha^{-1} with 210 mm reference water, from 42 to 80 kg.ha-1 at 350 mm and from 55 to 102 kg.ha-1 for 600 mm. It can be seen than percolation roughly doubles from the lowest to the highest efficiency.

Figure 17. Nitrate leaching versus water and efficiency in sunflower



The curve for overall nitrate percolation against water applied, (Figure 18) shows a rapid increase in nitrate percolation with the increase in irrigation water applied. As in the case of wheat, the slope of the relationship between nitrate percolation and water applied is significantly steeper than that of the yield response to water (Figure 16).

Figure 18. Nitrate percolation in response to actual water applied in sunflower



Figures 19 and 20 show the relationships linking yield and nitrate percolation to efficiency respectively. Figure 19 shows that yield response to full 600 mm reference irrigation is not always the highest in comparison with deficit irrigation levels of irrigation and increases with efficiency. The nitrate percolation response shown in Figure 20 is always consistent, decreasing with increasing efficiency and with a decrease in the reference water applied.

Figure 19. Relationship between sunflower yield and application efficiency at three levels of reference water applied

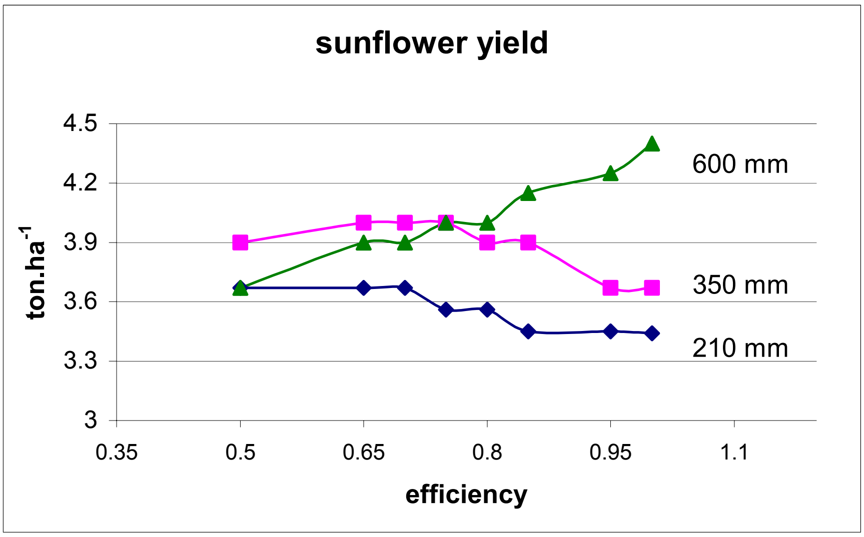
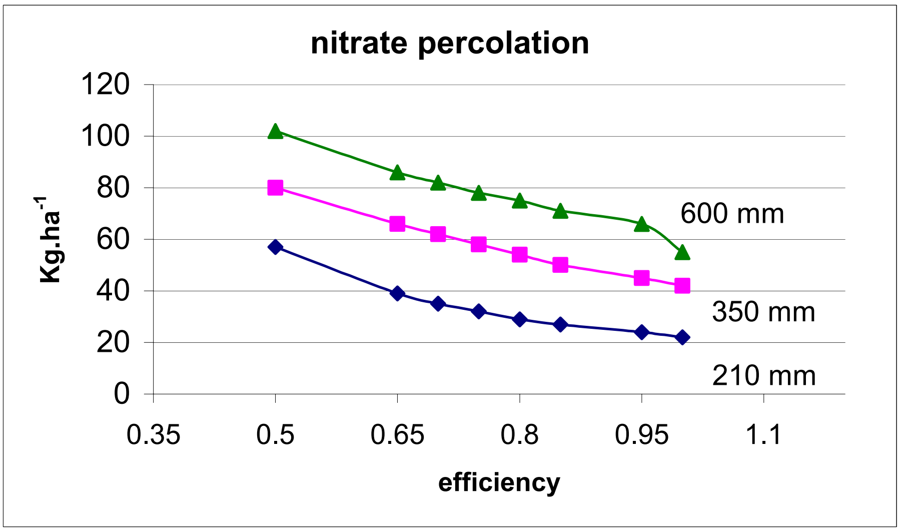


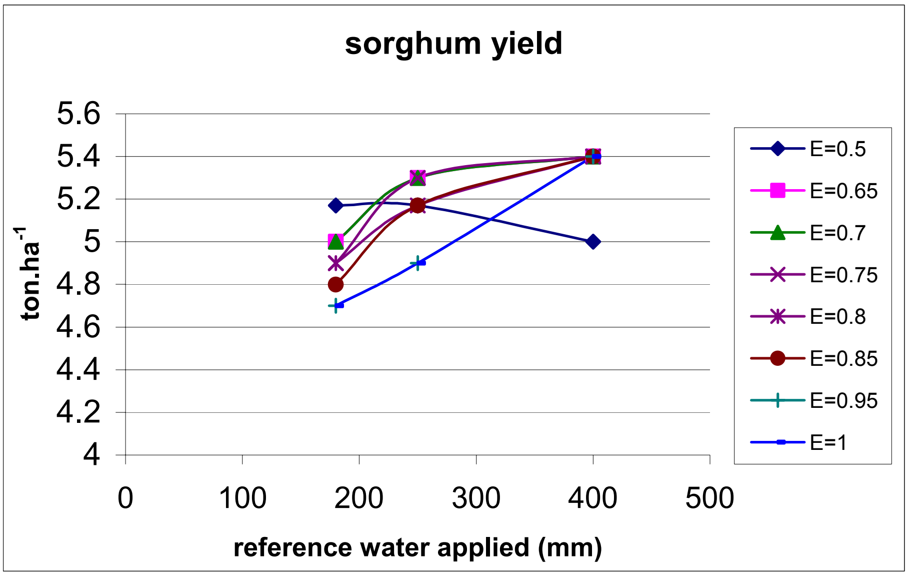
Figure 20. Relationship between nitrate percolation and application efficiency in sunflower at three levels of reference water applied



3. Sorghum

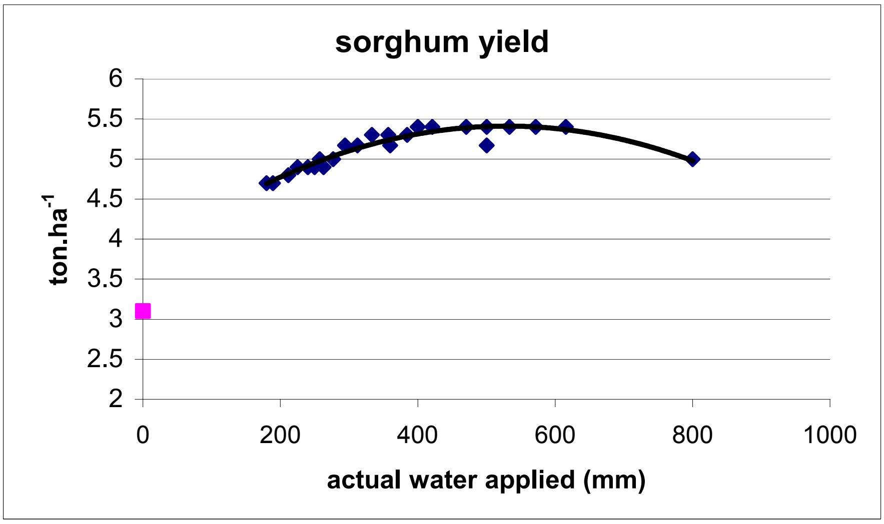
The yield response of sorghum to water for each level of efficiency and each level of reference water applied is shown in Figure 21. For the first sub-optimal level of irrigation, corresponding to 180 mm water applied, the yield increases with the decrease in application efficiency from 4.7 $t.ha^{-1}$ at 100% efficiency, to 5.17 $t.ha^{-1}$ at 50% efficiency, as a result of extra water added by inefficiency and potentially available in the root zone for the crop. The yield also increases in the second level of deficit irrigation (250 mm) with a decrease of application efficiency except for the lowest efficiency (0.5) where the yield reached 5.3 t.ha-1 at 65% efficiency and decreased to 5.17 $t.ha^{-1}$. At 400 mm water applied, all efficiencies gave the same yield (5.4 $t.ha^{-1}$) except for 50% efficiency, where the yield continued to fall to 5 t.ha-1 as the irrigation water depth was much greater than requirements and resulted in a negative crop response.

Figure 21 Sorghum yield response to water at three levels of reference water applied and eight levels of application efficiency



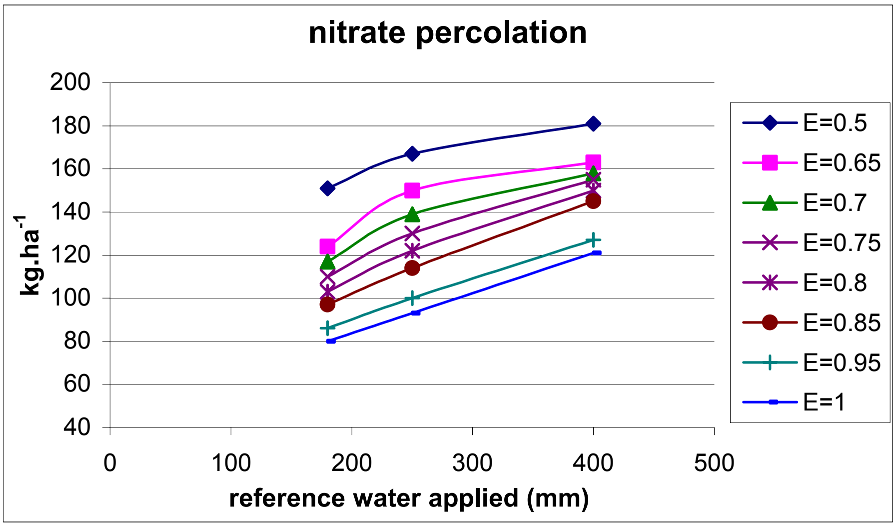
The results of the plotting of the yield response of sorghum against the actual water applied are shown in Figure 22. This figure shows a typical response curve of sorghum in the study area, where the yield under rainfed conditions is 3 t.ha^{-1}. The highest increment appears with the shift to 180 mm water applied, the first deficit irrigation. In this case, the yield is 4.7 t.ha^{-1}. The yield peaks at 5.5 t.ha^{-1} with the application of some 400 mm water. It then decreases to 5 t.ha^{-1} at 800 mm actual water applied.

Figure 22. Sorghum yield response to actual water applied



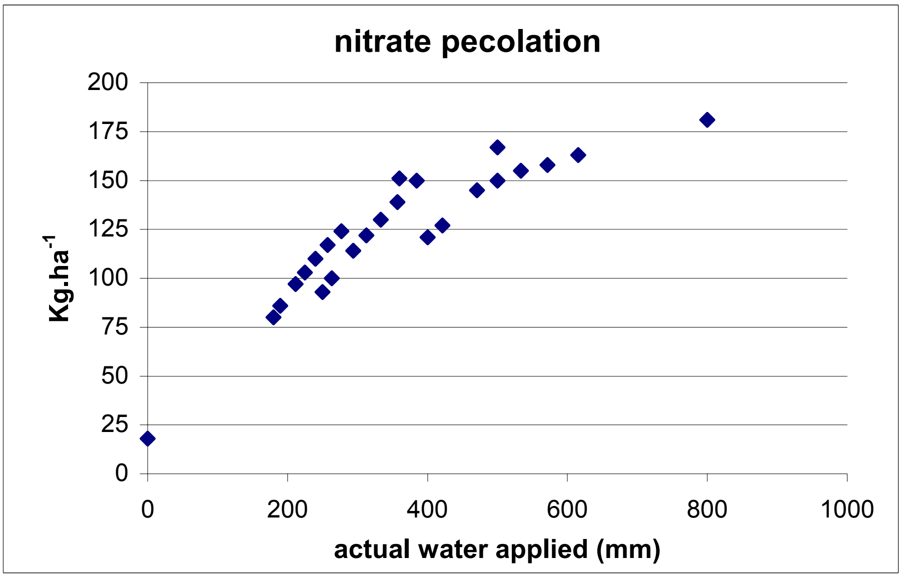
In Figure 23, nitrate percolation under sorghum is shown against the different levels of water amounts and efficiencies in a similar manner as for yield. This figure highlights the fact that the nitrate leaching increases with decreasing efficiency and with an increase in the reference water applied. This shows the disadvantages of low efficiencies with regard to environmental pollution. These leaching amounts vary between 80 and 151 kg.ha^{-1} for the first level of deficit irrigation (180 mm), between 93 and 167 kg.ha^{-1} for 250 mm reference water applied and from between 121 and 181 kg.ha^{-1} for full irrigation with 400 mm reference water applied.

