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title: **Coupling an unsaturated model with a hydro-economic framework for deriving optimal fertilizer application to control nitrate pollution in groundwater**

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ABSTRACT

In deriving management policies to control groundwater nitrate pollution, it is important to conduct an integrated modeling which takes into consideration the soil, the unsaturated and the saturated zone. In management regional studies the influence of the unsaturated zone is often neglected. The unsaturated zone can have an important influence in the time delay of nitrate transport and therefore in accomplishing the good groundwater chemical status required by the EU water framework directive. In this paper the unsaturated zone is coupled with a hydro-economic model that obtains the spatial and temporal fertilizer application rate that maximizes the net benefits in agriculture constrained by the quality requirements in groundwater at various control sites. The integrated model was applied to El Salobral-Los Llanos aquifer in central Spain, where the fertilizer allocation that accomplishes with the nitrate concentration in groundwater was obtained.

INTRODUCTION

The EU Water Framework Directive (Directive 2000/60/EC; WFD), proclaims an integrated management framework for sustainable water use, and requires that all water bodies reach a good status by 2015. According to article 4 of the WFD, this deadline can be extended if the "Member States determine that all necessary improvements in the status of the bodies of water cannot reasonably be achieved within the timescale". Therefore, the correct estimation of the timescale to achieve the good quality of the groundwater bodies is very important.

To control groundwater diffuse pollution is necessary to analyze and implement management decisions. The efficiency of these decisions depends on the inertia of the soil-unsaturated-groundwater system. In order to predict future groundwater-quality values, especially after implementation of environmental measures such as reduction in fertilizer use the response time has to be determined. The response time between the fertilizer application and the contamination at a particular site may depend on the distance between the source area and the control site where water quality is measured (Gutierrez, Baran, 2009). In Peña-Haro et al. (2009) an hydroeconomic model was developed to obtain the optimal allocation of fertilizer application in order to maximize the benefits in agriculture while maintaining the nitrate concentrations in groundwater below a predefined standard. In this methodology the unsaturated zone was not explicitly taken into account. In this paper the delay time that nitrate suffers while going through the unsaturated zone is coupled into the hydro-economic model. This is applied to El Salobral-Los Llanos aquifer (Mancha Oriental) in Spain, and some preliminary results are shown.

HYDROECONOMIC MODEL

The hydro-economic model (Peña-Haro et al., 2009) couples an agronomic model, flow and transport models in an optimization framework, where the benefits in agriculture are maximized. From agronomic simulations quadratic functions are derived that relate the nitrate leached and the crop yield with the water and fertilizer use. The groundwater flow and nitrate transport model are used to obtain concentration response matrices, which shows the influence of a pollutant source upon nitrate concentrations at different control sites over time. In this paper a simple unsaturated model, which only considers the gravity flow, was coupled into the hydro-economic model. With this model the time delay from the nitrate leaves the root zone until it arrives into the saturated zone is estimated. The time delay due to the nitrate transport trough the unsaturated zone was included into the concentration response matrix as a shift in the time (Fig. 1).

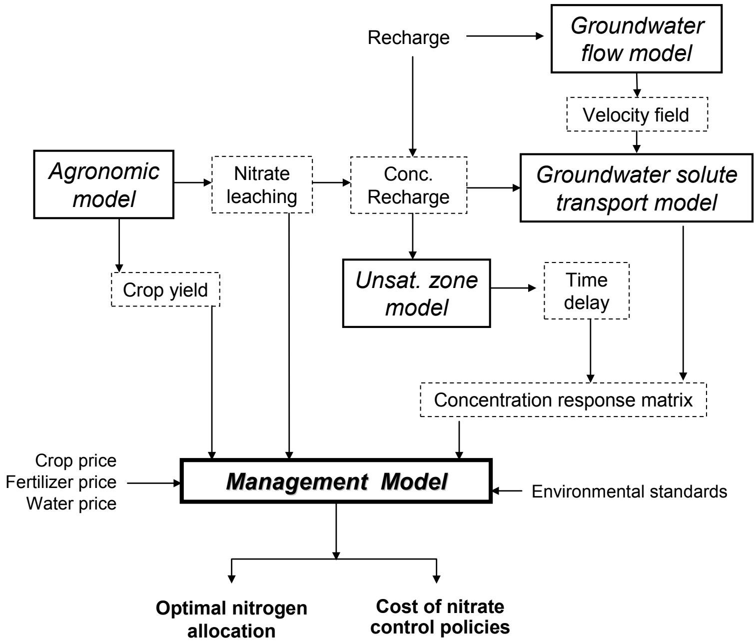

Figure 1. Modeling framework.

UNSATURATED ZONE MODEL

For the simulation of the water flow through the unsaturated zone, a simple model considering a simplification of Richards' equation with kinematic wave was used. Vertical flow through a homogeneous unsaturated zone can be represented by Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z} - K(\theta) \right] \tag{1}$$

where: θ is the volumetric water content [L^3/L^3], z is the elevation in the vertical direction [L], $D(\theta)$ is the hydraulic diffusivity [L^2/T], $K(\theta)$ is the unsaturated hydraulic conductivity as a function of water content [L/T] and t is time [T].

