Peña Haro, S.; Llopis Albert, C.; Pulido-Velazquez, M.; Pulido Velázquez, D. (2010). Fertilizer standards for controlling groundwater nitrate pollution from agriculture: El Salobral-Los Llanos case study, Spain. Journal of Hydrology. 392(3-4):174-187. doi:10.1016/j.jhydrol.2010.08.006.

Fertilizer standards for controlling groundwater nitrate pollution from agriculture: El Salobral-Los Llanos case study, Spain.

Peña-Haro, S.[a], Llopis-Albert C.[b], Pulido-Velazquez, M.[b], Pulido-Velazquez, D.[c]

[a]*Institute of Environmental Engineering, ETH Zurich, HIL G33.3, Wolfgang-Paulistrasse 15, CH-8093 Zurich, Switzerland. Email: pena@ifu.baug.ethz.ch*

[b]*Department of Hydraulics and Environmental Engineering, Universidad Politécnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain.*

[C]*Instituto Geológico y Minero de España (IGME)*

Abstract: This paper applies a ~~new~~ hydro-economic modeling framework to an aquifer, El Salobral-Los Llanos aquifer (Mancha Oriental, Spain), where nitrate concentrations higher than those allowed by the WFD are locally found due to the intense fertilizer use in irrigated crops. Although the legislation on groundwater quality refers to the pollutant concentration, the effects of most measures on groundwater quality are often evaluated in terms of their emission reduction potential at the source, not on their capacity of reducing the pollutant concentration in groundwater. The approach presented in this paper allows defining the economically optimal allocation of spatially variable fertilizer standards in agricultural watersheds using a hydro-economic model that links the fertilizer application with the groundwater nitrate concentration at different control sites while maximizing the net benefits. The methodology incorporates results from agronomic simulations, groundwater flow and transport into a management framework that yields the fertilizer allocation that maximizes the benefits in agriculture while meeting the environmental standards. The cost of applying fertilizer standards was estimated as the difference between the private net revenues from actual application and the scenarios generated considering the application of the standards. Furthermore, the cost of applying fertilizer standards was compared with the cost of applying taxes to fertilizer in order to reduce the fertilizer use to a level that the nitrate concentration in groundwater was below the limit.

This work aims to help application of the EU Water Framework Directive and the Groundwater Directive.

Key words: groundwater, nitrate pollution, fertilizer standards, optimization, management.

INTRODUCTION

In the last 25 years, an important transformation from dry to irrigated lands has taken place in La Mancha, a vast region located in central Spain. This transformation has promoted the development of an intensive agriculture that, nowadays, represents one of the main factors in the economic development of the region. In La Mancha Oriental System (MOS), more than 80,000 ha of irrigated lands equipped with modern technologies are currently settled, regarded as one of the most important in Spain, with most of these lands depending on the availability of groundwater (Ferrer and Gullón., 2004, López-Fuster, 2000). Water extraction, which has steadily increased since the 1980s, together with the intense period of drought experienced in recent years, has resulted in a continued fall of water table levels in the different subzones, with environmental consequences, such as the drying up of an important section of the Júcar River in the summers of 1994 and 1995 (Estrela et al., 2004, López-Fuster, 2000). An intense social, economic, political and environmental debate among farmers the administration and other stakeholders are currently trying to establish a sustainable management for the MOS. Despite confrontations derived from different points of view, all these sectors are convinced of the necessity to preserve such a valuable natural resource as water, especially in this area characterized by a Mediterranean-continental, semi-arid climate (Sanz et al., 2009). Furthermore, the River Basin Authority (CHJ, Confederación Hidrográfica del Júcar) has made public offers to buy water rights from farmers (to stop pumping) in order to protect the river downstream users. The Mancha

Oriental System (MOS) is part of the Jucar River Basin which was declared as EU Pilot Basin in 2002 for the implementation of the Water Framework Directive.

Another big concern in the area is the increase in nitrate pollution due to the increase of intensive farming and fertilizer use; the nitrate concentrations have reached values of 125 mg/l (Moratalla et al, 2009). An accurate quantification of nitrate leaching to groundwater is hampered owing to uncertainties in land use practices, on-ground nitrogen loading, groundwater recharge, climate, soil nitrogen dynamics and soil characteristics.

Economic theory mentions different control mechanisms of externalities but these instruments cannot be readily implemented nor can their efficacy be promptly assessed (Shortle and Dunn, 1986). Policy mechanisms for agricultural non-point pollution control include direct regulations (i.e. standards on the amount and use of potential pollutants and production practices) and pricing policy like taxes or subsidies. Taxes and subsidies can be applied directly to the polluting emissions (‘‘effluent’’ taxes or subsidies) or based on some emission proxies like polluting inputs or certain agricultural practices (‘‘influent’’ taxes or subsidies). Much less used are other economic incentives like tradable permits and contracts (Hahn, 2000).

Policy directives and corresponding administrations are calling for tools to aid in sustainable water management and for operational monitoring systems to assist in planning and control of water resources. This tool helps farmers to apply fertilizer according to the actual crop requirements and also to the EU standards, thus optimizing production and cost-effectiveness.

This paper is intended to validate in a real aquifer a new methodology, which was already presented for a 2D synthetic case (Peña-Haro et al., 2009). The methodology was applied to the aquifer El Salobral-Los Llanos Domain (SLD), which is located in the south of the MOS. The methodology allows obtaining the optimal fertilizer allocation that maximizes the welfare from crop production subjected to certain environmental constraints. This will allow establishing good agricultural practices, presenting a series of preventive measures, with regard to fertilizer allocation, to comply with the European Directive. The objective of this study is to evaluate standards in fertilizer application for nonpoint pollution control. The analysis focuses on nitrate pollution from irrigation, and the goal is to find the best allocation for fertilizer application. The framework incorporates an agronomic model to estimate nitrate leaching and a flow and transport model. Fate and transport of pollutants in groundwater systems should always be taken into account when designing optimal agricultural policies. The sustainable exploitation of water resources requires methods and modeling frameworks that allow the incorporation of a great number of spatial and temporal variables in the decisions.

This research aims to contribute to the ongoing policy process in the European Union (the Water Framework Directive and the Groundwater Directive) by analyzing the cost of measures for reducing nitrogen loadings and their effectiveness on maintaining groundwater nitrate concentration within the target levels, as part of the programme of measures to meet the WFD’s standards. Furthermore, this tool can help farmers to apply fertilizer according to the actual crop requirements and also to the EU standards, thus optimizing production and cost-effectiveness. In (semi)arid regions groundwater is a strategic resource both for population and for humid areas. People depend on groundwater resources for drinking purpose.

STUDY AREA

The methodology was applied to “El Salobral-Los Llanos Domain” (SLD) which is located in the southeast of the Mancha Oriental System and extends over about 420 km^2 (Figure 1). The SLD contains a total population of about 5,000 inhabitants. According to the information from 2004 (CHJ, 2004) 80% of the land is agriculture (337 km^2), from which 100 km^2 are irrigated crops.