Figure 23. Nitrate percolation in response to reference water applied in sorghum at three levels of water amounts and eight levels of application efficiency



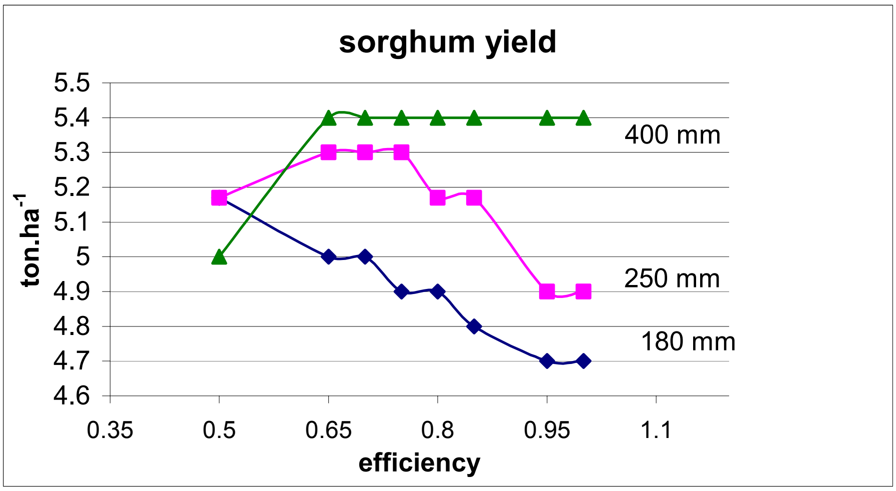
The overall nitrate percolation response against actual water applied is plotted in Figure 24. In this figure, percolation is very low (20 $kg.ha^{-1}$) under rainfed conditions (zero water applied) in comparison with irrigated techniques which begin at 76 $kg.ha^{-1}$ for 180 mm. Nitrate percolation under sorghum is significantly higher than under wheat and sunflower, reaching 176 $kg.ha^{-1}$. The curve is steep, but there is some distribution in the points because there may be more than one value for percolation for the same amount of actual water applied as a result of the timing and amounts of irrigation.

Figure 24. Nitrate percolation in response to actual water applied to sorghum



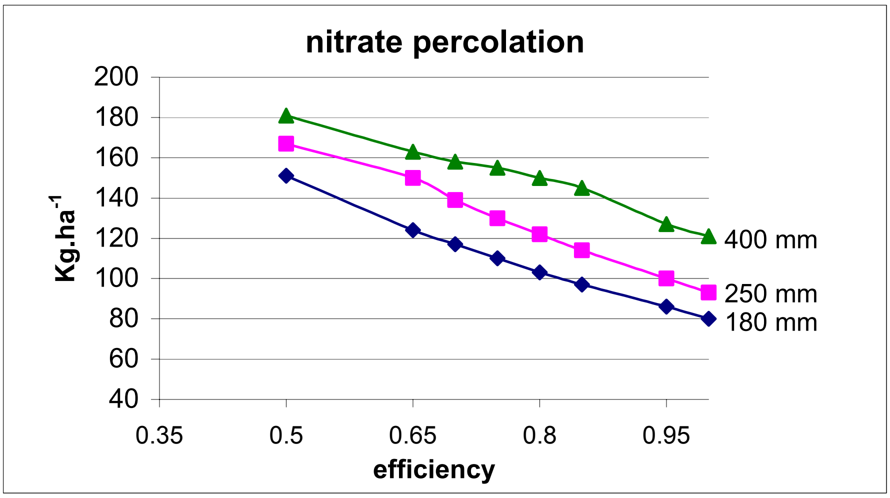
The links between yield and nitrate percolation and efficiency are deduced from these results and shown respectively in Figures 25 and 26. The curve is downward in Figure 25, showing the decrease in yield with the increase in irrigation application efficiency. But with 400 mm and 250 mm water application, yield increases with efficiency from 0.5 to 0.65 and then remains constant, indicating that the extra water contributed by 0.5 efficiency has an adverse effect on sorghum yield.

Figure 25. Relationship between sorghum yield and application efficiency at three levels of reference water applied



The trend of percolation response to different efficiencies (Figure 26) is always consistent, decreasing with the increase of application efficiency and with the decrease of reference water applied.

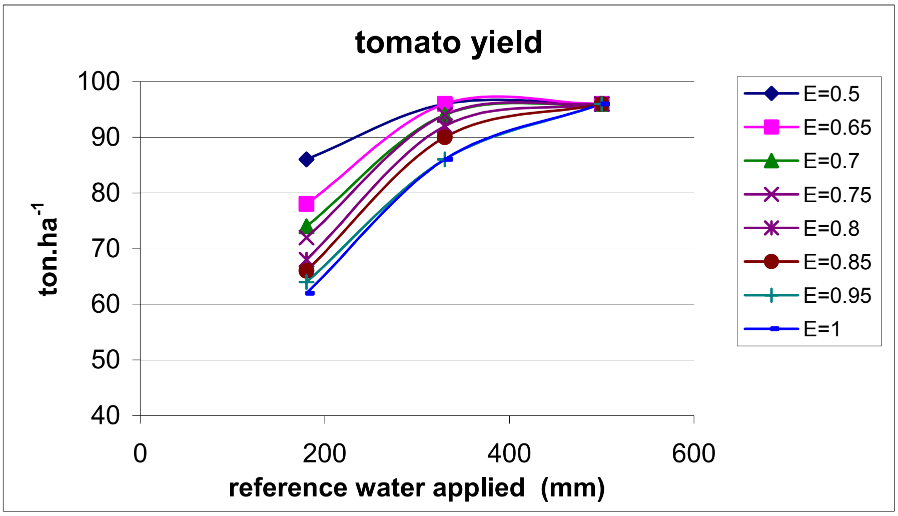
Figure 26. Relationship between nitrate percolation and application efficiency in sorghum at three levels of reference water applied



4. Tomato

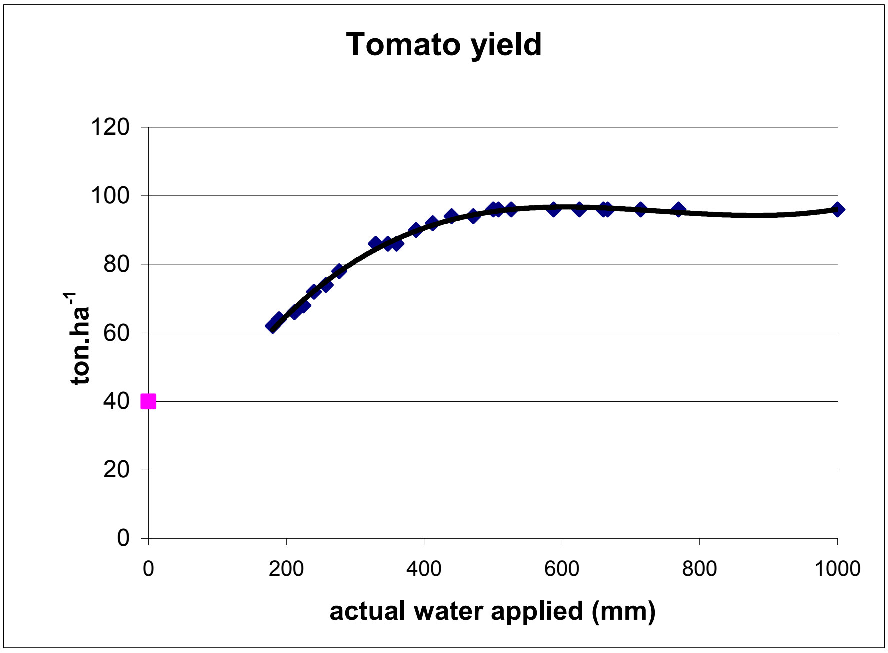
Tomato yield response to water and each efficiency level and for the three levels of reference water applied is presented in Figure 27. The yield increases with the decrease in efficiency and with the increase in reference water. For the first level of deficit irrigation (180 mm), the variation of the yield from high efficiency to low efficiency is substantial, from 62 to 86 $t.ha^{-1}$ respectively. This variation is lower when the reference water applied increases to 330 mm, changing from 86 to 96 $t.ha^{-1}$ for efficiencies changing from 1 to 0.5 respectively. At full irrigation (500 mm), the yields are always unchanged from one efficiency level to another (96 $t.ha^{-1}$).

Figure 27. Tomato yield response to water at three levels of reference water applied and eight levels of application efficiency



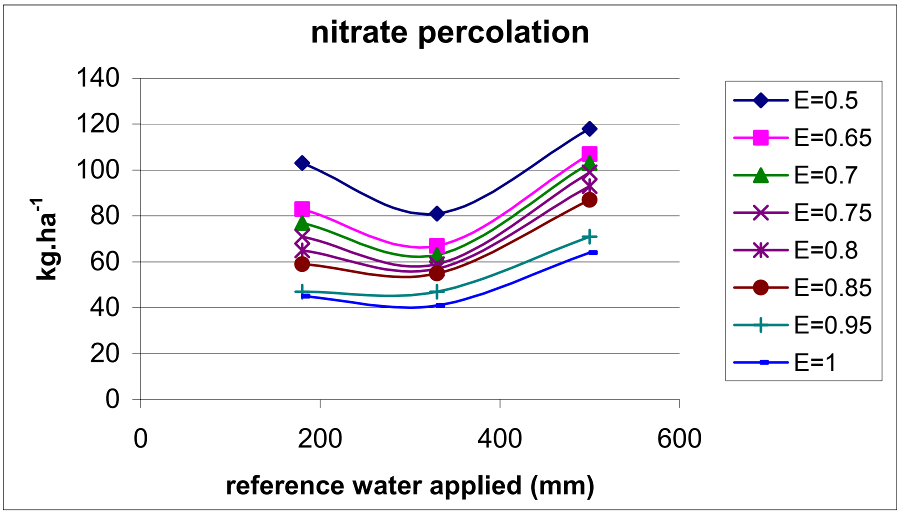
The results of the plotting the overall yield response of tomato to water applied are shown in Figure 28. The yield varies from 40 t.ha^{-1} for rainfed conditions, reaching 62 t.ha^{-1} at 180 mm of irrigation water and 96 t.ha^{-1} with full irrigation; the figure subsequently remains constant even when water application is increased.

Figure 28. Tomato yield response to actual water applied



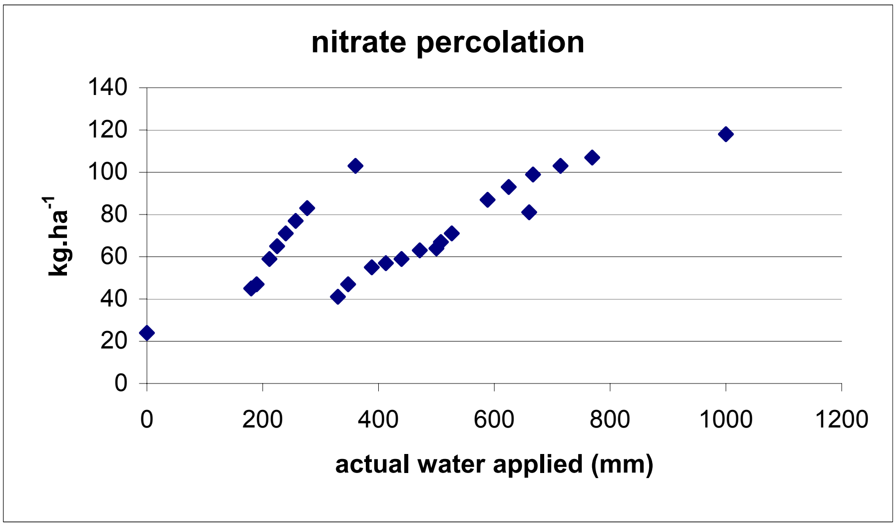
Nitrate percolation under tomato for the three levels of irrigation and the eight levels of application efficiency is shown in Figure 29. In this figure, nitrate leaching increases with the inefficiency of water application. It can be seen that that the second sub-optimal irrigation level (350 mm) gave nitrate percolation values lower than that of the first irrigation deficit level (180 mm). In fact, it varies between 45 and 103 kg.ha^{-1} for 180 mm reference water applied, between 41 and 81 kg.ha^{-1} for 350 mm and between 64 and 118 kg.ha^{-1} for 500 mm. This response may result from the timing and amounts of irrigation applications. Application in the first deficit level of irrigation are characterised by large amounts and long intervals, inducing more percolation than the second sub-optimal irrigation level.

Figure 29. Nitrate percolation in response to reference water applied to tomato at three levels of water amounts and eight levels of application efficiency



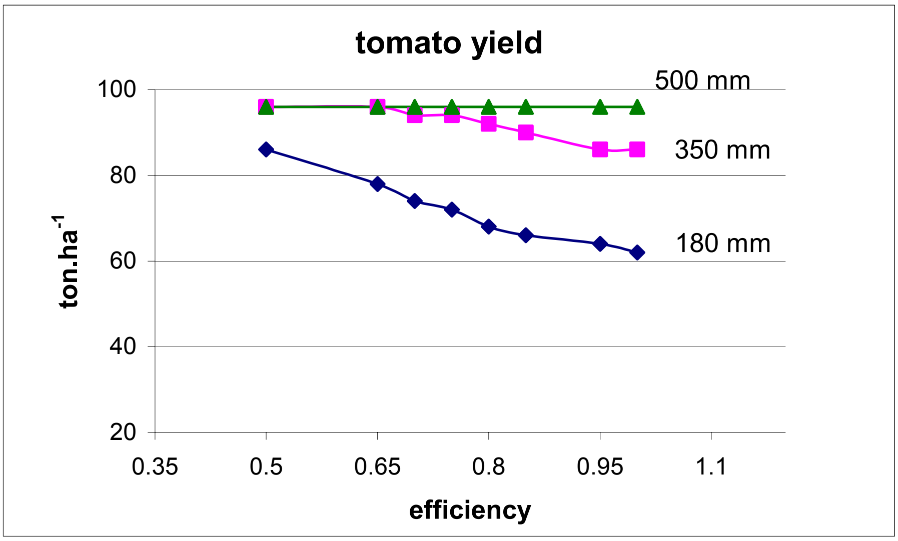
The overall nitrate percolation response of tomato to actual water applied is plotted in Figure 30. Apart from the percolation under rainfed conditions, which is 24 kg.ha^{-1}, the points seem to form two response curves resulting from the high percolation of the first sub-optimal irrigation level and the relatively lower percolation of the second sub-optimal level. This led to more than one value of nitrate percolation for the same amount of actual water applied.

