An integrated framework for sustainable agriculture land use and production practices

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Abstract

Diffuse pollution is among the major environmental concerns in terms of prevention of further deterioration and restoration of water to a "good status" in terms of ecological and chemical parameters. A step forward should be made for finding better land use, crop irrigation and fertilization practices to avoid damaging water bodies. This paper presents a framework for obtaining the decisions to be implemented in order to define a sustainable agriculture land use and production practices. A multidisciplinary approach is proposed for building a decision model capable of representing all the issues involved in the scope of an integrated management of land and water resources. The framework proposed is the basis of a research project recently financed by the Portuguese research foundation (Fundação para a Ciência e a Tecnologia). The main objectives of the project can be summarized as follows: 1) Improve the scientific knowledge regarding the interrelation between the agriculture land use and the production practices and the groundwater and the surface water quality protection, towards a more sustainable agriculture; 2) Contribute to support future decisions in terms of more adequate policies regarding rural land use planning (type of crops and associated fertilizers and treatment techniques), taking into consideration the protection of the environment based on vulnerability and risk concepts.

Keywords: diffusion pollution, Sustainable agriculture practices, decision models.

1 Introduction

There is a major challenge ahead for Europe in what concerns the management of the environment through the concept of integrated river basin management. This challenge is being driven by an important piece of European legislation concerning water protection, the Water Framework Directive. The overall aim of the Directive is to establish a legal framework to protect surface water and groundwater using a common management approach and following common objectives and principles.

Diffuse pollution is among the major environmental concerns in terms of prevention of further deterioration and restoration of water to a "good status" in terms of ecological and chemical parameters. This objective is stated in the Water Framework Directive paragraph "Member States shall implement the measures necessary to prevent or limit the input of pollutants into groundwater and to prevent the deterioration of the status of all bodies of groundwater".

In fact, one of the basic principles of the Directive says that "Surface waters and groundwater are in principle renewable natural resources; in particular, the task of ensuring good status of groundwater requires early action and stable long-term planning of protective measures, owing to the natural time lag in its formation and renewal. Such time lag for improvement should be taken into account in timetables when establishing measures for the achievement of good status of groundwater and reversing any significant and sustained upward trend in the concentration of any pollutant in groundwater".

This paper presents a framework for obtaining the decisions to be implemented for accomplishing a sustainable agriculture land use and production practices. This framework is the basis of a research project recently financed by the Portuguese research foundation (Fundação para a Ciência e a Tecnologia). In this project we want to go a step further on analysing how can land planning be used to improve the surface and groundwater quality. An improved knowledge of the vadose zone role (usually an area where the phenomena are more difficult to measure and to study) would be crucial. The construction of a decision tool integrating all the knowledge gathered in the foreseen multidisciplinary approach will contribute to more rational decisions.

This project will concentrate efforts in gathering and integrating the knowledge of the processes that interfere in the migration of pollutants originated by soil fertilization, for the different media (soil, vadose zone, groundwater and surface water), encouraging the future utilization of more sustainable crops and fertilizer practices that can decrease the risk of groundwater and surface water quality degradation.

This project will give scientific proves for the implementation of decision-making strategies for environmental protection of water resources. It will support political decisions from county administrations, responsible for regional planning, taking into account the sustainable development of the region and the appropriate use of nitrogen fertilizers on the basis of several European and national directives: EU-Nitrate Directive (91/676/EEC); Drinking Water Directives (80/778/EEC); Environmental Farming Proposals (91/2078/EEC);

Delimitation of Vulnerable Zones to Nitrates (91/676/EEC) and EC Water Framework Directive (2000/60/EC).

2 The decision model

The decision tool will be built to maximize the net benefits from land use, taking into consideration the different soils present in the area (and its behaviour measured in the field and lab experiments), the fertilization practices for each crop, the groundwater and surface water availability and vulnerability, the costs of land use changes, socio-economic aspects in such a way that agricultural practices can be compatible with water consumption and respecting the ecological status of associated water bodies.
Having Figure 1 as a reference scenario to implement the decision model, and taking into account the interrelationship between practices and consequences in water bodies (Figure 2), the objective function of general decision model can written as follows:

$$\max\ BLA = \sum_{ijk}\left(p_j y_{aijk} A_{ijk}\right) - \sum_{ijk}\left(ca_{ijk} A_{ijk}\right) - \sum_{ijk}\left(ci_{ijk} I_{ijk}\right) - t_p \sum_i N_i$$

BLA: net benefits;

i: zone index;

j: crop index;

k: agriculture practice index;

p_j: unitary price of the crop j;

y_{aijk}: actual production of the crop j in the zone i with the agriculture practice k;

A_{ijk}: area of the zone i, concerning the crop j with the agriculture practice k;

ca_{ijk}: unitary cost for cultivating the zone i, with the crop j, with the agriculture practice k;

ci_{ijk}: unitary cost of irrigating the zone i, with the crop j, with the agriculture practice k;

t_p: unitary cost (tax) for pollution;

N_i: pollution from the zone i.