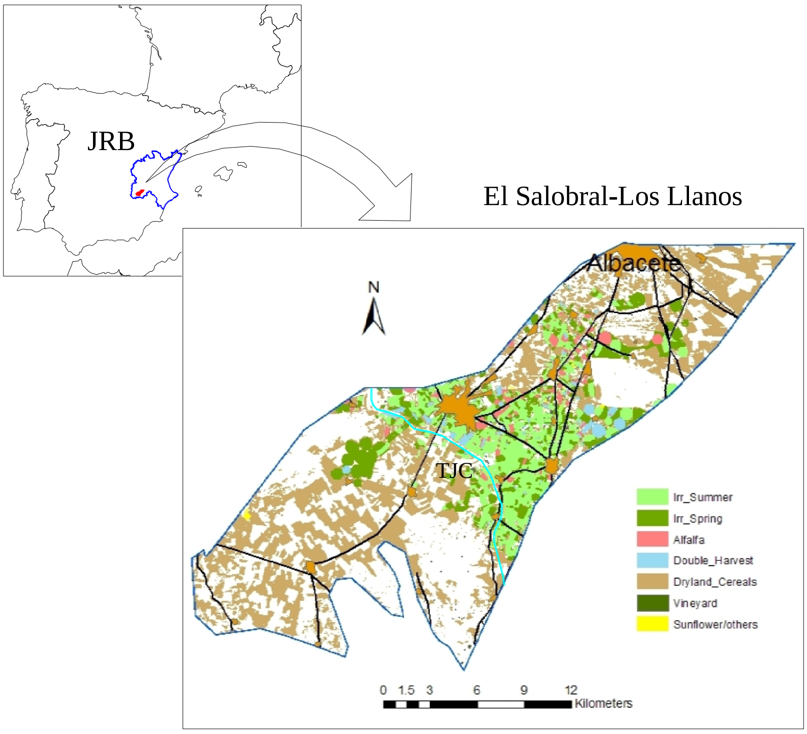

Figure 1. Study area location.

The climate of Castilla-La Mancha can be defined as appropriate of a Mediterranean climate, with continental degradation, noticeable fluctuations in daily and seasonal temperatures, an unequal distribution of scant rains, dry summers and precipitations in spring and autumn. The mean summer temperature is about 22°C and the mean winter temperature is about 6°C, the average annual temperatures vary between 13°C and 14.5°C. The mean annual precipitation is about 360 mm. The average groundwater recharge is estimated in 165 mm/year (CHJ, 2008).

The concentration of irrigated crops has induced negative environmental and economic impacts in the area, since the groundwater table has decreased from 60 to 80 meters in the period 1970 to 2002, with an average decrease of about 2.5 to 3 meters per year. The development of the irrigated crops has also led to significant consequences for regional groundwater flow and high nitrate concentrations in the groundwater. The irrigated area in 1961 was about 29.4 km^2 (Spanish Geological Survey, IGME, 1976); in 2004, the irrigated surface area increased to 100 km^2. The maximum groundwater nitrate concentrations in 1971 were about 29 mg/l and in 2005 of 54. 1mg/l. The highest nitrate concentrations are located in the middle part of the aquifer where the irrigated agriculture is located (Moratalla et al., 2009). The bad quality of the groundwater forced to close some drinking water wells in 2003, which were substituted by surface water from the Alarcon reservoir, in the Jucar River (UCLM, 2006). The reduction in groundwater withdrawal had a positive impact in the aquifer by reducing groundwater demand in some 8 Mm^3/yr. In 2001, some irrigations wells were closed representing 15 Mm^3/yr, water that was taken from a derivation from the Tajo-Segura transfer channel. This reduction in groundwater withdrawal has reduced the groundwater level lowering in the zone. A pumping wells substitution we are dealing with an overdrafted aquifer, which does not meet the good groundwater quantitative status as stated in the WFD. The highest nitrate concentration, within El Salobral-Los Llanos, was recorded in the well named El Salobral with 54.1 mg/l (Moratalla et al., 2009), exceeding the allowed concentration for human consumption of 50 mg/l (Drinking water directive, 80/778/EEC). All these facts ended up with the declaration of the aquifer as a nitrate vulnerable area by the Castilla-La Mancha regional government (DOCM, 1998).

El Salobral-Los llanos aquifer is formed mainly by 2 units. The deepest one is constituted by mid Jurassic dolostones and limestones that can reach 250 m in thickness. This unit has a mean transmissivity of 10,000 m^2/day (Sanz, 2005). A detrital aquitard overlies it and reaches a maximum thickness of about 75 m. El Salobral-Los Llanos domain is limited by low permeability boundaries which do not allow the lateral inflow of groundwater from/to the neighbouring domains.

MODELING APPROACH

In order to find the optimal fertilizer reductions that maximize the private net revenue from crop production subject to the constraints in groundwater nitrate concentration, a management modelling framework has been developed for the case study. Private net revenue was calculated through crop production functions and data on crops, nitrogen and water prices as explained in Peña-Haro et al (2009). In these framework, groundwater flow and nitrate transport are included into the management model using concentration responses matrices, and the crop response to changes in water and fertilizer with quadratic functions.

The modelling framework can be divided into four basic steps. The first one is the estimation of the temporal and spatial distribution of on-ground nitrogen loads and the resulting groundwater nitrate concentration; second, the simulation of the crop-soil nitrogen dynamics to obtain quadratic functions representing the nitrate leached and the crop yield as a function of the water and the fertilizer applied; third, modelling of nitrate transport in groundwater to obtain nitrate concentrations; and the last one comprises the calculation of the optimal fertilizer by means of benefit maximization while complying with the quality standards. With this modelling framework is possible to link the on-ground loadings with the nitrate concentrations in groundwater, as well to estimate the costs of the different measures through crop production variations.

On-ground nitrogen loads in El Salobral-Los Llanos

The identification of the state and dynamics of crops was obtained from multi-temporal image sequences of high spatial resolution. This information was collected from the ERMOT project (Calera et al., 1999, 2003; CHJ, 2006). The images are available from 1982 to 2005. In 2005 the main crops where corn, wheat, barley and onion (Figure 1).

Agronomic simulation

The crop yield as well as the nitrate leaching were estimated with GEPIC (Liu et al., 2007), a GIS-based crop growth model integrating a bio-physical EPIC model (Environmental Policy Integrated Climate) (Williams, 1995) with a GIS to simulate the spatial and temporal dynamics of the major processes of the soil-crop-atmosphere-management systems. The GEPIC package simulates crop growth using local conditions on climate, soil, irrigation water, tillage and other operations. EPIC considerers nitrate losses in leaching, surface runoff and lateral subsurface flow. The transformations considered in the soil are denitrification, mineralization, immobilization, nitrification and volatilization, it also considerers as an input the N contribution from rainfall (Figure 2). Denitrification is a function of temperature and water content. The model considers two sources of mineralization: fresh organic N pool, associated with crop residue and microbial biomass, and the stable organic N pool associated with the soil humus. The daily amount of immobilization is computed by subtracting the amount of N contained in the crop residue from the amount assimilated by the microorganisms. Nitrification is estimated using the first-order kinetic rate equation. Volatilization of surface-applied ammonia is estimated as a function of temperature and wind speed. Depth of ammonia within the soil, cation exchange capacity of the soil, and soil temperature are used in estimating below surface volatilization. Nitrate leaching is simulated by using an exponential function to describe the decrease in nitrate concentration caused by water flowing through a soil layer.

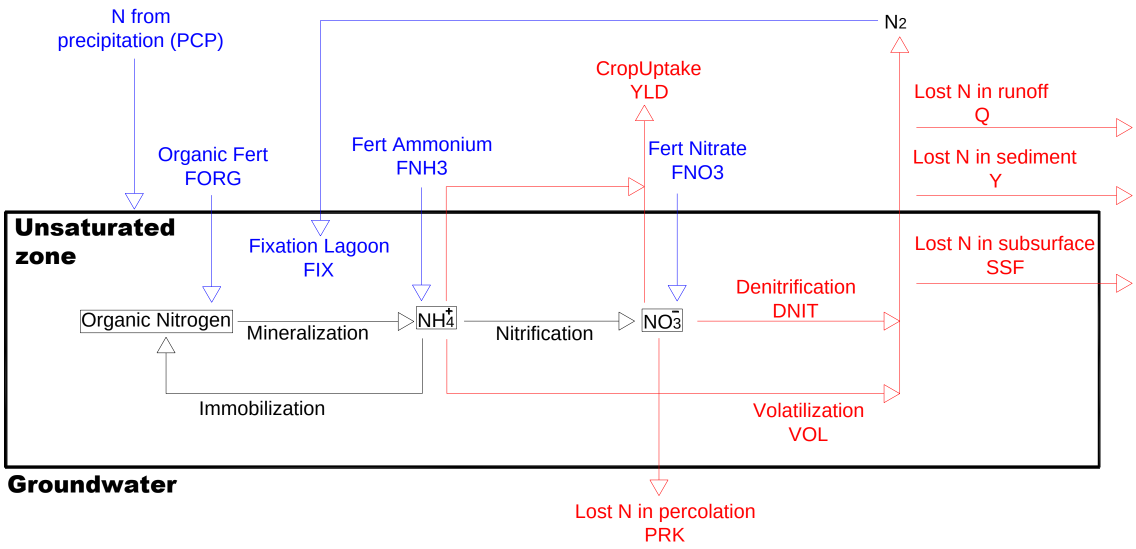

Figure 2. Nitrogen balance in EPIC

The crop yield, required to estimate the crop benefits was calculated through production function (Peña-Haro et al., 2010b) according to the following polynomial equation, calibrated with the values simulated with the EPIC package:

$$Y_{s,y} = a + b \cdot W_{s,y} + c \cdot W_{s,y}^2 + d \cdot N_{s,y} + e \cdot N_{s,y}^2 + f \cdot W_{s,y} \cdot N_{s,y}$$

where $Y_{s,y}$ is the crop yield located at source s for a year y (kg/ha), $W_{s,y}$ is the water applied to the crop located at source s (m^3/ha) and $N_{s,y}$ is the fertilizer applied to the crop located at source s (kg/ha) within the year y.

The amount of nitrogen leached was introduced into the management model as quadratic functions as follows:

$$L_{s,y} = g + h \cdot W_{s,y} + i \cdot W_{s,y}^2 + j \cdot N_{s,y} + k \cdot N_{s,y}^2 + l \cdot W_{s,y} \cdot N_{s,y}$$

where $L_{s,y}$ is the nitrogen leached (kg/ha), $W_{s,y}$ is the water applied to the crop located at source s (m^3/ha) with in the year y, and $N_{s,y}$ is the fertilizer applied to the crop located at source s (kg/ha).

Several simulation were done to obtain different values of yield and leaching for different applications of water and fertilizer, then a regression analysis was performed to obtain the coefficients of the quadratic functions (Table 1 and 2).

Table 1. Coefficients for the production functions

Crop	**a**	**b**	**c**	**d**	**e**	**f**
Wheat	8.53e+02	1.50e+01	-2.30E-02	4.66E+01	-1.32E-01	-1.90E-02
Corn	2.91E+02	2.24E+01	-1.80E-02	3.43E+01	-6.60E-02	1.10E-02
Barley	1.84E+03	4.31E+00	-1.10E-02	4.23E+01	-1.39E-01	1.40E-02
Alfalfa	-1.89E-12	2.72E+01	-1.40E-02	2.45E+02	-1.28E+00	-1.62E-01
Onion	2.31E+04	1.71E+02	-3.05E-01	-1.6E-07	-8.45E-01	7.34E-01

Table 2. Coefficients for the leaching functions

Crop	**g**	**h**	**i**	**j**	**k**	**l**
Wheat	-2.28E+01	2.05E-01	-2.46E-04	1.97E-01	8.13E-04	-5.31E-04
Corn	-5.95E+00	8.30E-02	-9.82E-05	1.90E-02	6.66E-06	4.93E-04
Barley	3.40E+00	8.30E-02	-2.27E-04	-2.10E-02	5.23E-04	7.52E-04
Alfalfa	-1.07E-09	2.70E-02	-1.89E-05	-2.67E-01	6.00E-03	1.84E-04
Onion	-1.03E+01	4.50E-01	-2.76E-05	9.25E-09	4.51E-04	2.73E-04

A difficulty inherent in simulation models is that coefficients and processes must be calibrated to reflect local conditions. Such calibration is essential as it ensures that results are applicable to the region of interest. Proper calibration of EPIC is complicated by a lack of data on nitrate leaching and the parameters that represent the related processes. EPIC parameters regarding nitrogen leaching were difficult to calibrate and a big uncertainty is present; however, the results of nitrate leached are consistent with some values reported in literature (Martinez et al., 2004; Basso and Ritchie, 2005), while the yield (Table 5) was calibrated using data from the ITAP (ITAP, 2005, www.itap.es)

Groundwater flow and nitrate transport simulation

Solute transport and fate in groundwater depends on the velocity of groundwater flow, which can be obtained solving the groundwater flow equation for transient flow through a saturated anisotropic porous medium. The solute concentration throughout the aquifer can be described by the general equation for advective-dispersive transport, incorporating equilibrium-controlled sorption and first-order irreversible reactions.

The groundwater flow was modelled with MODFLOW (McDonald and Harbough, 1988). Two layers were considered, according to the geology, the deeper aquifer is where most of the water is withdrawn (Moratalla et al., 2009). The model was discretized into a finite-difference grid of 500 x 500m with 60 rows and 82 columns. It has monthly time steps from 1975 to 2005 starting from 1975 until 2005. The aquifer is bounded in all direction by low permeability conditions except for the northern one. The transmissivity and storage coefficients' distribution was obtained from Sanz (2005), although these values were further modified during the calibration process.

Transmissivity values are between 2,000 and 30,000 m^2/day while the storage is between 10^{-4} and 10^{-5}. The groundwater recharge due to rainfall was taken from CHJ (2008), with an average value of 7 Mm^3/year. The recharge values are homogenously distributed in five different areas. Another source of recharge is the superficial water used in irrigation taken from the Tajo-Segura channel; this recharge is only from 2001 due to the program to reduce groundwater extraction. The oldest piezometric data is from 1975, and it was considered that they represent the initial conditions~~,~~ of the system. The piezometric heads for 1975 are around 700 meters above sea level in the south-west part and 665 meters in the north-east, therefore original flow direction was from south-west to north-east. The groundwater withdrawal was taken from CHJ (2008) these values take into account the reduction in groundwater withdrawal in 2001 due to the closure of some boreholes. The water extraction from the aquifer in 2001 was about 58 Mm^3/year and in 2005, 30 Mm^3/year.

The model calibration involves determining the magnitude and spatial distribution of the model parameters, which reproduce the observed values. The piezometric head was calibrated using the information measured in 21 wells from 1975 to 2005, the hydraulic parameters were adjusted to fit these values, a good calibration was obtained. Not all of the 21 wells had information the whole period (Figure 3).