Figure 30. Nitrate percolation in response to actual water applied in tomato



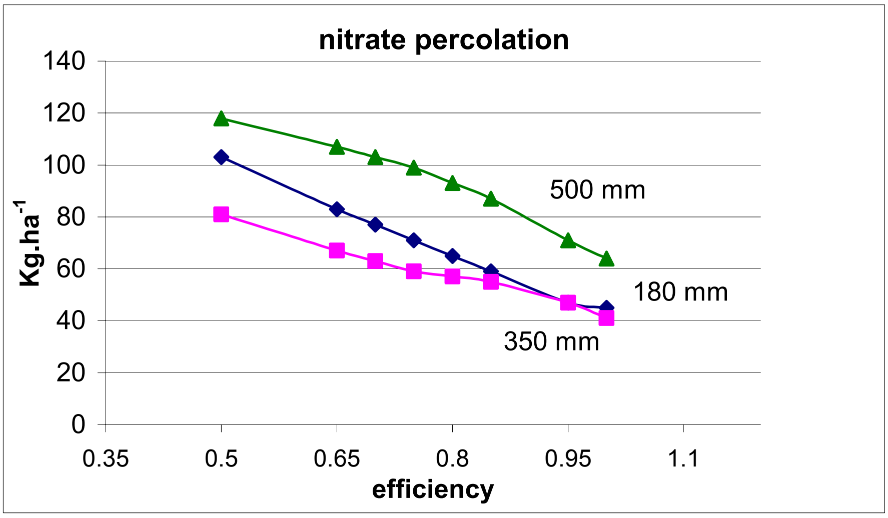
Figures 31 and 32 show the links between yield response and nitrate percolation and efficiency. Yield is seen to decrease with increasing in Figure 31, with no significant difference between the second optimal level of irrigation and full irrigation.

Figure 31. The relationship between tomato yield and application efficiency at three levels of reference water applied



In Figure 32, the curve corresponding to 180 mm reference water applied is higher than that for 350 mm and they overlap at higher levels of application efficiency. The overall trend shows that percolation always decreases with the increase in efficiency.

Figure 32. The relationship between nitrate percolation and application efficiency in tomato at three levels of reference water applied



5. Sugar beet

The yield response of sugar beet to the eight levels of efficiency and to the three levels of reference water applied is shown in Figure 33. Yield increases with the decrease in application efficiency, with highest rate being at low reference water applied (250 mm) where yield varies between 47 $t.ha^{-1}$ at 100% efficiency and 65 $t.ha^{-1}$ at 50% efficiency. The variation is lower at 450 mm reference water applied, where the yield is 58 $t.ha^{-1}$ at 100% efficiency and 73 $t.ha^{-1}$ at 50% efficiency. The yield is constant at 75.6 $t.ha^{-1}$ for all the efficiency levels with 700 mm water. This means that crop water requirements are already satisfied at this level and any additional water applied by inefficiency does not bring a benefit as at the reference application of 250 mm and 450 mm irrigation water.

The overall yield response to actual water applied is plotted in Figure 34. The yield, which was 33.2 t.ha^{-1} under rainfed conditions, increased to 47 t.ha^{-1} with the application of 250 mm of water and continued to increase to 76 t.ha^{-1} at 700 mm and then remained constant.

Figure 33. Sugar beet yield response to water at three levels of reference water applied and eight levels of application efficiency

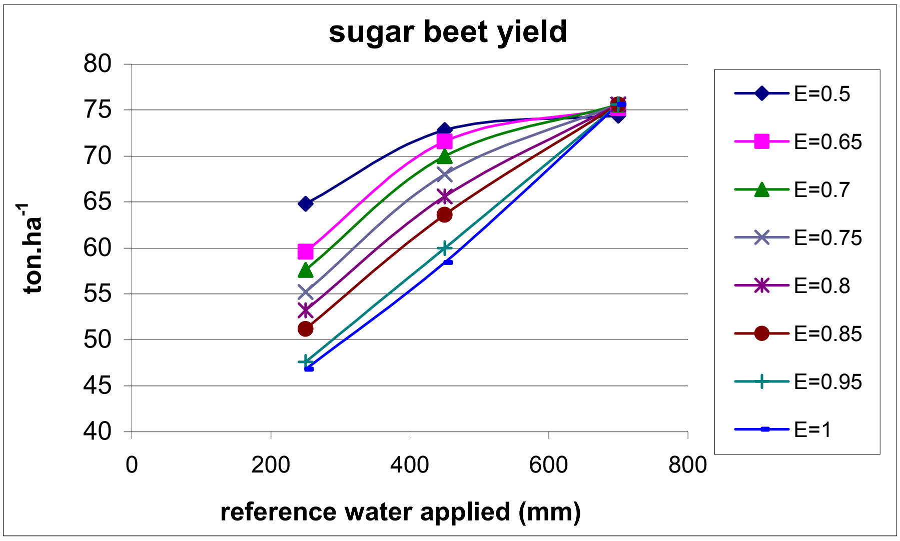
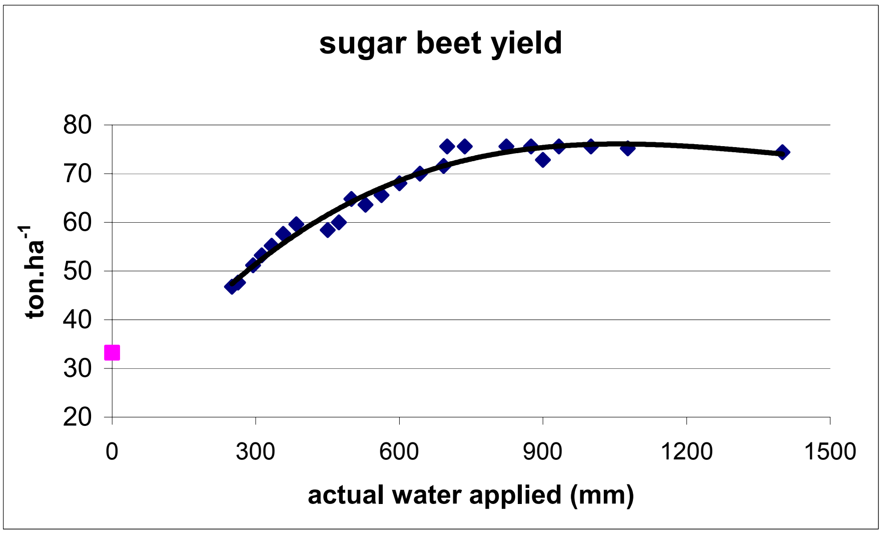
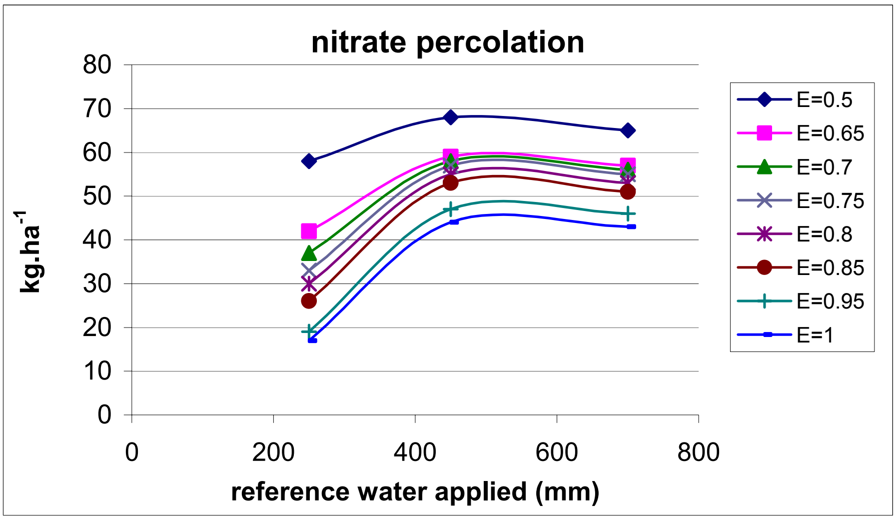


Figure 34. Sugar beet yield response to actual water applied



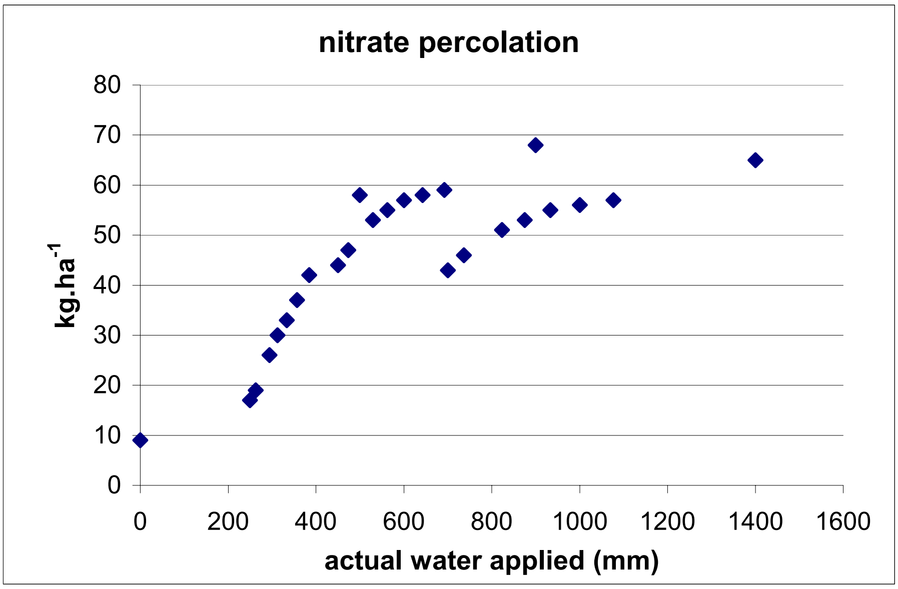
Nitrate percolation corresponding to different application efficiencies and three levels of irrigation water amounts can be observed in a similar manner. Nitrate percolation for different amounts of reference water applied is shown in Figure 35. The increase in percolation with the decrease of the application efficiency is relevant. However, nitrate percolation does not always increase with the increase in water application. This can be seen in the percolation corresponding to 450 mm, which is higher than the nitrate percolation corresponding to 700 mm reference water applied. For 250 mm, percolation varies from 17 to 58 kg.ha^{-1} for efficiencies 1 and 0.5 respectively. For 450 mm reference water applied, percolation varies between 44 and 68 kg.ha^{-1} for the highest and lowest efficiencies respectively and for 700 mm it varies between 43 and 65 kg.ha^{-1}.

Figure 35. Nitrate percolation in response to reference water applied to sugar beet, at three levels of water amounts and eight levels of application efficiency



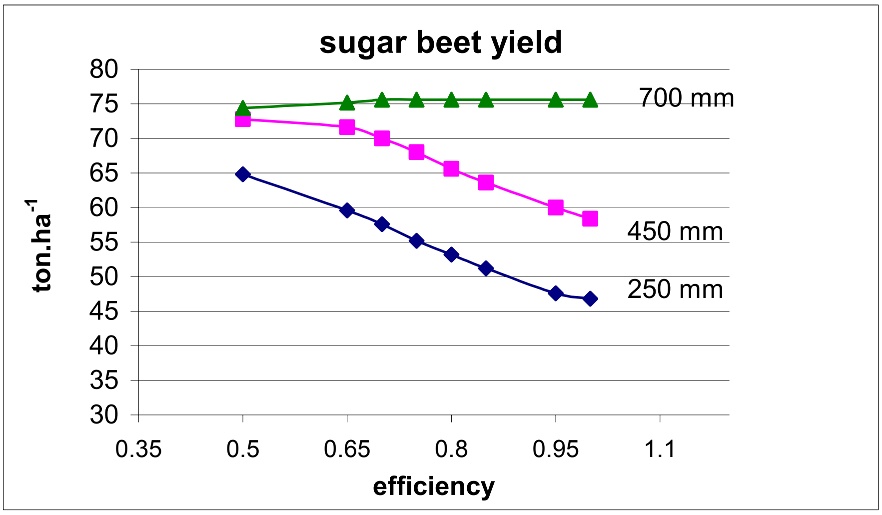
The overall nitrate percolation response is shown in Figure 36. It is characterised, as for tomato (Figure 30), by a dispersion of points that seem to constitute two different response curves because percolation in the second sub-optimal irrigation level is greater higher than in full irrigation. While nitrate percolation under rainfed conditions is 9 kg.ha^{-1}, irrigated techniques gave percolation of between 18 and 70 kg.ha-1, with a relatively steeper slope than that of the yield response in Figure 34.