Equation (1) can be written as follows (Singh, 1997):

$$\frac{\partial \theta}{\partial t} + \frac{dK(\theta)}{d\theta}\frac{\partial \theta}{\partial z} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z} \right] \tag{2}$$

If we assume that the vertical flux is only driven by gravitational forces the diffusive term can be neglected (right side of equation 2), and considering that $q=-K(\theta)$, equation 2 is reduced to the kinematic wave equation:

$$\frac{\partial \theta}{\partial t} + \frac{dq}{d\theta}\frac{\partial \theta}{\partial z} = 0 \tag{3}$$

Equation (3) can be solved by the method of characteristics. The characteristics showing the velocity of the wave is (Niswonger et al., 2006):

$$\frac{dz}{dt} = \frac{\partial K(\theta)}{\partial \theta} = v(\theta) \tag{4}$$

where v(θ) is the characteristic velocity [L/T]

The Brooks-Corey function is used to define the relation between unsaturated hydraulic conductivity and water content (Singh, 1997).

$$K(\theta) = K_s \left[\frac{\theta - \theta_r}{\theta_s - \theta_r} \right]^{\varepsilon} \tag{5}$$

where θ_r is the residual water content, θ_s is the saturated water content, K_s is the saturated hydraulic conductivity [L/T] and ε is the Brooks-Corey coefficient.

EL SALOBRAL LOS LLANOS AQUIFER

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. 80% of the land is agriculture from which 100 km^2 are irrigated crops (CHJ, 2004). The climate can be defined as Mediterranean. The mean summer temperature is about 22°C and the mean winter temperature about 6°C. The mean annual precipitation is about 360 mm. The average groundwater recharge is estimated in 165 mm/year (CHJ, 2008). The irrigated area has increased considerably, in 1961 was about 29 km^2 (Spanish Geological Survey, IGME, 1976) and in 2004 was of 100 km^2. This has provoked a decline of the groundwater levels of between 60 and 80 meters as well as high nitrate concentrations. The highest nitrate concentration is about 54 mg/l and was recorded in the well "El Salobral" (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 with 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.

RESULTS

In this paper the time delay we estimated by using the unsaturated zone model, which only considers the gravity flow. The unsaturated zone thickness was calculated by considering the difference between the average ground level and the average groundwater level for 2005 for each one of the management areas (Figure 2). These management areas were defined by taking into account the type of crop and the administrative aggregation of farmers.

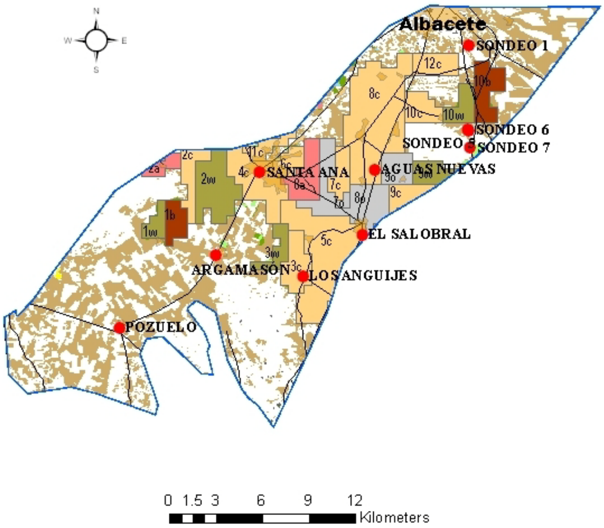

Figure 2. Control sites (red dots), agricultural management areas and dry-land areas.

The estimation of the time delay was done considering a K_s=0.015m/day, ε=3.5 and n=0.025. For estimating the recharge it was considered the values of a dry year. The average recharge was 40 mm/year. The delay time was between 6 and 16 years, with a mean value of 7 years.

The results of the optimal fertilizer allocation were obtained as a reduction from the actual fertilizer use. When taking into consideration the unsaturated zone, the results from the optimization shows that the target value of 50 mg/l can not be reached before 2023. In order to accomplish with the maximum nitrate concentrations, the fertilizer application has to be reduced on all areas, but especially on area 5c which has to be reduced by an 87% and in area 9c by a 64%. With this fertilizer application the benefits are 95.5 M€/year. The difference in time to achieve the target limits is not only influenced by the time that the reduced leaching takes to arrive to the control sites, but also because there is high nitrate concentrations already travelling trough the unsaturated zone (Figure 3).

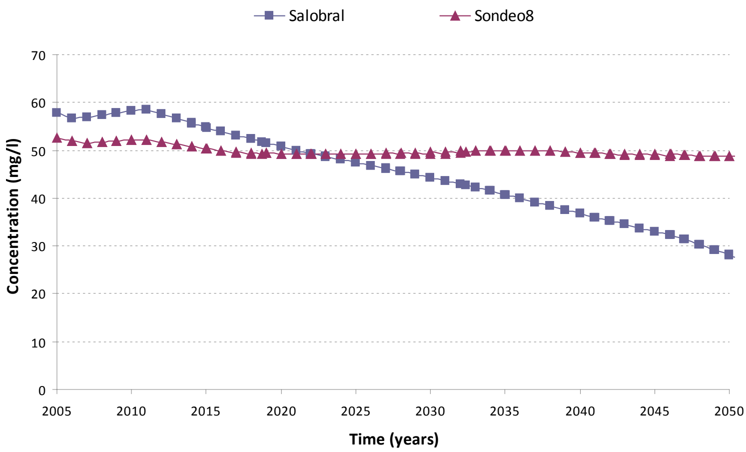

Figure 3. Nitrate concentrations for the optimal fertilizer allocation.

CONCLUSIONS

The WFD established the year 2015 as a deadline for the achievement of the good status and also the possibility to extend it. In this paper it was evaluated the influence of the unsaturated zone in the time of achieving the good status. A dry year (worst case) was selected. The average travel time of the nitrate trough the unsaturated zone was of 7 years, and the nitrate concentrations levels can not be achieved before 2023. The fertilizer had to be reduced to accomplish with the target concentration levels; therefore the benefits were also reduced.

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