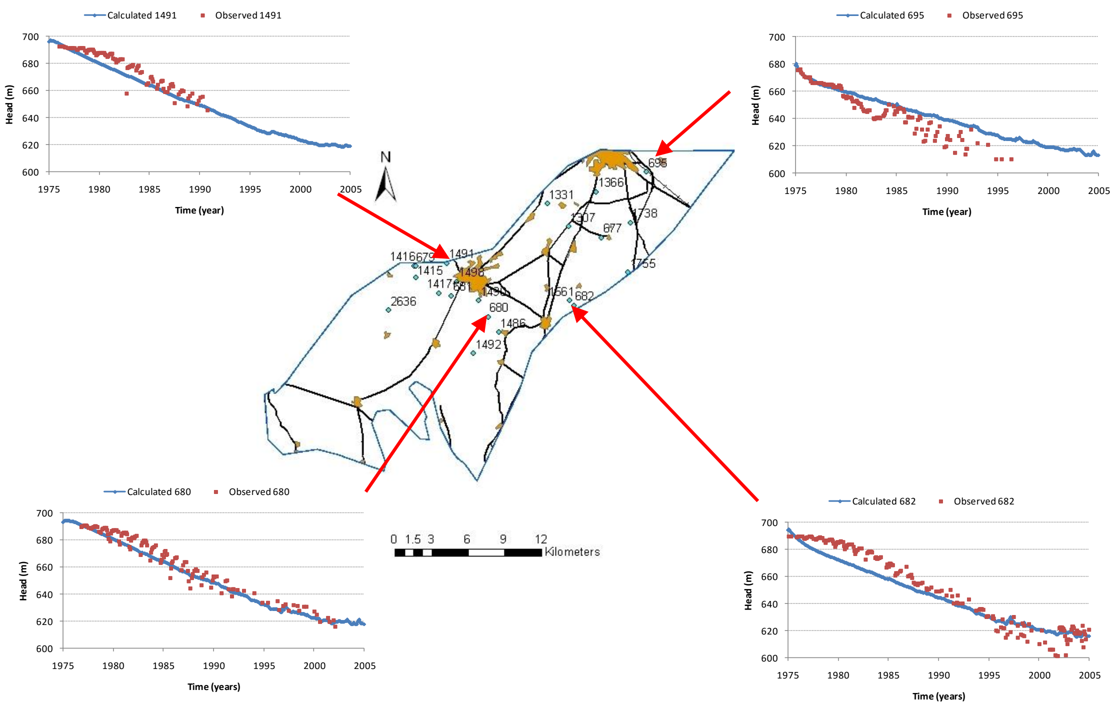

Figure 3. Groundwater model calibration

Nitrate fate and transport in groundwater was simulated using MT3DMS model (Zheng and Wang, 1999). This model interfaces directly with MODFLOW it retrieves the saturated thickness, fluxes across cell interfaces and the locations of flow rates of the various sources and sinks. It uses the same spatial and temporal discretization as MODFLOW. Few data is available to conduct a real calibration. For the transport model calibration the maximum values were calibrated shown in Figure 4.

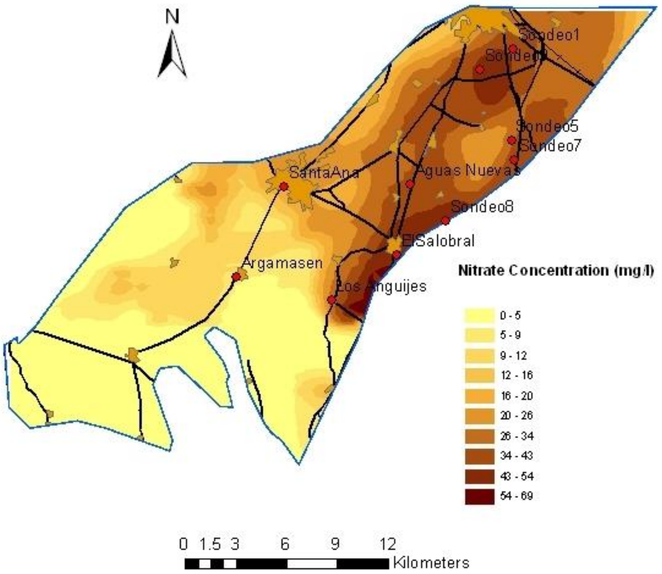

Figure 4. Simulated groundwater nitrate concentrations (year 2005) and control sites (red dots)

Optimal fertilizer standards.

In order to apply the hydro-economic model, the crop areas (pollution sources) have to be defined. These pollutant areas represent administrative zones where the fertilizer application will be subjected to standards. Two criteria were taken into account, the first one was the type of crop and the second the administrative distribution of the crop fields. There are around 150 administrative areas, but 11 main areas can be distinguished. These areas were taken as a starting point in defining the areas, which were subdivided taking into account the main crops in those areas and the information from remote sensing. The number of resulting areas was 24 (Figure 5).

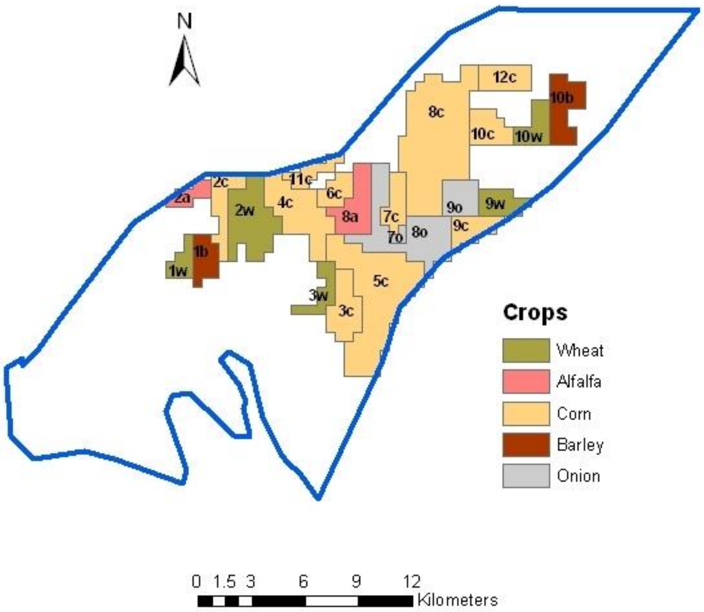

Figure 5. Crop aggregation

Table 3. Crop areas

Area	**Corn (ha)**	**Wheat (ha)**	**Barley (ha)**	**Onion (ha)**	**Alfalfa (ha)**	**Total (ha)**
1		271	331			602
2	463	849			232	1,544
3	519	280				799
4	736					736
5	1,750					1,750
6	296					296
7	366			75		441
8	1,990			1,142	553	3,685
9	245	406		195		846
10	391	345	414			1,151
11	326					326
12	450					450
TOTAL	7,533	2,151	745	1,412	784	12,626

The influence of the pollutant areas upon the concentration in groundwater at different control sites is represented in the model using a concentration response matrix. Once the control areas were defined, the concentration response matrix was developed considering a unitary fertilizer applications. The simulation time horizons were determined by the time for which the peak solute concentration completely passed the control sites for the most important crop areas. Note that the simulation was done until the year 2300. Breakthrough curves were obtained for each crop area (figure 5) and for the ten different control sites (Figure 4). The majority of the control sites correspond to current well fields for drinking water supply. Only control sites “sondeo 8” and “sondeo 9” are not supply wells, but are selected in order to control nitrate concentrations at different locations within the groundwater body. Each crop area has different influence over the different observation wells. Some of them have a very small influence upon the concentration in the control sites (like 11c, 10w, 10b and 2a). The ones that arrive the latest to the control sites are 1w and 1b, but also have a very small influence on the final nitrate concentration. In general the crop areas that have bigger influence are those located closer to the control sites “El Salobral” and “Sondeo 8”.

The dryland (rainfed crop land) was not taken into account as a decision variable; however, the corresponding nitrate loads had to be considered, as well as the initial concentration in the aquifer. This was by superposing the effects, including the influence of the dryland and the initial concentration upon the control sites, into the constraints. The initial formulation presented in Peña-Haro et al. (2009), was modified as follows:

$$Max\,\Pi = \sum_{s}\sum_{y}\frac{1}{(1+r)^{y}} A_s\left(p_s \cdot Y_{s,y} - p_n \cdot N_{s,y} - p_w \cdot W_{s,y} - C_s + S_s\right)$$

$$\text{s.t. } \sum_{s} RM_{c\times t,s\times y} \cdot cr_{s\times y} + DL_{c\times y} + IC_{c\times y} \leq q_{c\times y} \quad \forall c,t,y$$

where Π is the objective function to be maximized and represents the present value of the net benefit from agricultural production (€) defined as crop revenues minus fertilizer and water variable costs (other costs are not included); A_s is the area cultivated for crop located at source s; p_s is the crop price (€/kg); $Y_{s,y}$ is the production yield of crop located at source s at planning year y (kg/ha), that depends on the nitrogen fertilizer and irrigation water applied; p_n is the nitrogen price (€/kg); $N_{s,y}$ is the fertilizer applied to crop located at source s at year y (kg/ha), pw is the price of water (€/m^3), and $W_{s,y}$ is the water applied to crop located at source s at each planning year y (m^3); C_s is the aggregation of the remaining per hectare costs for crop located at source s (€/ha); S_s are the subsidies for the crop located at source s (€/ha); r is the annual discount rate, RM is the unitary pollutant concentration response matrix; q is a matrix of water quality standard imposed at the control sites over the simulation time (kg/m^3); cr is a matrix which corresponds to the nitrate concentration recharge (kg/m^3) reaching groundwater from a crop located at source s; $DL_{c,y}$ is the nitrate concentration at the control site $_c$ and the planning horizon $_y$ due to fertilizer application in dryland and $IC_{c,y}$ is the nitrate concentration at the control site c and the planning horizon y due to the initial nitrate concentrations in the aquifer.