Figure 36. Nitrate percolation in response to actual water applied to sugar beet



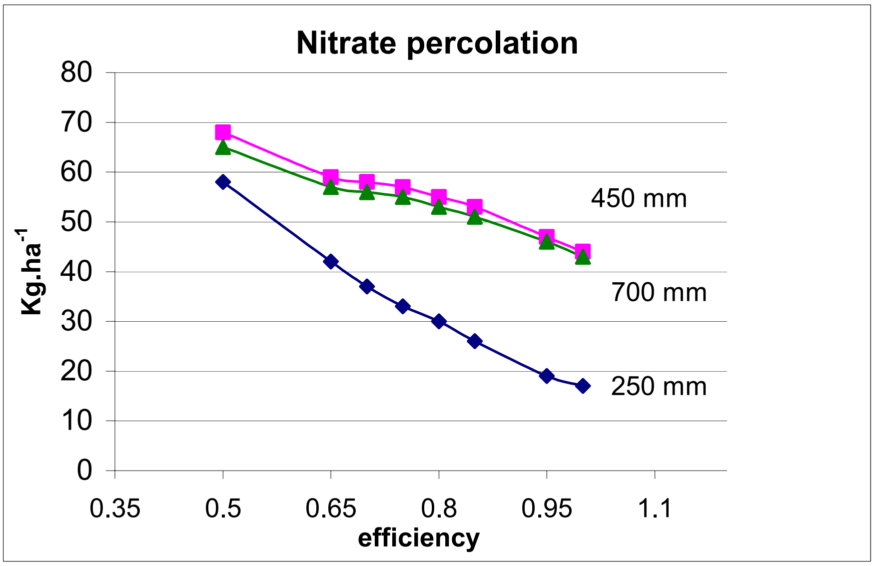
The links between yield and nitrate percolation and efficiency are deduced from these results and shown respectively in Figures 37 and 38. In Figure 37, the yield decreases with increasing efficiency, except for the full irrigation at 700 mm, where the yield does not change with the efficiency levels.

Figure 37. Relationship between sugar beet yield and application efficiency at three levels of reference water applied



In Figure 38, nitrate percolation decreases with increasing efficiency, but the slope is steeper in the first level of deficit irrigation (250 mm). Whereas nitrate percolation under full irrigation is slightly lower than that for the second deficit level of irrigation and the slope of the two curves is gentler than that for 250 mm reference water applied.

Figure 38. Relationship between nitrate percolation and application efficiencies in sugar beet at three levels of reference water applied



II – Results of the economic model

The results of the simulation of yield response and nitrate percolation of the five crops in the agronomic model were entered in the economic model together with the economic inputs. The economic model is constructed in GAMS language and is an optimisation model aimed at maximising the net income of the farmer with the minimum risk.

The optimum solutions given by this model for every simulation make it possible to observe the cropping pattern, irrigation methods and technique, the management efficiency used, the farmer's net income and total nitrate percolation. It is pointed out that all these variables change in each optimum solution.

Three policies were simulated:

- water pricing, with demonstration of the effect of different levels of water pricing (volumetric pricing) on pollution and, at the same time on all the other variables;
- high management incentives to induce the use management to increase irrigation efficiency and thus decrease nitrate pollution (it has been seen above that nitrate pollution increases with decreasing efficiency);
- taxing the inputs that cause pollution, that is to say nitrogen fertilisers.

1. Water pricing

Many simulations were performed after the construction of the economic model to observe the effect of changes in water price. Sixteen simulations were performed from Lit 0 to 750 per m^{-3} with Lit 50 stepwise increases. The actual price is a block rate pricing system varying from Lit 170 per m^{-3} to Lit 340 per m^{-3} (Table 3) with an average of around Lit 200 per m^{-3}.
The model gave a optimal solution for every water price. Every solution is characterised by a certain cropping pattern, techniques and methods of irrigation and management efficiency levels with corresponding levels of water consumption, nitrate pollution and farmer's net income.

A. The cropping pattern

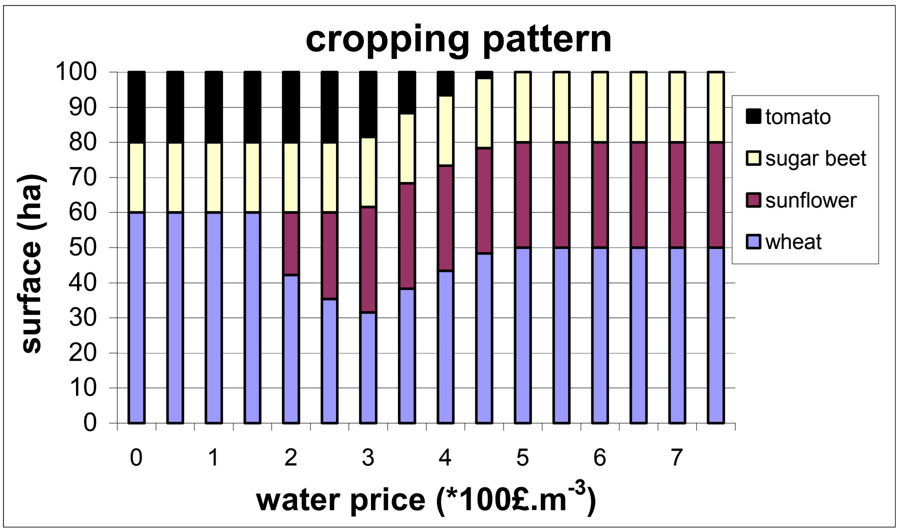
Table 9 shows that in the first iterations (with the price of water than Lit 450 per m^{-3}) the crops were: wheat, sunflower, tomato and sugar beet. When the price of water increased, sugar beet was replaced by wheat and sunflower because they require less water, whereas the tomato remains because of its high income. The other variables also changed, leading to variation in methods, techniques and irrigation management efficiency levels. Crop distribution is also shown in Figure 39. Here, the columns represent the area of each crop, whatever the technique, method and management efficiency of irrigation. As the price of water increases, the area under tomato is constant, that under wheat and sunflower decreases and that under sugar beet decreases .

Table 9. Surface distribution (ha) of the different crops associated with different irrigation methods (R), level of water applied (I) and efficiency level (M), with variation in water price

Iterations	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**	**L11**	**L12**	**L13**	**L14**	**L15**	**L16**
Water price (*Lit 100 per m^{-3})	**0**	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**
Crops & technique																
wheat.R0.I0.M0					4.4	13	25	38	43	48	50	50	50	50	50	50
wheat.R1.I1.M1			12	32	38	22	6.5									
wheat.R1.I2.M1	15	23	20	11												
wheat.R2.I3.M1	45	37	28	17												
sunf .R0.I0.M0					18	25	30	30	30	30	30	30	30	30	30	30
toma .R1.I2.M1	0.6	1.2	1.8	2.6	3.1											
toma .R1.I3.M1	19	19	18	17												
toma .R2.I2.M1						3.2	3.5	4.3	5	5.7	6	6.1	6.2			
toma .R2.I3.M1					17	17	17	16								
toma .R2.I2.M3														6.4	6.6	6.8
toma .R2.I3.M3											14	14	14	14	13	13
toma .R3.I3.M1									15	14						
sugb .R1.I3.M1	20	20	20													
sugb .R2.I1.M1							1.4									
sugb .R2.I2.M1						0.6										
sugb .R3.I3.M1				20	20	19	17									
sugb .R1.I3.M3								12	6.6	1.6						
total (ha)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

With,
sunf = sunflower, toma = tomato, sugb = sugar beet
R0 = rainfed irrigation, R1= surface irrigation, R2= sprinkler irrigation
R3= drip irrigation
I0 = rainfed, I1= first level of supplemental irrigation, I2= second level of supplemental irrigation, I3= full irrigation
M0 and M1 = no management, M2= medium management, M3= high level of management.

Figure 39. Crop areas at different water prices

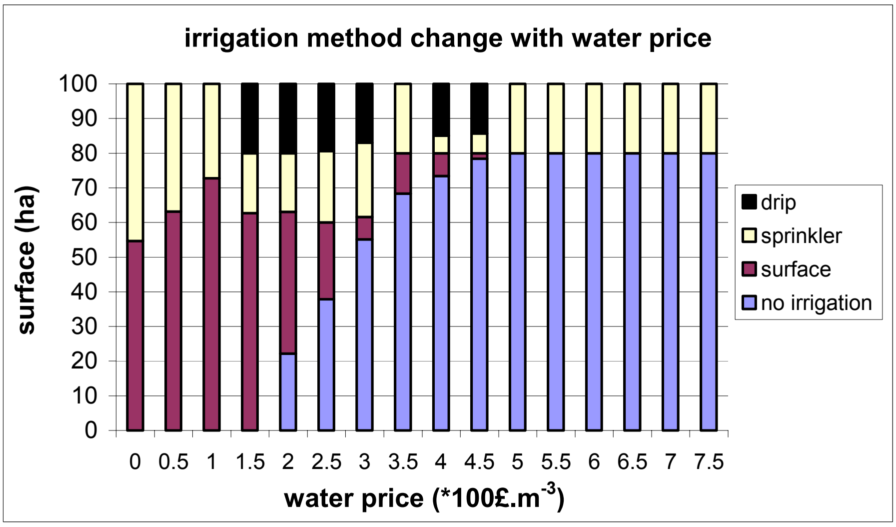


B. Techniques, methods and irrigation management levels

Variation in methods, techniques and levels of management of irrigation is presented after observation of the cropping pattern variation.

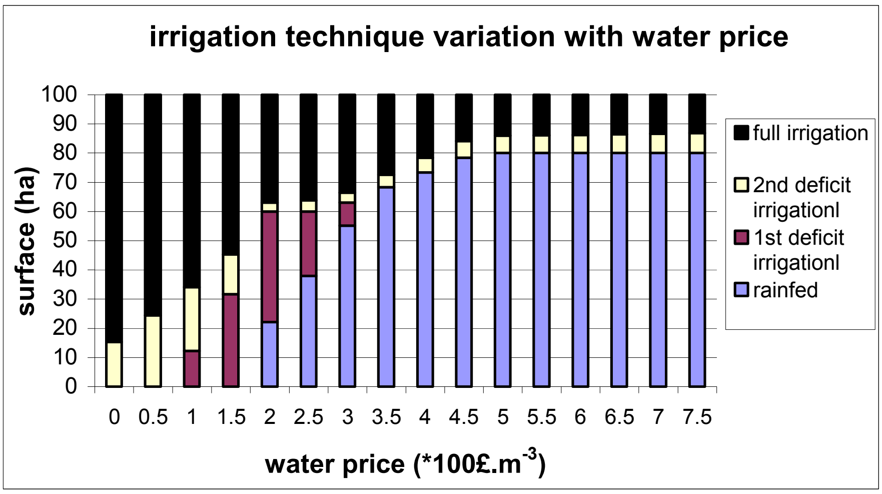
The variation of the irrigation method with the variation of water price is shown in Figure 40. It is expressed as the total area occupied by each method. Initially, the two dominant methods were surface and sprinkler irrigation because of their lower costs in terms of equipment. As the price of water rises, surface irrigation disappears and drip irrigation and rainfed conditions appear until there are finally only rainfed conditions (80% of the land) and sprinkler irrigation (20%). Drip irrigation disappears because of its high implementation cost.

Figure 40. Variation of irrigation method with water price



In irrigation techniques (Figure 41), it can be seen that the initial 85% full irrigation decreased to 13%. The first level of deficit irrigation appeared for a while from price level Lit 100 per m^{-3} to Lit 300 per m^{-3} and then disappeared. The second level of deficit irrigation was used more than the first but on a very small area varying from around 20 ha with low water prices to less than 5 ha for higher water prices. Rainfed conditions were absent at the beginning but reached 80% from water price Lit 450 per m^{-3} until the end.

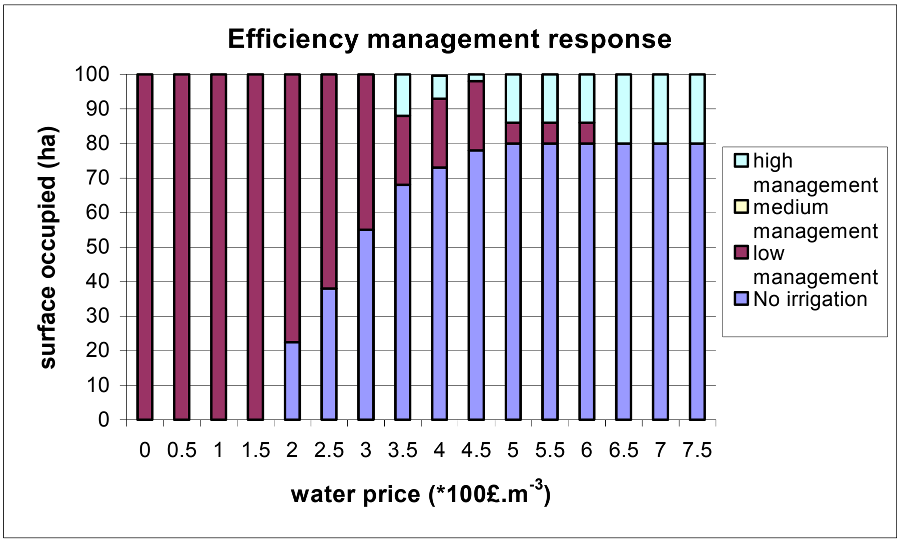
Figure 41. Variation in irrigation technique with water price



The variations in irrigation methods and techniques are caused not only by changes in water prices but also in cropping patterns; this is also related to yields and rotation constraints.