The pollution from zone i is determined, through the use of a transfer function χ_{il}, taking into account the area and the quantity of fertilizer used:

$$N_i = \sum_{jkl} \chi_{il} n_{ijk} A_{ijk}$$

χ_{il}: transfer function that represents the fraction of the pollution from zone i that reaches the l water body (vadose zone, groundwater and the surface water), depending on the soil type, the infiltration, the piezometric level, etc.;

n_{ijk}: quantity of fertilizer used in the zone i, for the crop j with the agriculture practice k.

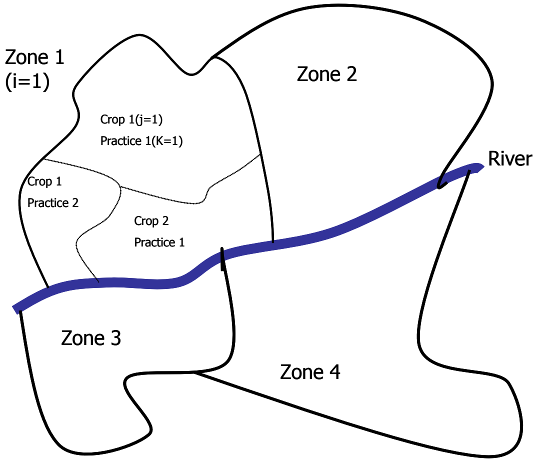

Figure 1: Reference scenario.

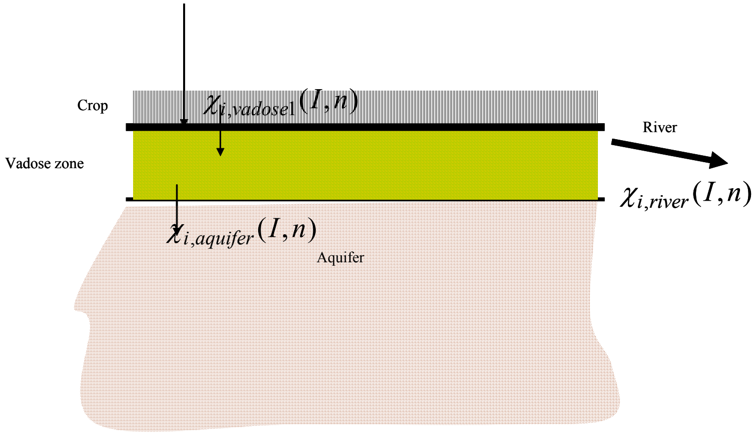

Figure 2: Reference water bodies transfer functions.

The decision model will include constraints representing water and land availability, limits on the amount the pollution allowed in each water body, physical limitation relating crop production with the production factors.

To built the decision tool the following tasks have to be accomplished:

- Development of cost and benefit functions from land use. Production functions relating the agriculture production and the production factors like water, soil and crop type, fertilizers, agriculture response factors will be considered.
- Development of the transfer functions to evaluate the consequences of land use and agriculture practices. For such purposes, the project will thus focus on assessing the impacts of agriculture on groundwater and

surface water quality through an integrated and multidisciplinary approach including:

i) Agro-Hydrosystem Characterisation - Inventory and quantification of diffuse pollution sources, inventory of crops, identification of associated fertilizers and treatment techniques, irrigation schemes for each crop, and after all the movement of pollutants in the soil, vadose zone an, groundwater, surface water associated with each crop.

ii) Soil and Vadose Zone Characterization and Modelling - Characterisation of soil and unsaturated zone hydraulic properties and mass flow and transport modelling calibration through the unsaturated zone using deterministic models for nitrate and pesticides (HYDRUS 1D or 2D).

iii) Aquifer Monitoring and Modelling - mass flow and transport modelling (MODFLOW), interactions between groundwater and surface water; water balance modelling; recharge assessment; and groundwater seasonal monitoring (nitrates, pesticides, phosphates, and water level).

iv) Surface water quality modelling - mass flow and transport modelling (QUAL2K), evaluation of the ecological status resulting from non-point sources pollution coming from the different agriculture practices.