The nitrate loads were estimated considering the dryland area of 2005 and a nitrate leaching rate of 20 kg/ha. The influence of the dryland upon the concentration at the observation wells is very low. The effect of the initial concentration corresponding to the state of the aquifer in 2005 also had to be taken into account.

Four scenarios were simulated in order to compare the groundwater nitrate concentrations that could be achieved under different fertilizer management options for the 50 year planning period.

Scenario 1. Business-as-usual. This scenario uses the N fertilizer rates that were used to calibrate the nitrate transport model to the observed conditions.

Scenario 2. Maximum benefits. This scenario uses the fertilizer applications that return the maximum net benefits at each crop were used.

Scenario 3. Reference values. The Mancha Oriental System has been declared “nitrate pollution vulnerable area”, and maximum values of fertilizer application have been published. This scenario simulates nitrate concentrations under these fertilizer application rates.

Scenario 4. Constrained optimal fertilizer application. This scenario considers the distribution of N fertilizer rates that yields the maximum aggregated net profit constrained to the groundwater nitrate concentration standards (50 mg/l) at the control wells.

Another important input to the model is the crop and fertilizer prices (Table 4) (ITAP, 2005, www.itap.es). The irrigation water applied was kept constant at the level where the crop yield is maximum, in order to keep the linearity of the problem (Table 4).

Table 4. Crop, irrigation and prices

Crop	**Applied irrigation water [1] (mm/year)**	**Crop price[1] (€/kg)**	**Fertilizer price[1] (€/kg)**	**Production costs[2] (€/ha)**	**Subsidies[2] (€/ha)**
Wheat	260	0.136	0.6	650.8	598.1
Corn	665	0.142	0.6	856.5	424.8
Barley	300	0.115	0.6	604.4	552.0
Alfalfa	900	0.138	0.6	1,051.1	0.0
Onion	650	0.700	0.6	4,204.4	0.0

[1] ITAP, Informacion historica 2005

[2] Ministerio de Medio Ambiente (2005). Costes del agua en la agricultura.

Scenario 1. Baseline or business-as-usual (BAU) scenario

This baseline scenario is intended to simulate nitrate concentrations in groundwater if the fertilizer rates of 2005 were maintained, i.e., to show the projected trends in nitrate concentration if the current crop management practices persist. These values are estimated through the calibration of the nitrate transport model. Table 5 compares the calibrated fertilizer rates with the fertilizer application rates reported by the local Agronomic Institute (ITAP). We have to consider that farmers often use N inputs higher than the recommended values, and sometimes even greater than what they actually report in the official surveys, as it has been proved using N balances (e.g., Ramos et al., 2002). In any case, the values estimated by calibration are subject to the inevitable uncertainties of the modeling process.

Nitrate leaching values (Table 5) are calculated through the nitrate leaching functions. In this scenario the nitrate concentrations will keep increasing on the control sites “El Salobral” reaching 72 mg/l and “Sondeo 8” up to 63 mg/l. Both control sites are located under the crop areas 5c and 8o, which are among the biggest sources of nitrate pollution. The nitrate evolution at the control sites “Santa Ana”, “Anguijes” and “Aguas Nuevas” shows an increasing trend, while the others seems to become stable. The WFD sets that good status has to be reached by 2015 by this year the maximum nitrate concentrations (Control site “El Salobral”) would be of about 60 mg/l. Nitrate concentrations at “Sondeo 8” will also overpass 55 mg/l. According to these results, the management in the BAU scenario would not be “sustainable” (for the EU standards) with regards to nitrate pollution. Regarding the economic results, the net benefits for the period amounts to 96.6 M€/year on average. This result will be later compared with those obtained for the other scenarios to valuate the opportunity cost (considered as benefit forgone) of imposing constraints on groundwater nitrate concentration.

Table 5. Fertilizer application and nitrate leaching. Scenario 1

Crop	**Actual fertilizer application (kg/ha)[1]**	**Nitrate leaching (kg/ha)**	**ITAP Fertilizer application. 2005 (kg/ha)[2]**
Corn	315	116	296
Wheat	160	44	144
Barley	165	52	124
Onion	285	94	216
Alfalfa	40	15	20

1 Values obtained from the calibration of the groundwater nitrate transport model

2 ITAP (2005). www.itap.es

Scenario 2. Maximum net benefits

In this scenario, the fertilizer application was optimized in order to maximize the total net benefits, without groundwater quality restrictions. The fertilizer loading rates (Table 6), these values are lower than the value reported in Table 5 referring to the current (calibrated) fertilizer rates (although quite similar for onions and alfalfa). With the required caution given the uncertainties and the lack of data, this tells us that farmers might be over-fertilizing their crops, which are in agreement with the finding of other authors (e.g., Ramos et al., 2002). With these applications the total net benefits amounts to 96.7 M€/year (quite close to the average values obtained in the BAU scenario). The maximum concentration goes up to 66.7 mg/l in “El Salobral” control site (Figure 8). The nitrate concentration in the control sites exhibits a very similar trend than in scenario 1, but with slightly lower values since less fertilizer is applied. Even though the nitrate concentrations are lower, the water quality objectives are not met making this scenario unsustainable for the EU environmental standards.

Table 6. Fertilizer application and nitrate leaching. Scenario 2

Crop	Maximum benefit fertilizer application (kg/ha)	Nitrate leaching (kg/ha)
Corn	283	105
Wheat	141	38
Barley	146	46
Onion	282	93
Alfalfa	39	14

Scenario 3. Reference values

The Mancha Oriental System has been defined as “nitrate pollution vulnerable area” in the DOCM “Diario Oficial de Castilla La Mancha” (DOCM, num 16 January 22nd, 2007), therefore reference values of fertilizer use there have been published (Table 7).

Table 7. Reference values for maximum nitrate fertilizer application (kg/ha) (DOCM, 2007)

Crop	Fertilizer application (kg/ha)
DryLand	
Barley	60
Wheat	70
Irrigation	
Barley	110
Corn	210
Wheat	110
Alfalfa	35
Onion	160

The maximum nitrate concentrations obtained with the reference values are shown in Figure 9 and 10. Even though the maximum nitrate concentrations are above 50 mg/l in the control sites “El Salobral” and “Sondeo 8”, given the high starting conditions they do not show an increasing trend. However, in order to reduce nitrate concentration below the 50 mg/l more reduction of fertilizer application would be necessary. For this scenario the net benefits average are 80.9 M€/year, a 16% less than the average net benefits for the BAU scenario.

Scenario 4. Constrained optimal fertilizer application

This scenario is intended to determine the optimal spatial distribution of fertilizer application over 50 years of planning horizon that meets the groundwater nitrate concentration limits by two time horizons: year 2015 (first deadline for the achievement of environmental objectives in the EU WFD) and year 2021 (which correspond to the second deadline, 6 years later) . To consider possible long-term effects of the 50 years of fertilizer application, nitrate transport in groundwater is simulated for more than 100 years.

Recovery time in year 2015

Figure 6 shows the results of the optimization referring to fertilizer application, reduction from actual use (Scenario 1, BAU) for the case in which groundwater nitrate concentrations below 50 mg/l are imposed beyond year 2015. 5c and 9c are the areas that need the biggest reduction. The area 5c has a big influence on the concentration of the control site “El Salobral”, as 9c has on the control site “Sondeo 8”, the one in which the highest concentrations are reached. 40 kg/ha is very low rate for corn, making this crop not very attractive for farmers. The total profits are 95.4 M€/year, only a 1.2% lower then scenario 1 (96.6 M€/year).