Variation in management efficiency variation with rising water prices is shown in Figure 42. Low management level is dominant initially but gradually disappears with higher prices. Use of the high level of management efficiency begins when the water price reaches Lit 350 per m^{-3}.

Figure 42. Variation in management efficiency with increasing water prices

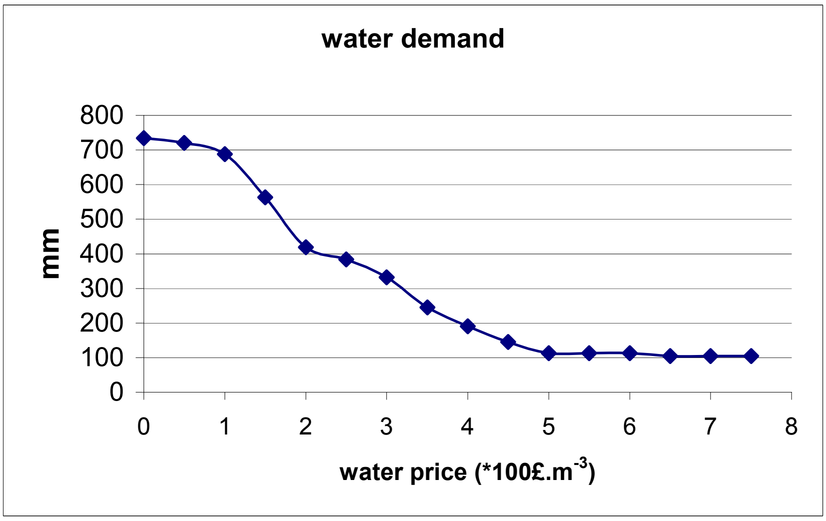


C. Water consumption and weighted efficiency

The water consumption corresponding to each cropping pattern and thus to each water price is shown in Figure 43. In this figure, water is calculated in mm, corresponding to the average for the entire area. Consumption varies between 734 mm with free water and 113 mm at Lit 500 per m^{-3}. The curve is in three parts:

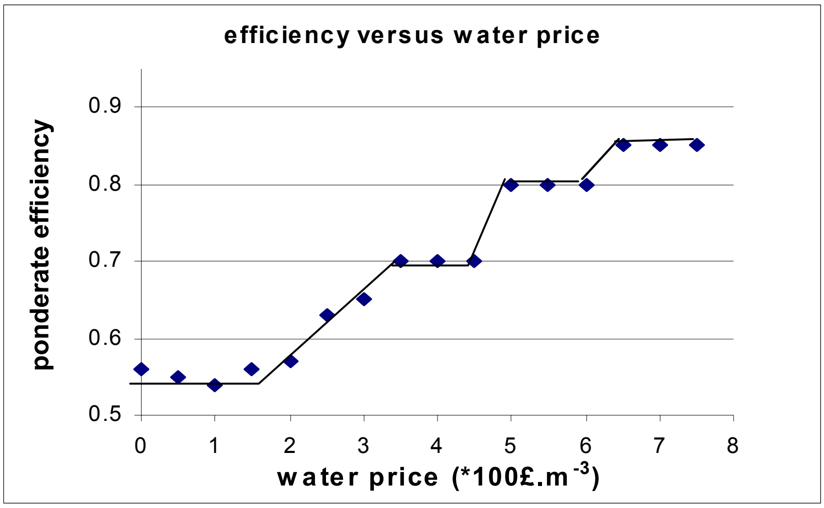
- the first part has little elasticity, with a slow decrease (for the first 3 iterations, which means from free water to Lit 150 per m^{-3});
- the decrease is stronger in the second part, representing higher elasticity, to a water price of Lit 450 per m^{-3};
- the last part, from Lit 500 per m^{-3}, is inelastic. Water consumption remains constant even with an increasing water price. This is due to the fact, that this water is used for tomato, which gives a high return.

Figure 43. The response of water consumption to water price increase



After introduction of the different levels of management with different efficiency levels, the weighted efficiency has been calculated for all the land for each cropping pattern and technique of irrigation and thus for each water price level. The results shown in Figure 44 show that efficiency changes from 54% to 85%. It increases with the increase in water price because farmers change from a low level of management to a higher level in order to save water that is becoming expensive.

Figure 44. Variation of weighted efficiency with water price.

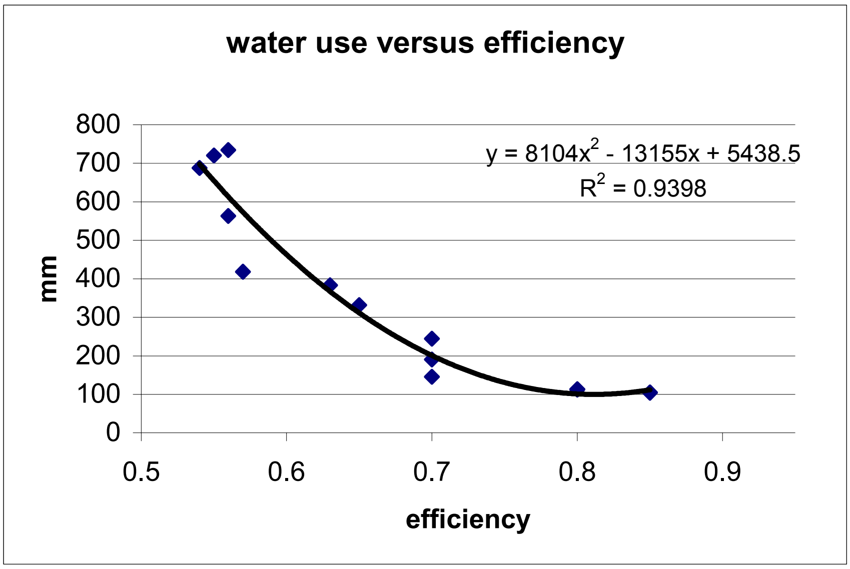


However, it can be seen that this increase in efficiency is not constant but stepwise. Furthermore, the more the water price increases, the smaller the step, indicating that each subsequent increase of efficiency requires an increasingly higher water price. In other words, further improvement of efficiency when it is already in the high range requires a smaller water price increase than improving efficiency when it is in the low range.

For example, with efficiency of about 0.55, the water price can vary from 0 to Lit 100 per m^{-3} without any significant change in efficiency. To increase the efficiency of one unit in the 0.55 – 0.7 range, the water price must be increased by Lit 166 per m^{-3}, while to increase the efficiency of one unit in the range of 0.7 – 0.8, the water price has to increase by about Lit 100 per m^{-3} and by about Lit 50 per m^{-3} in 0.8 – 0.9 range.

After calculation of the weighted efficiency for the whole area, Figure 45 below shows the relationship between water consumption and weighted efficiency. This curve decreases with high correlation (r^2=0.9398), explaining why water consumption decreases significantly with rising efficiency.

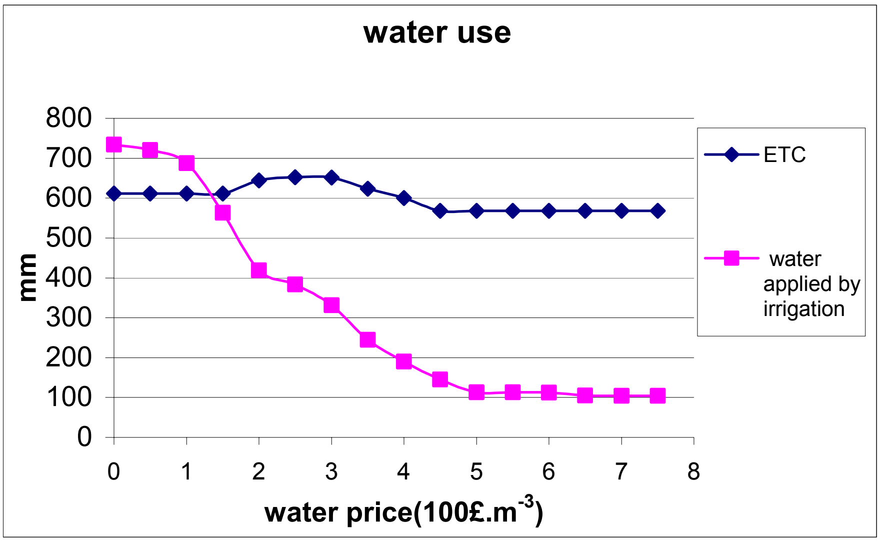
Figure 45. Water use response to increased efficiency



D. Biomass production and water consumption

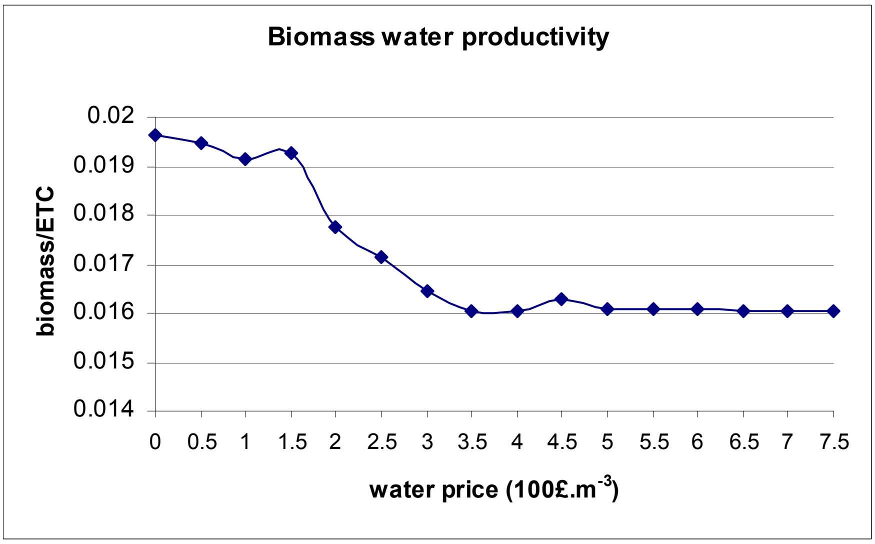
Annual evapotranspiration (ETc) on the 100-ha farm (according to different crop areas) and the water applied by irrigation are compared in Figure 46 as water prices change. When the water price is still low, it can be seen that the irrigation volume is higher than crop ETc and that irrigation volume decreases as the price of water increases. Crop water consumption (ETc) does not change very much. There is a little increase when the price of water reaches Lit 200 per m^{-3} as a result of the cultivation of sugar beet, which has a relatively long cycle and high water requirements. It then decreases when the price of water reaches Lit 350 per m^{-3} because wheat requires less water than sugar beet. The application volume is the same as crop requirements when the price is about Lit 150 m^{-3}.

Figure 46. Annual ETc and the variation in irrigation water applied to the entire 100-ha area according to variation of the price of water



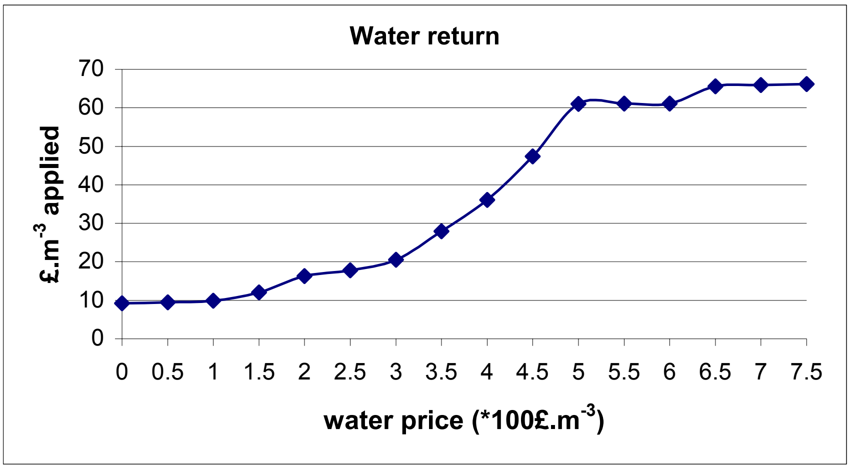
When the overall biomass (weighted by the overall ETc) is plotted against the price of water, it can be seen that biomass decreases against this price when the latter increases (Figure 47). This results from wheat cultivation under rainfed conditions as the crop has comparatively lower biomass production than the other irrigated crops used at the beginning when the price of water was still low.