The nitrate concentrations at the control sites that results from applying the fertilizer shown in Figure 6 are depicted in Figure 8 and 9. The maximum values are below 50 mg/l. Note that the maximum concentrations are observed in control site “Sondeo 8”.

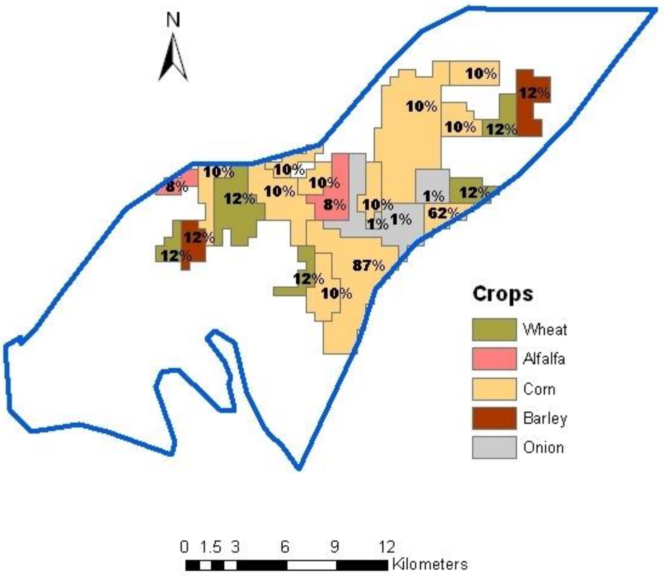

Figure 6. Allocation of fertilizer reduction. Recovery time 2015

Recovery time in year 2021

An additional simulation was performed to obtain the optimal fertilizer application considering that the quality standards had to be met in 2021 instead of 2015. This could be useful for an analysis of derogations in the application of the WFD, according to the considerations of article 4 of the Directive. The results show that in this case the fertilizer application in area 5c had to be reduce to a 68% of the current application. The average total net benefits were of 96.0 M€/year are higher than in the scenario of recovery fro 2015 (95.4 M€/year), as expected. The allocation of the fertilizer reduction is presented in Figure 7. Figures 8 and 9 show the resulting nitrate concentrations at the control sites. When the recovery time is increased, the fertilizer reduction in area 5c becomes lower; nitrate concentrations in the control site “El Salobral” are below 50 mg/l after year 2021.

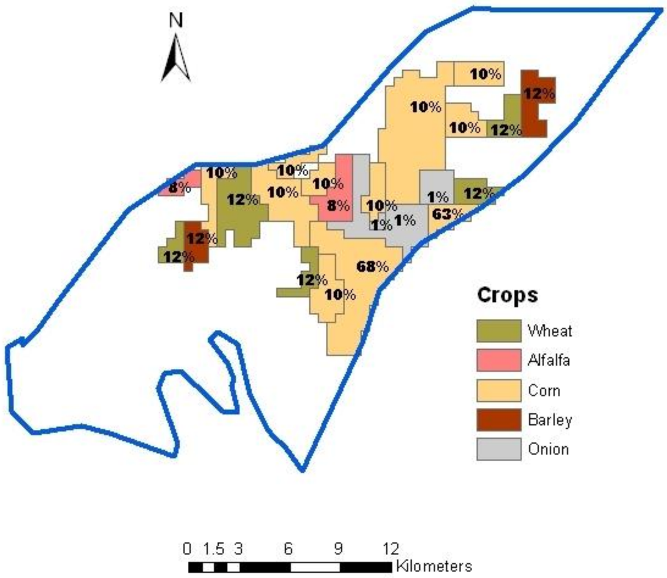

Figure 7. Allocation of fertilizer reduction. Recovery time 2021

DISCUSSION

The BAU scenario (scenario 1) leads to the highest nitrate concentrations, reaching values of 71.7 mg/l but it returns an average net benefits of 96.6 M€/year. This value is very close to the maximum net benefit scenario (scenario 2) of 96.7 M€/year, although the nitrate concentrations in the scenario 2 are lower (lower fertilizer applications). In spite of using more fertilizer in scenario 1 than 2 the resulting net benefits are lower, since the costs are higher and no grater crop yield is obtained out of that fertilizer excess (Table 8). Applying the fertilizer rate recommended for nitrate vulnerable zones in “La Mancha” (DOCM, 2007) (scenario 3), the maximum nitrate concentrations in groundwater becomes 57.5 mg/l, much lower than in BAU scenario. In fact, the maximum nitrate concentrations are mostly inherited from the high initial concentrations and not because of the fertilizer use after 2005. However, in this scenario the total net benefits are reduced by 15.7 M€/year, and it still does not comply with the 50mg/l standard. This implies that applying the Nitrate Directive in not an optimal option.

In scenario 4 for 2015 recovery time, the total net benefits are 95.4 M€/year, just 1.2 M€/year lower than the maximum net benefits scenario, and 15.5 M€/year more than in the scenario 3. This 1.2 M€/year would be the estimate of the cost (in terms of net benefits forgone) of complying with the WFD in relation to groundwater nitrate pollution for year 2015. For the planning period of 50 years, this amounts to 60 M€. If the quality standard is imposed in year 2021, the cost of compliment would be reduced to 30 M€. In order to justify derogation as permitted by article 4 of the WFD, the cost of reaching the objective in 2015 and not in 2021 should be compared with the avoided treatment cost for drinking water utilities.

Table.8. Comparison among scenarios.

	Average fertilizer application (kg/ha)	**Maximum nitrate concentration (mg/l)**	**Total net benefits (M€/year)**
Scenario 1. **Business as usual**	240.4	71.7	96.6
Scenario 2. **Maximum benefits**	218.7	66.7	96.7
Scenario 3. **Reference values**	157.8	57.5	80.9
Scenario 4. **Optimal fertilizer. 2015**	201.1	50.0 (after 2015)	95.4
Scenario 4. **Optimal fertilizer. 2021**	203.7	50.0 (after 2021)	96.0

Figure 8 and 9 show nitrate concentration at the most critical control sites, “El Salorbal” and “Sondeo 8”, for the different scenarios. The only scenario in which nitrate concentrations are reduced below the target is scenario 4. For the control site “Sondeo 8” nitrate concentrations are reduced below 50 mg/l and maintained very close to that value in the whole planning period, while nitrate concentration in the control site “El Salorbal” are steadily dropping. If the optimal fertilizer application were allowed to vary over the planning horizon, nitrate concentrations could be maintained close to 50 mg/l during the whole simulated period.

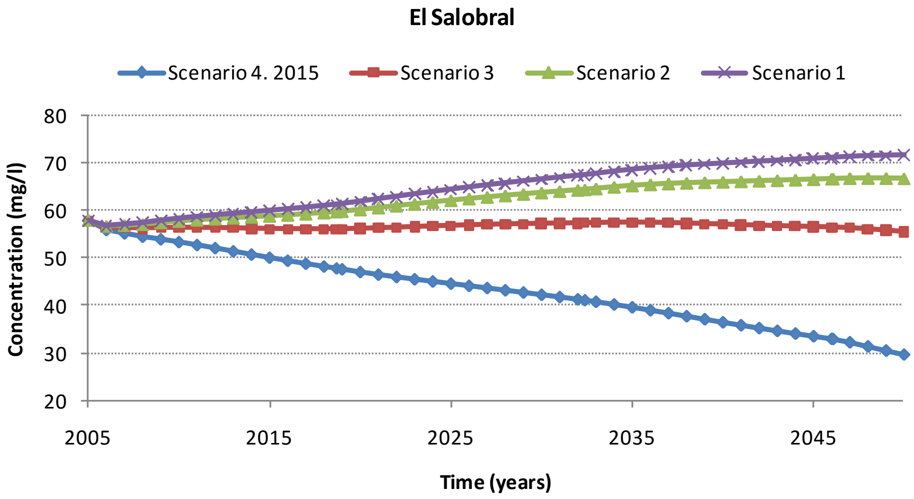

Figure 8. Concentration time curves for different scenarios at control site *“El Salobral”*.