Figure 47. Biomass water productivity variation of the entire 100-ha farm according to variation of the price of water



The return per unit of water applied is shown for the entire farm in Figure 48. It is the return per additional unit of irrigation water in terms of yield multiplied by the price of each crop. The return per water unit is initially low, and begins to increase as the price of water rises. The return per unit of water becomes significantly high when the price of water price exceeds Lit 300 per m^{-3}. This is because with higher water prices, cash crops such as tomato are introduced on the cropping pattern whereas wheat, for example, is only cultivated under rainfed conditions. However, when the price of water exceeds Lit 500 per m^{-3}, the curve for the return per unit of water applied becomes flatter.

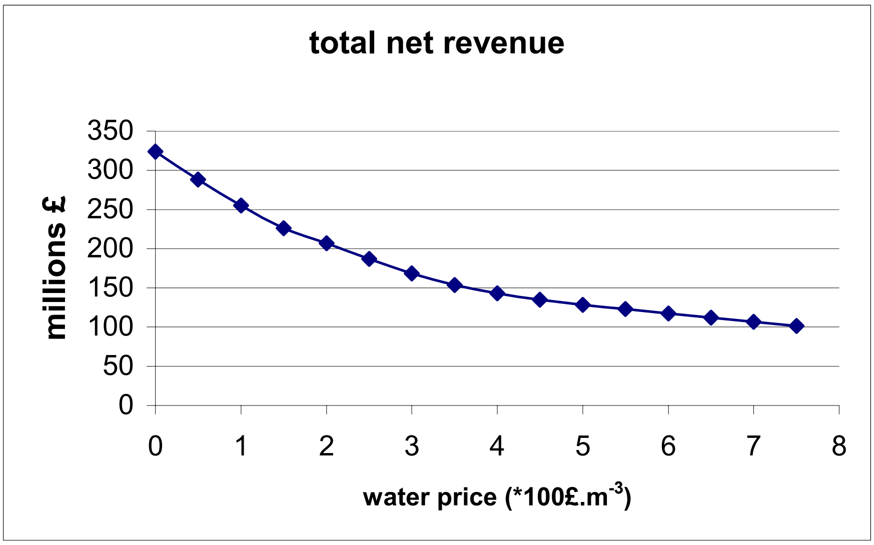
Figure 48. Return on water for the whole 100-ha farm according to variation of the price of water



E. Net income

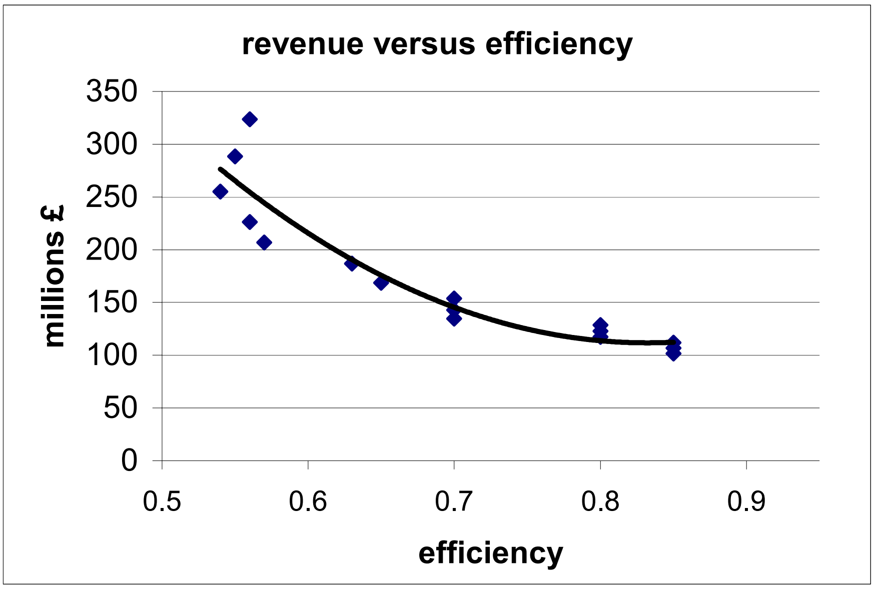
The results show a decreasing response in the farmer's net income with the increase in the price of water; the curve (Figure 49) shows a certain elasticity with regard to price variation. The curve is downward and flattening. The net income decreases from Lit 3.24 million per ha^{-1} to Lit 1.02 million per ha^{-1}, a decrease in income of about 65%.

Figure 49. Total net income in relation to the increase in the price of water



The relation between the farmer's net income and area-weighted efficiency is shown in Figure 50. This figure shows that with an increase in efficiency from around 55% to 85%, income decreased to a third (from Lit 3.2 million to Lit 1 million). At the beginning of the water price increase, when the price is still lower that the current pricing (lower than Lit 200 per ha^{-1}), it can be seen that there is no significant change in efficiency (decrease from 56% to 54% in weighted efficiency) with the decrease in income; this is because the technique changes with no effect on efficiency (the farmer decides to change from full to deficit irrigation levels without trying to increase the level of management efficiency). It should be specified here that the costs of management (and the related efficiency) were estimated because no data was available to relate equipment and operations to efficiency. However, the results show why high management efficiency levels should not be used unless the price of water is very high.

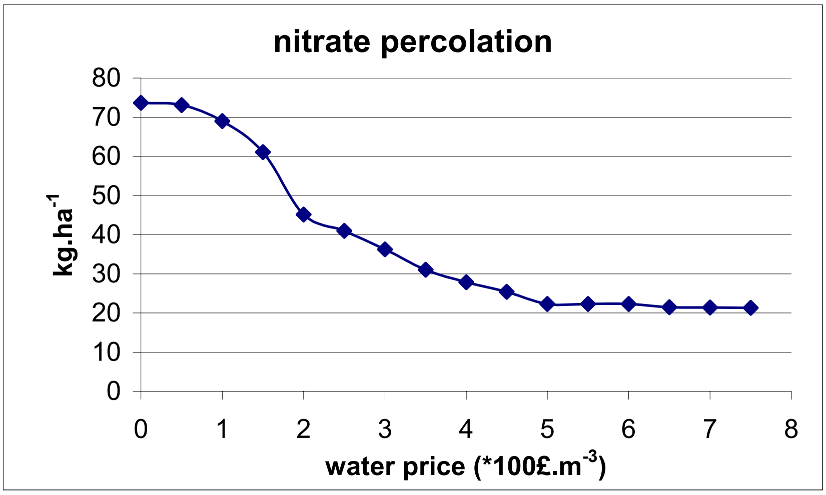
Figure 50. The relationship between increasing efficiency and net income at farm level.



F. Nitrate pollution

Represented in the same way as water consumption, the nitrate pollution occurring with each level of water pricing and each related optimal solution given by the model gave the results shown in Figure 51. It is seen that this curve has the same shape as that of water consumption response (Figure 43). Percolation varies between 73.6 $kg.ha^{-1}$ with free irrigation water to 22.3 $kg.ha^{-1}$ with water at Lit 500 per m^{-3} and then remains constant.

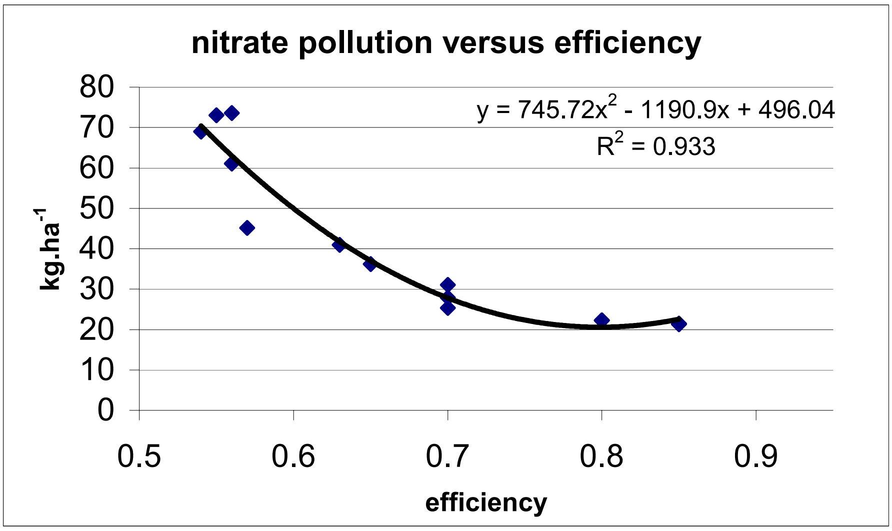
Figure 51. The nitrate percolation response of the entire farm to water price increase



This graph displays the same falling curve in three parts, the first with low elasticity, the second with high elasticity and the third totally inelastic.

Figure 52 represents the nitrate pollution level against weighted efficiency for the entire farm. This curve, which has a downward slope, with a high 0.933 correlation, highlights the results of the agronomic model, i.e. a decrease in nitrate percolation with increasing efficiency. This shows the importance of increasing application efficiency of application, thus encouraging high irrigation management efficiency to reduce the environmental impact.

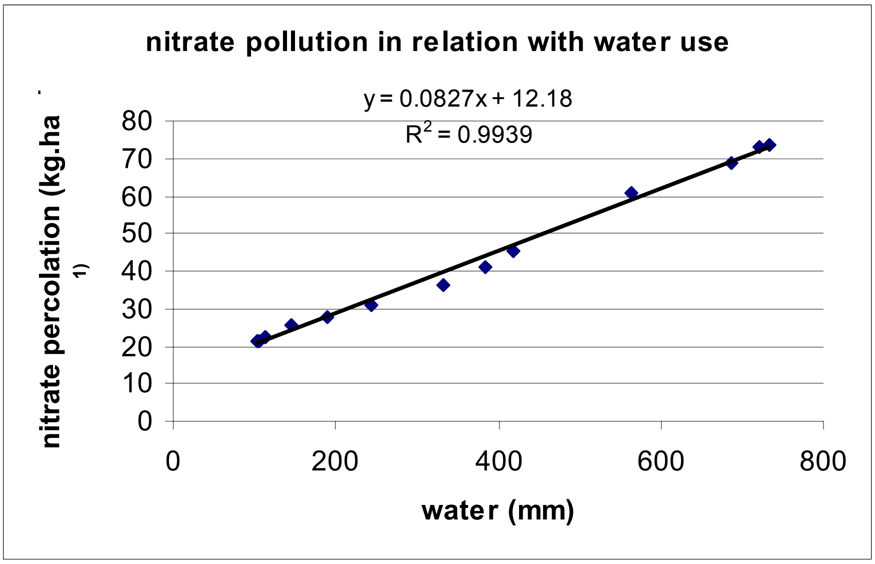
Figure 52. The response of nitrate pollution to increased efficiency



Percolation decreases significantly when efficiency starts to increase, but total nitrate leaching increases only very slightly from about 80% onwards. This shows that efficiency must be increased to achieve very low nitrate leaching and that reducing pollution is more difficult at high levels of efficiency.

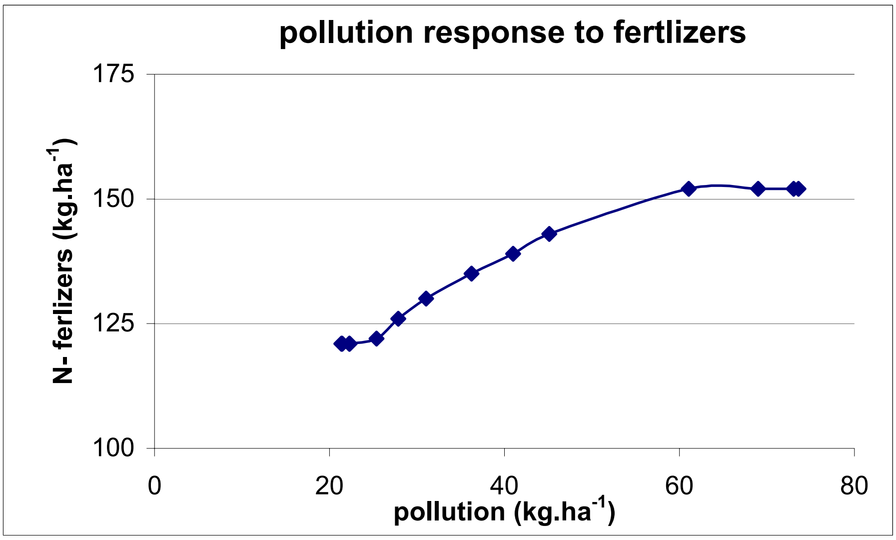
As water consumption and nitrate pollution have the same response to efficiency with water price variation, water use is related to nitrate percolation in Figure 53. The curve is steep and upward with high correlation (r^2=0.99). This also confirms the results of the agronomic model, in which percolation generally increased as water application increased.

Figure 53. Nitrate pollution in relation to water use



By analogy, calculating the amount of fertiliser applied in each iteration gave Figure 54. It represents the amount of fertiliser applied to the whole farm and the associated nitrate pollution. This demonstrates that nitrate pollution also increases with the increase in fertiliser application.