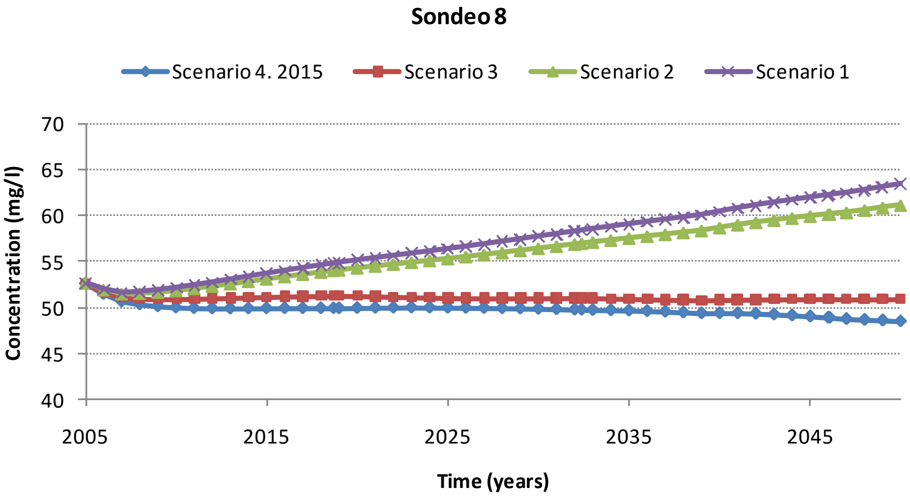

Figure 9. Concentration time curves for different scenarios at control site *"Sondeo 8"*.

"El Salorbal" and "Sondeo 8" are the control sites most affected by pollution, and the crop areas 5c and 9c are the polluters with bigger influence over them. Another simulation was performed to limiting the percentage of fertilizer reduction in these areas, but the problem turned out to be infeasible, since the other crop areas have very little influence over these control sites.

One of the assumption of this methodology is that the system has to be lineal, but the aquifer is not in steady state, the velocity field in not invariant, therefore the results obtained using the concentration response matrices could not be very accurate. Therefore, the results obtained by superposition were compared with those obtained simulating the optimal fertilizer application with MT3D code. The results are shown in Figure 10, where it can be seen that the differences are minor.

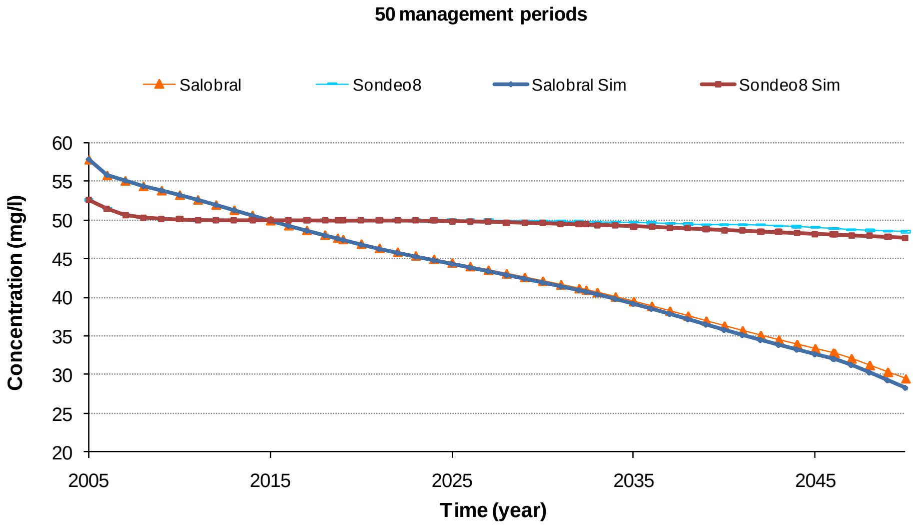

Figure 10. Concentration time curves for the optimal fertilizer application vs MT3D results

The differences become a bigger for longer times since the groundwater table is dropping and the velocity field is showing bigger changes.

Fertilizer taxes

The results showed the costs of applying fertilizer standards in order to reduce nitrate pollution in groundwater. Another economical instrument that can be used to control the nitrate pollution is the fertilizer taxes (references). In this paper the cost of applying fertilizer taxes was also analyzed. Several optimizations were carried out in order to obtain the fertilizer tax that would reduce its use to the level were the nitrate leached does not generate nitrate concentrations in groundwater above 50 mg/l. For this, the fertilizer price in the optimization model was parameterized, increasing its value until the nitrate concentration sin groundwater was below 50 mg/l.

In order to reach nitrate concentrations below 50 mg/l in all control sites, the fertilizer price has to be increased up to 5.15 €/kg (i.e., a tax of 858 % would be required); in that case the profits will go down to 86.6 M€/year (Figure 11). The benefits obtained by increasing the fertilizer price are 8.9 M€/year lower than those obtained from the fertilizer standards corresponding to scenario 4.

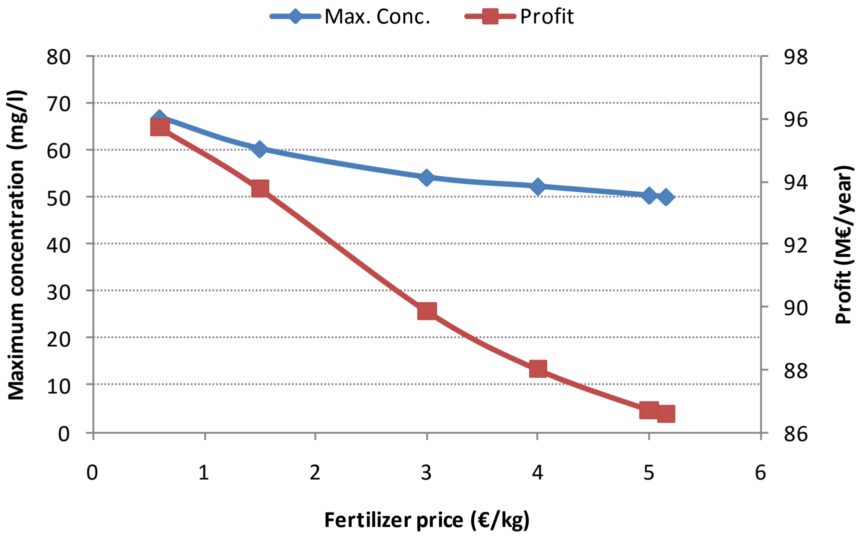

Figure 11. Maximum nitrate concentration achieved with different fertilizer price and total benefits

These results suggest that farmers are not sensitive to fertilizer tax until it reaches a very high level. However, we have to keep in mind that this model assumes that farmers only adjust the level of fertilizer use but not change crops. In reality farmers may decide to stop producing one crop or switch to another one, in response to changes in prices.

CONCLUSIONS

This paper shows the application of a hydro-economic model to the Salobral-Los Llanos aquifer (within the Mancha Oriental groundwater body) to obtain optimal fertilizer allocation (fertilizer standards) that maximizes the net benefits in agriculture while accomplishing with the quality standards. The results of applying fertilizer standards (scenario 4) show that the fertilizer reduction represents an average decrease in the net benefits of about 1.2 M€/year with regard to the expected benefit under the baseline scenario. Additionally, the farmer's response to an increase in the fertilizer price was simulated, showing that an extremely high price would be required to reduce the fertilizer use so that nitrate concentrations in groundwater stay below the 50 mg/l. These results show that it is more cost-efficient to apply standards to fertilizer use than taxes. However, the instrument of fertilizer standards is more difficult to implement and control. The use of fertilizer taxes constitutes a promising policy instruments that need to be further explored. The optimal results represent an upper bound to second-best solutions for controlling nitrate pollution. The optimal results can be used to compare with the limited achievement of different control policies.