Fig 54. Nitrate pollution response to fertiliser application

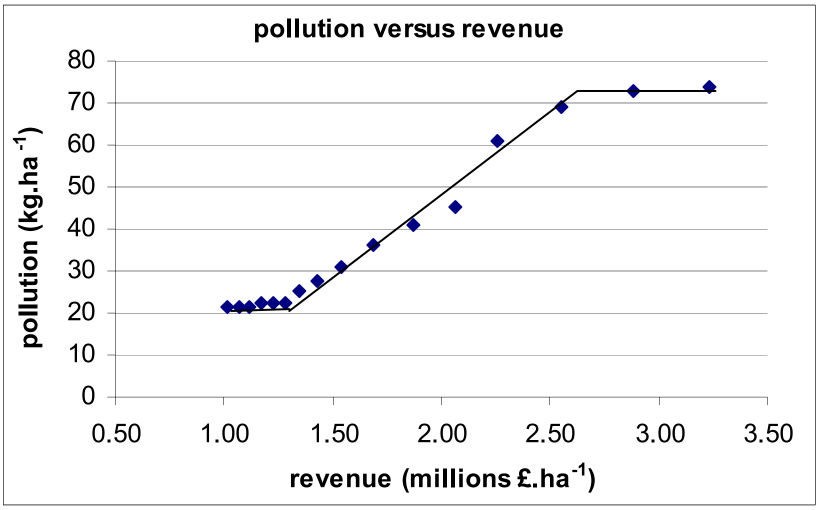


G. Pollution and income

The relationship between income and pollution level (Figure 55) is in three parts. Two plateaux can be seen at very high and very low incomes, with and increasingly steep slope between the two. This shows that under the management conditions of the farm, 20 kg.ha^{-1} nitrate leached cannot be further decreased. Likewise, 70 kg.ha^{-1} gives the highest pollution achievable with the highest income.

In fact, a range of points exists between the two levels in which policy makers could specify the level of pollution desired and the related farmer's income. It is observed that reducing the pollution level by 50% (from 73kg.ha^{-1} to 36 kg.ha^{-1}) reduces income by about 48% and the price of water should be increased to Lit 300 per m^{-3}. The social cost of this reduction is evaluated at Lit 557,000 per ha^{-1}, calculated as the losses incurred by the farmer minus the difference in the income of the water agency or consortium. The social cost is used to compare the three policies. It is a simplified calculation because it takes into consideration the losses and the gains of the economic agents, such as the water agency and the farmer, but it does not include the overall losses and gains of all the economic agents of society. To reduce this pollution by 40% (from 73 kg.ha^{-1} to 45 kg.ha^{-1}), the farmer's income falls by 36% (from Lit 3.24 million per ha^{-1} to Lit 2.07 million per .ha^{-1}), the price of water is Lit 200 per m^{-3} and the social cost is about Lit 333,000 per ha^{-1}, representing 16% of the farmer's income. To reduce pollution by 20% (from 73.6 kg.ha^{-1} to 61 kg.ha^{-1}), the farmer's income is decreased by about 30% and the social cost is Lit 136,000 per ha^{-1}, representing 6% of the farmer's income. In comparison with the real price, and assuming that it is weighted to about Lit 200 per m^{-3} to reduce pollution by 25% (from 45 to 33 kg.ha^{-1}), the price of water should be increased from Lit 200 to 300 per m^{-3}, with a decrease in the farmer's income from Lit 2.06 to 1.68 million per ha^{-1} and a social cost of about Lit 223,000 per ha^{-1}. To reduce pollution by 40% (from 45 to 28 kg.ha^{-1}), the price should be increased from Lit 200 m^{-3} to Lit 400 per m^{-3} and the farmer's income reduced by 26% (from Lit 2.06 million per ha^{-1} to Lit 1.53 million per ha^{-1}). The social cost of this reduction is estimated to be Lit 600,000 per ha^{-1}. In comparison with real block-rate pricing, the 40% reduction (from 56 to 33 kg.ha^{-1}) in nitrate pollution leads to a social cost of Lit 690,000 per ha^{-1}. To reduce this pollution by 50%, starting with the present situation, the price should be increased to Lit 500 per m^{-3}. This reduces pollution from 45 to 22.4 kg.ha^{-1}, the farmer's income decreases from Lit 2.06 to 1.28 million per ha^{-1} and the social cost is very high at about Lit 1,051,000 per ha^{-1}, representing about 50% of the farmer's income.

Figure 55. Pollution level response to net income



2. High management incentives

Simulations were performed, including subsidies for the equipment for improving management and using the real water pricing system, to encourage the use of high management efficiency that generally reduces nitrate pollution. Thus, 50% of the management cost was covered by a subsidy (Table 10). Under these conditions, the net income is higher, water consumption is lower, nitrate pollution is slightly lower (from 56 to 50 kg.ha^{-1}) and efficiency increases slightly (from 67% to 70%). This shows that the cost of management is very high comparison with the cost of equipment and the price of water. This is one of the reasons why this equipment and methods are not used by the farmers in practice.

Here, the cost of reducing pollution is not paid by the farmer. It is covered by a subsidy of about Lit 244,000 per ha^{-1}, forming 10% of the farmer's net income. The social cost is Lit 114,000 per ha^{-1}, calculated as the difference between the subsidy and the change in the farmer's income.

Table 10. The effect of decreasing the management cost

	real	50% subsidies
income (Lit million per ha^{-1})	2.24	2.37
water applied (mm)	448	364
pollution (kg.ha^{-1})	56	50
crops (ha)		
wheat.R1.I1.M1		11.3
wheat.R2.I2.M1	60	48.7
toma.R2.I2.M1	4.6	4.6
toma.R2.I3.M1	15.4	
toma.R2.I3.M3		15.4
sugb.R2.I1.M3	5.8	7.6
sugb.R1.I2.M3		5.6
sugb.R1.I3.M3	14.2	6.8
total area (ha)	100	100
weighted efficiency	0.67	0.7

With,
Toma = tomato, Sugb = sugar beet
R1= surface irrigation, R2= sprinkler irrigation
I1= first level of supplemental irrigation, I2= second level of supplemental irrigation, I3= full irrigation
M1 = no management, M3= high level of management.

As has been noted, the second management efficiency level (M2) was not present in the previous simulations. But with a subsidy of Lit 300,000 per ha^{-1} as an incentive for the use of the two levels of management (M2 and M3), pollution is reduced by about 20 % (43.7 kg.ha^{-1}) and efficiency increased to 78%. To reach a higher level of efficiency (81%) and some 40% reduction in pollution (33.8 kg.ha^{-1}), the subsidy for the use of high management efficiency (M3) reached Lit 370,000 per ha^{-1}, which is 15% of the farmer's net income of the farmer, and the social cost is Lit 170,000 per ha^{-1}, which is 7% of the farmer's income. For a 30% reduction, the social cost is Lit 97,000 per ha^{-1}, representing 4% of the farmer's income. These results and the cropping pattern variation are shown in Table 11.

Table 11. Results of the application of subsidies on high levels of irrigation management

Subsidies (Lit 1000 per ha^{-1})	**M2 = 200**	**M2 = 200**	**M2 = 200**	**M2 = 300**
	M3 = 370	**M3 = 350**	**M3 = 300**	**M3 = 300**
Income (Lit million per	2.44	2.42	2.37	2.38
Water demand (mm)	311	318	342	360
Pollution (kg.ha^{-1})	33.8	35	40	43.7
Pollution reduction	40 %	37.5 %	30 %	20 %
Social cost (Lit 1000 per	170	151	97	160
Crops (ha)				
Wheat.R1.I1.M3	59.1	54.1	40.4	12.9
Wheat.R2.I2.M1		5.4	19.6	
Wheat.R2.I2.M2				47.1
Wheat.R2.I2.M3	0.9			
Toma.R2.I2.M1			4.5	
Toma.R2.I2.M3	4.5	4.5		
Toma.R2.I2.M2				4.5
Toma.R2.I3.M3	15.5	15.5	15.5	15.5
Sugb.R1.I3.M3	13.2	13.2	13.2	13.1
Sugb.R2.I1.M3	6.8	6.8	6.8	6.9
Total	100	100	100	100
Weighted efficiency	0.81	0.77	0.77	0.78

With,
Toma = tomato, Sugb = sugar beet
R1= surface irrigation, R2= sprinkler irrigation
I1= first level of supplemental irrigation, I2= second level of supplemental irrigation, I3= full irrigation
M1 = no management, M2= medium level of management, M3= high level of management.

3. Taxes on N fertiliser

Another way to reduce pollution is to tax the inputs that generally lead to this pollution (Figure 54). Simulations were performed with a per-kg tax on nitrogen fertiliser. The results are presented in Table 12. The social cost is calculated in this case as the difference between the taxes and the loss in the farmer's income. With this policy, reducing nitrate percolation by 15% from 56 kg.ha^{-1} to 47.8 kg.ha^{-1}, the farmer's income is reduced by about 35% (from Lit 2.24 million per ha^{-1} to Lit 1.45 million per ha^{-1}) and the social cost is Lit 31,000 per ha^{-1}. Reducing pollution by about 25% (from 56 kg.ha^{-1} to 42 kg.ha^{-1}) results in farmer's losses of about 35% (from Lit 2.24 million ha^{-1} to Lit 1.44 million per ha^{-1}), social cost of about Lit 130,000 per ha^{-1} and the taxes of Lit 5,900 per kg^{-1} N (the price of this fertiliser is of about Lit 450 per ha^{-1}). To reduce the pollution by 40% (from 56 to 32.6 kg.ha^{-1}), the tax is Lit 6,100 per kg^{-1} N applied, income decreases by about 36% and the social cost is Lit 285,000 per ha^{-1}, representing 20 % of the farmer's net income.

Table 12. The results of the application of taxes on nitrogen fertiliser

Taxes (Lit per kg N)	0	5800	5900	6100
Income(Lit million per	2.24	1.45	1.44	1.42
Water (mm)	448	358	325	273
Pollution (kg.ha^{-1})	56	47.8	42	32.6
Pollution reduction		15%	25%	40%
Total taxes (Lit 1000	0	759	670	535
Social cost(Lit 1000 per		31	130	285
Crops (ha)				
Wheat.R1.I1.M1		6.9	2	
Wheat.R2.I2.M1	60	39.9	30.2	10.8
Toma. R2.I2.M1	4.6	4.8	4.8	4.8
Toma. R2.I3.M1	15.4	15.2	15.2	15.2
Sugb.R1.I3.M3	14.2			
Sugb.R2.I1.M3	5.8	10.3	10.4	10.5
Sugb.R2.I2.M1		6.6	6.5	6.5
Sugb.R2.I3.M1		3.1	3.1	3

With,
Toma = tomato, Sugb = sugar beet
R1= surface irrigation, R2= sprinkler irrigation
I1= first level of supplemental irrigation, I2= second level of supplemental irrigation, I3= full irrigation
M1 = no management, M3= high level of management.

4. Comparison of the policies

After analysis of each policy individually, the social cost of these policies is now analysed for purposes of comparison. This is shown in Table 13 in terms of percentage of reduction of nitrate pollution and the social cost associated with each policy.

The social costs were calculated as the difference between the losses and the gains of the different economic agents of society as a result of the implementation of each policy.

It can be seen that for a 40% reduction of pollution, the policy of increasing the price of water has a social cost of Lit 600,000 per ha^{-1}, the subsidy policy for the use of high management efficiency has a social cost of Lit 170,000 per ha^{-1} while tax on the use of nitrogen fertilisers has a social cost of Lit 285,000 per ha^{-1}. The subsidies for efficiency have the lowest cost. In addition, other costs—those of the implementation and control costs of different policies—should be taken into consideration.

Table 13. Comparison of policies for reducing nitrate pollution

	Pollution reduction (%)	**Social cost (Lit 1000 per ha^{-1})**
Increasing price	20.0	136
	40.0	600
	50.0	566
Subsidies	30.0	97
	37.5	151
	40.0	170
Taxes on N	15.0	31
	25.0	130
	40.0	285

However, the effectiveness of the implementation of each policy should be taken into account. Water pricing and taxes are easy to implement but less well accepted by farmers. The subsidy policy is better accepted by farmers but more difficult to control. The combination of more than one policy (such as the price of water and subsidies or taxes) is worth analysing as it may give better results. This could be the subject of further studies.

This can show the importance of the introduction of high irrigation efficiency levels for the reduction of nitrate pollution. However, the problem is that the relationship between the improvement of efficiency and the associated operation and equipment is uncertain because of the lack of studies on this particular issue.

Conclusion

The methodological approach combining agronomic and economic models, made it possible to analyse the environmental impact (nitrate pollution) of agricultural production. It therefore enabled the analysis of the effect of different policies on the reduction of this pollution.

The agronomic model (EPIC) was used to simulate crop response to climate, irrigation scheduling and fertilisation in terms of yield and nitrate leaching. The simulations demonstrated that the yield increases with an increase in the application of irrigation water and with a decrease in irrigation efficiency management. Nitrate leaching increases with increasing water application and with decreasing levels of irrigation management efficiency management.

These outputs, in addition to economic inputs such as the costs and prices of different activities were introduced in a positive economic model written in GAMS language. This simulated farmers' response to different agricultural policies analysed.

Three agricultural policies were analysed: irrigation water pricing, the subsidies awarded for on the use of high levels of management efficiency and taxes on nitrogen fertilisers.

The theoretical social cost was calculated to compare these three policies. The social cost of a 40% decrease in nitrate pollution was 333,000 lire.ha^{-1} for the water pricing policy, 285,000 lire.ha^{-1} for the application of taxes on fertilisers and 170,000 lire.ha^{-1} for subsidies for high management efficiency. This showed that the subsidies had the lowest social cost, followed by taxes, and finally by the price of water price, without there being a large difference between the last two. However, it should specified that these are theoretical costs, to which must be added the control and the implementation costs for the application of each policy. Implementation effectiveness should also be taken into account because the taxes and water pricing of water are fairly easily applied and controlled but are not readily accepted by farmers. Subsidies for good management may be better accepted by farmers but implementation and control of the results are more difficult.

These results show that increasing irrigation efficiency leads to a reduction in nitrate pollution with a relatively low social cost. However, the assumptions made concerning the operations and equipment used for achieving each level of management efficiency should not be neglected because the relationships between the improvement of efficiency and the associated costs (operations and equipment) are uncertain. This remains a weak point that requires further studies to define the real costs of increasing management efficiency and to define what operations and equipment could actually lead to increasing this efficiency.

This is a simplified approach in which only field crops were studied with a single environmental impact (nitrate pollution). Further studies can be developed with the study of other environmental impacts or other possible agricultural policies.

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Annex

Operations and equipment used for achieving medium and high levels of irrigation efficiency management for each crop, methods and technique of irrigation

Crop	Method	Management	technique	operations and equipments used
wheat	surface	medium	1st deficit irrigation	10 water markers/ha 5 days of expert consultations/total surface 20 partial flumes /ha
			2nd deficit irrigation	10 water markers/ha 10 days of expert consultations/total surface 20 partial flumes /ha
		high	1st deficit irrigation	land levelling 20 water markers/ha 10 days of expert consultations/total surface 40 partial flumes /ha
			2nd deficit irrigation	land levelling 20 water markers/ha 20 days of expert consultations/total surface 40 partial flumes /ha
	sprinkler	medium	1st deficit irrigation	10 water markers/ha 2 days of expert consultations/total surface 1 water meter/large machine
			2nd deficit irrigation	10 water markers/ha 4 days of expert consultations/total surface 1 water meter/large machine
			full irrigation	10 water markers/ha 10 days of expert consultations/total surface 1 water meter/large machine
		high	1st deficit irrigation	20 water markers/ha 5 days of expert consultations/total surface 1 water meter/large machine
			2nd deficit irrigation	20 water markers/ha 10 days of expert consultations/total surface 1 water meter/large machine
			full irrigation	20 water markers/ha 20 days of expert consultations/total surface 1 water meter/large machine
sunflower and sorghum	surface	medium	1st deficit irrigation	10 water markers/ha 5 days of expert consultations/total surface 20 partial flumes /ha
			2nd deficit irrigation	10 water markers/ha 10 days of expert consultations/total surface 20 partial flumes /ha
			full irrigation	10 water markers/ha 20 days of expert consultations/total surface 20 partial flumes /ha
		high	1st deficit irrigation	land levelling 20 water markers/ha 10 days of expert consultations/total surface 40 partial flumes /ha
			2nd deficit irrigation	land levelling 20 water markers/ha 20 days of expert consultations/total surface 40 partial flumes /ha
			full irrigation	land levelling 20 water markers/ha 40 days of expert consultations/total surface 40 partial flumes /ha
	sprinkler	medium	1st deficit irrigation	10 water markers/ha 2 days of expert consultations/total surface 1 water meter/large machine
			2nd deficit irrigation	10 water markers/ha 4 days of expert consultations/total surface 1 water meter/large machine
			full irrigation	10 water markers/ha 10 days of expert consultations/total surface 1 water meter/large machine

Crop	Method	Management	technique	operations and equipments used
sunflower and sorghum	sprinkler	high	1st deficit irrigation	20 water markers/ha 5 days of expert consultations/total surface 1 water meter/large machine
			2nd deficit irrigation	20 water markers/ha 10 days of expert consultations/total surface 1 water meter/large machine
			full irrigation	20 water markers/ha 20 days of expert consultations/total surface 1 water meter/large machine
	drip	medium	1st deficit irrigation	10 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 6 days of expert consultation/total surface
			2nd deficit irrigation	10 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 10 days of expert consultation/total surface
			full irrigation	10 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 20 days of expert consultation/total surface
		high	1st deficit irrigation	20 water markers/ha 20 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 8 days of expert consultation/total surface 1 electronic programmer/total surface
			2nd deficit irrigation	20 water markers/ha 20 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 12 days of expert consultation/total surface 1 electronic programmer/total surface
			full irrigation	20 water markers/ha 20 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 20 days of expert consultation/total surface 1 electronic programmer/total surface a agro-meteo-station/total surface

Crop	Method	Management	technique	operations and equipments used
tomato	surface	medium	1st deficit irrigation	30 partial flumes/ha 30 water markers/ha 15 days of expert consultation/total surface
			2nd deficit irrigation	30 partial flumes/ha 30 water markers/ha 20 days of expert consultation/total surface
			full irrigation	30 partial flumes/ha 30 water markers/ha 30 days of expert consultation/total surface
		high	1st deficit irrigation	land levelling 40 partial flumes/ha 40 water markers/ha 20 days of expert consultation/total surface
			2nd deficit irrigation	land levelling 40 partial flumes/ha 40 water markers/ha 30 days of expert consultation/total surface
			full irrigation	land levelling 40 partial flumes/ha 40 water markers/ha 40 days of expert consultation/total surface
	sprinkler	medium	1st deficit irrigation	30 water meters/ha 1 water meter/large machine 6 days of expert consultation/total surface
			2nd deficit irrigation	30 water meters/ha 1 water meter/large machine 12 days of expert consultation/total surface
			full irrigation	30 water meters/ha 1 water meter/large machine 20 days of expert consultation/total surface
		high	1st deficit irrigation	40 water meters/ha 1 water meter/large machine 10 days of expert consultation/total surface
			2nd deficit irrigation	40 water meters/ha 1 water meter/large machine 15 days of expert consultation/total surface
			full irrigation	40 water meters/ha 1 water meter/large machine 25 days of expert consultation/total surface
	drip	medium	1st deficit irrigation	30 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 8 days of expert consultation/total surface
			2nd deficit irrigation	30 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 12 days of expert consultation/total surface
			full irrigation	30 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 20 days of expert consultation/total surface

Crop	Method	Management	technique	operations and equipments used
tomato	drip	high	1st deficit irrigation	40 water markers/ha 15 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 15 manometers/ha 1 water meter/ha 12 days of expert consultation/total surface 1 electronic programmer/total surface
			2nd deficit irrigation	40 water markers/ha 15 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 15 manometers/ha 1 water meter/ha 18 days of expert consultation/total surface 1 electronic programmer/total surface
			full irrigation	40 water markers/ha 15 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 15 manometers/ha 1 water meter/ha 25 days of expert consultation/total surface 1 electronic programmer/total surface 1 agro-meteo station/total surface
sugar beet	surface	medium	1st deficit irrigation	20 partial flumes/ha 20 water markers/ha 15 days of expert consultation/total surface
			2nd deficit irrigation	20 partial flumes/ha 20 water markers/ha 20 days of expert consultation/total surface
			full irrigation	20 partial flumes/ha 20 water markers/ha 30 days of expert consultation/total surface
		high	1st deficit irrigation	land levelling 30 partial flumes/ha 30 water markers/ha 20 days of expert consultation/total surface
			2nd deficit irrigation	land levelling 30 partial flumes/ha 30 water markers/ha 30 days of expert consultation/total surface
			full irrigation	land levelling 30 partial flumes/ha 30 water markers/ha 40 days of expert consultation/total surface
	sprinkler	medium	1st deficit irrigation	30 water meters/ha 1 water meter/large machine 6 days of expert consultation/total surface
			2nd deficit irrigation	30 water meters/ha 1 water meter/large machine 12 days of expert consultation/total surface
			full irrigation	30 water meters/ha 1 water meter/large machine 20 days of expert consultation/total surface
		high	1st deficit irrigation	40 water meters/ha 1 water meter/large machine 10 days of expert consultation/total surface
			2nd deficit irrigation	40 water meters/ha 1 water meter/large machine 15 days of expert consultation/total surface
			full irrigation	40 water meters/ha 1 water meter/large machine 25 days of expert consultation/total surface

Crop	Method	Management	technique	operations and equipments used
sugar beet	drip	medium	1st deficit irrigation	30 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 8 days of expert consultation/total surface
			2nd deficit irrigation	30 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 12 days of expert consultation/total surface
			full irrigation	30 water markers/ha 10 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 10 manometers/ha 1 water meter/ha 20 days of expert consultation/total surface
		high	1st deficit irrigation	40 water markers/ha 15 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 15 manometers/ha 1 water meter/ha 12 days of expert consultation/total surface 1 electronic programmer/total surface
			2nd deficit irrigation	40 water markers/ha 15 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 15 manometers/ha 1 water meter/ha 18 days of expert consultation/total surface 1 electronic programmer/total surface
			full irrigation	40 water markers/ha 15 tensiometers/ha 5 pressure regulators/ha 5 volumetric valves/ha 15 manometers/ha 1 water meter/ha 25 days of expert consultation/total surface 1 electronic programmer/total surface 1 agro-meteo station/total surface

Annexes

Règles pour l'attribution du prix annuel de la meilleure thèse du CIHEAM

Article 1
Il est institué un prix annuel de la meilleure thèse du CIHEAM.

Article 2
En vue de décerner ce prix, la première sélection est opérée par le directeur de chaque institut, qui choisit les deux meilleures thèses soutenues durant l'année civile écoulée, réalisées dans son institut ou en coopération avec une institution nationale associée, et les transmet au Secrétariat Général avec une brève note explicative sur les motifs du choix

La deuxième étape de sélection est confiée à un jury composé des membres du Comité Scientifique Consultatif qui classe les thèses par ordre de mérite selon une évaluation chiffrée :

- 50 % pour la valeur scientifique du travail,
- 25 % pour son originalité et applicabilité,
- 25 % pour son caractère exemplaire dans le domaine de la coopération méditerranéenne.

La notation se fera jusqu'au deuxième chiffre après la virgule.

Article 3
Après délibération à huis clos des membres du jury, une proposition est transmise au Secrétaire Général qui la soumet au Conseil d'Administration pour agrément.

Article 4
Le prix consiste en un voyage d'études, un séjour dans un laboratoire ou la participation à un congrès ou à un séminaire.

Il sera déterminé d'un commun accord entre le Secrétaire Général, le(s) directeur(s) des instituts concernés et

Ce prix est destiné à encourager le(s) lauréat(e)(s) dans la poursuite de ses(leurs) recherches et ne pourra, en aucun cas, consister en l'attribution d'une somme d'argent correspondant au montant du séjour proposé.

La réalisation du prix devra se faire dans l'année (douze mois) qui suit son attribution, faute de quoi, ce droit cessera.

Article 5
Tous les candidats recevront une attestation sous forme de lettre du Président du Comité Scientifique Consultatif reconnaissant la qualité de leur travail et le fait qu'il a été proposé à l'obtention du prix de thèse du CIHEAM.

Liste des thèses ayant obtenu le prix du CIHEAM depuis 1994

Année	Nom	Pays d'origine	IAM	Sujet
1994	M. Pandeli **Pasko**	Albanie	Saragosse	A study on pepper resistence to potato virus and Y (PVY).
1994	M. Myrta **Arben**	Albanie	Bari	Sanitary status of plum, peach and apricot in Albania and characterization of some Albanian plum pox virus isolates.
1995	M. Zeramdini **Hamda**	Tunisie	Bari	Sanitary status of almond and apricot in Tunisia and use of high sensitive techniques for the detection of plum pox potyvirus (PPV).
1996	Melle Nihal **Buzkan**	Turquie	Bari	Use of PCR for the diagnosis and epidemiology of grapevine trichoviruses.
1997	M. Karim **Jerate**	Maroc	Bari	Impact de l'irrigation par des eaux usées épurées par infiltration, percolation et par épuvalisation sur une culture d'œillet sous serre.
1997	M. Frej **Chemak**	Tunisie	Montpellier	Aide à la décision au niveau d'un périmètre irrigué : essai de mise en œuvre des concepts des modèles multi-agents.
1998	Melle Ibtissam **El Hilali**	Maroc	Chania	Evaluation of the genetic diversity in *Salvia Fruticosa* clones from Crete, using RAPD markers.
1999	M. Antoine **Harfouche**	Liban	Chania	Identification of Randomly Amplified Polymorphic DNA (RAPD) markers associated with crown form in common cypress.
2000	M. Habib **Yahyaoui**	Tunisie	Saragosse	Le polymorphisme génétique chez les caprins. Etude de la bêta lactoglobuline, de la caséine kappa et de la stéaroyl coenzyme A désaturase.
2001	Melle Joséphine **Semaan**	Liban	Bari Montpellier	Un modèle bio-économique pour l'analyse des politiques en conditions de pénurie d'eau et de pollution par les nitrates. Etude de cas : une région irriguée du sud de l'Italie.