The method applied obtains the optimal fertilizer allocation according with predefined crop location and water applied, a better optimal application can be obtained if the crops could be moved to a different place taking advantage of the influence of the crop location upon the control sites. Another important issue is to take into account the uncertainty in the physical parameters (Peña-Haro et al., 2010a), since it can lead to erroneous policies.

The method presented can contribute to implementing the EU Water Framework Directive by providing insights for the definition of cost-efficient policies or programme of measures to control diffuse groundwater pollution. The modeling framework allows estimation of the opportunity cost (as forgone benefits) of measures to reduce nitrogen loadings and their effectiveness for maintaining groundwater nitrate concentration within the target levels. The method also can be applied to identifying economically efficient "good quality status" threshold values. Finally, it can be used to justify less stringent environmental objectives based on the existence of disproportionate cost (for cases in which opportunity costs surpass the expected benefits) or to ask for deadline extensions when it is not feasible or the objectives cannot "reasonably" be achieved within the required timescales.

ACKKNOWLEDMENTS

The study was supported by the European Community 7th Framework Project GENESIS (226536) on groundwater systems.

REFERENCES

Basso, B. and Ritchie, J. T., 2005 Impact of compost, manure and inorganic fertilizer on nitrate leaching and yield for a 6-year maize–alfalfa rotation in Michigan. Agriculture Ecosystems and Environment 108 329-341.

Calera, A., Medrano, J., Vela, A. And Castaño, S., 1999. GIS tools applied to the sustainable management of water resources. Application to the aquifer system 08-29. *Agricultural Water Management* 40. 207-220.

Calera, A., Jochum, A. and Cuesta A. 2003. Space-assisted irrigation management: Towards user-friendly products. ICID Workshop on Remote Sensing of ET for Large Regions, 17 Sept. 2003.

CHJ, 2004. Jucar Pilot River Basin. Provisional Article 5 Report pursuant to the Water Framework Directive. Ministry for the Environment, Valencia, Spain. http://www.chj.es/CPJ3/imagenes/Art5/Articulo_5_completo.pdf.

CHJ, 2006. Convenio ERMOT, Evolución del regadío en la Unidad Hidrogeológica 08.29: Mancha Oriental, Periodo: 2000 – 2006. Convenio de colaboración entre la Confederación Hidrográfica del Júcar, la Consejería de Agricultura de la Junta de Comunidades de Castilla- la Mancha, la Universidad de Castilla-La Mancha y la Junta Central de Regantes de la Mancha Oriental, para la realización de un estudio sobre la evolución de las superficies de regadío, en el ámbito del acuífero Mancha Oriental mediante el empleo de técnicas de teledetección. http://www2.chj.gob.es/docus/OPH/EvolucionRegadiosEERMOT2006.pdf

CHJ, 2008. Modelo de flujo subterráneo de los acuíferos de la Mancha Oriental y sus relaciones con los ríos Júcar y Cabriel. UPV-IDR

DOCM, 1998. Orden de 21-08-1998. Resoulción de 07-08-98 de la Consejería de Agriculutra y Medio Ambiente por la que se designan, en el mabito de la Comunidad Autonoma de Castilla-La Mancha, determindas áreas como zonas vulnerables a la contaminación producida por nitratos porcedentes de fuentes agrarias.

DOCM, 2007. Orden de 10-01-2007. Consejería de Medio Ambiente y Desarrollo rural, por la que se aprueba el Programa de Actualización aplicable a las zonas vulnerables a la contaminación por nitratos de origen agrario en la Comunidad Autónoma de Castilla-La Mancha, designadas por las resoluciones de 07-08-1998 y 10-02-2003.

Estrela, T., Ferrer, J., Pérez, M.A., Font, V. 2004. Modelo hidrogeológico del acuífero de la Mancha Oriental para el análisis de los efectos de las diferentes alternativas de sustitución de extracciones por aguas superficiales. VIII Simposio de Hidrogeología. Zaragoza, Octubre 2004.

Ferrer, J., Gullón, N. 2004. Actuaciones de gestión y regularización administrativa en el acuífero Mancha Oriental. VIII Simposio de Hidrogeología. Zaragoza, Octubre 2004.

GAMS Development Corporation, (2008). GAMS Home Page. http://www.gams.com/.

Hahn, R.W. (2000). The Impacts of Economics on Environmental Policy. Journal of *Environmental Economics and Management* 39, 375–399.

IGME, 1976. Informe sobre la zona regable de Los Llanos.Madrid, España: Instituto Geológico y Minero de España

Liu, J., Williams, J. R., Zehnder, A. J. B., Hong, Y. 2007. GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale. Agricultural Systems 94 (2). 478-493.

López-Fúster, P. 2000. Los regadíos de la Mancha Oriental: Una quimera hecha realidad. Diputación Provincial de Albacete, Spain.

Martínez, Y. and Albiac, J. (2004) Agricultural pollution control under Spanish and European environmental policies. *Water Resources Research* 40: W10501. doi:10.1029/2004WR003102.

McDonald, M. G. and Harbough, A. W. (1988) A Modular Three-Dimensional Finite-Difference Groundwater Flow Model. US Geological Survey Technical Manual of Water Resources Investigation, Book 6, US Geological Survey, Reston, Va, 586 pp

Moratalla, A., Gómez-Alday, J.J., De las Heras, J., Sanz, D., Castaño, S. (2009), Nitrate in the water-supply well in the Mancha Oriental hydrogeological system (SE Spain). Water Resour. Manage. 23. 1621-1640. DOI 10.1007/s11269-008-9344-7

Peña-Haro, S., Pulido-Velazquez, M., Sahuquillo, A., 2009. A hydro-economic modeling framework for optimal management of groundwater nitrate pollution from agriculture. J. Hydrol., doi:10.1016/j.jhydrol.2009.04.024.

Peña-Haro S., Llopis-Albert, C., Pulido-Velazquez, M., 2010a. Stochastic hydro-economic modeling for optimal management of nitrate pollution under groundwater parameter uncertainty. Water Resources Research, under review.

Peña-Haro S., Pulido-Velazquez, M., Yang, H., Liu, J., Llopis-Albert, C., 2010b. Application of an agronomic model to determine optimal management strategies to reduce nitrate concentrations in groundwater. Groundwater Quality Management in a Rapidly Changing World 7th International IAHS Groundwater Quality Conference, held in Zurich, Switzerland, 13-18 June 2010.

Ramos, C., Agut, A., and Lidón, A. L., 2002. Nitrate leaching in important crops of the Valencian Community region (Spain). *Environmental Pollution* 118, 2, 215-223.

Sanz, D. 2005. Contribución a la caracterización geométrica de las unidades hidrogeológicas que integran el sistema de acuíferos de la Mancha oriental. Ph.D. Thesis, Univ. Complutense de Madrid, 224 p

Sanz, D., Gómez-Alday, J. J., Castaño, S., Moratalla, A., De las Heras, J., Martínez-Alfaro, P. E. 2009. Hydrostratigraphic framework and hydrogeological behaviour of the Mancha Oriental System (SE Spain). *Hydrogeology Journal*. DOI 10.1007/s10040-009-0446-y

Shortle J. and Dunn J., 1986. The Relative Efficiency of Agricultural Source Water Pollution Control Policies. *American Journal of Agricultural Economics*, 68 (3). 668-677

UCLM, 2006. Uncertainty assessment on the quantitative status of the Mancha Oriental Aquifer, Jucar River basin, Spain November 2006. Harmonised techniques and representative river basin data for assessment and use of uncertainty information in integrated water management Contract EVK1-CT-2002-00109

Williams, J. R. 1995. The EPIC model. In: Singh, V.P. (Ed.) Computer Models of Watershed Hydrology, 909-1000. Water Resources Publisher

Zheng, C., and Wang, P. 1999. MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispertion and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User`s Guide.