- Development of decision models (objectives and constraints). These models will include the cost and benefit functions, the agriculture production function, the groundwater and surface water quality model. They will incorporate also the information and the models used in the previous tasks in order to link the groundwater and surface water response to the agriculture practices regarding quantity and quality issues. Socio-economic aspects will be also taken into account in the benefits and in the cost terms.
- Assessment of the more suitable optimization methods to solve the decision models developed. The decision models previously built will be stochastic non-linear mixed integer models. In fact these models will involve uncertainty, non-linear functions, numerical approximations of differential equations with partial derivatives and combinatorial decisions (yes or no decisions). Robust optimization techniques combined with new metaheuristics like simulated annealing or genetic algorithms will be used for solving such decision models.
- Resolution of the decision models through the use of the chosen methods. Some work calibration of the metaheuristics algorithms have to be accomplished and different robustness measures have to be evaluated.

3 Models calibration and validation

A pilot area has been defined to conduct field experiments and analysis that will provided the understanding and the data for the application of the decision model to a real world case study. Diffuse pollution is a problem of increasing concern in Alentejo rural region (South Portugal) and particularly in the new areas of Alqueva Irrigation Project. Several previous studies have been conducted to analyse the effects of diffuse pollution in the water resources, in Portugal and elsewhere. The main hydrogeological and agriculture features of the study area were previously identified by the project partners and published [8]. Project partners have large experience on this type of studies [2–9]. Also the study of nitrate pollution associated to agriculture and its direct and indirect effect on the rates and compositions of groundwater recharge flux and aquifer biogeochemistry have been studied by several other authors, namely [1] and [10]. The study area is located in Alentejo region (South Portugal), with semi-arid climatic conditions. That area represents the first irrigation perimeter (64 km^2) starting 2004 in the context of Alqueva Irrigation Project (the biggest artificial lake in Europe) expected to achieve 110 000 ha of irrigated land in 2025. It is an intensively agricultural site of arable land with different cultivations scenarios and techniques located above a regional aquifer used for water supply. The different tasks to be developed for models calibration and validation are described next.

3.1 Task 1

In the first task a complete characterisation of the agro-hydrosystem in the study area, and its seasonal variations, is to be carried out for a 2-year period. The results expected in this task are: field quantification of nitrogen, pesticide and phosphates inputs for 3 different crops, considering their different irrigation schemes, and fertilizers and treatment techniques; field quantification of nitrogen, pesticide and phosphates migration paths in 2 different soils and for 3 different crops: pollutants quantification in soils, vadose zone and groundwater; laboratory soil-column simulation of field experiments: pollutants quantification in soils and water.

The results are expected to be obtained through the following actions:

• Selection of a small watershed basin area within the "Infra-estrutura 12" 64 km^2 total area, with different crops along the year.

• Delimitation of two irrigation plots with different soil types (A and B). Selection and characterisation of 6 irrigation portions with different soil types (2) and crops (3).

• Inventory of the historical and existing annual land use plan at the site.

• Analysis of previous studies in the area and inventory of existing infrastructures that can be used for further groundwater monitoring.

• Analysis and interpretation of previous groundwater and surface water quantity and quality data and its connection to the land use practices. Analysis of the following relations, by using statistical modelling (trend and cluster analyses):

i) Type of land use / type and amount of fertilizers applied (including the season for its application);

ii) Type of land use / agriculture techniques / groundwater quality/ surface water.

• Installation of tensiometer to measure soil humidity, which will allow following the progression of water in the soil.

• Installation of Teflon capsules in the vadose zone for water sampling.

•Assessment of different land use scenarios effects in the migration of pollutants (nitrates, phosphates, and some applied pesticides). This action will be carried out in (a) two field crops and in (b) laboratory soil-columns:

i) The field monitoring of crop effects will be carried out for two soil types (A and B) in which three different types of crop (corn, sunflower and melon) will be tested. For both soil types, the effects of the migration of nitrates, chlorides, phosphorous and some pesticides, will be monitored and analysed in three media: soil (soil itself), vadose zone (Teflon capsules) and groundwater (piezometers).

ii) The laboratory tracer tests, to be performed in soil-columns, will be used to reproduce the field experiments in the saturated zone and possibly also in the vadose zone. In that sense, this task will be done by measurements in the same (two) soils and the effect of the three crops will be reproduced in lab conditions by the type and intensity of fertilizer applications that characterise each crop.

3.2 Task 2

This task is devoted to a complete characterisation of soil and unsaturated zone hydraulic properties and will be made on the base of field permeability tests, soil bulk density, granulometry and laboratory pF curves determination on undisturbed samples. After that, it will be developed and calibrated a mass flow and transport modelling through the unsaturated zone using deterministic models for nitrate and pesticides. These models are widely used and accepted by international scientific community (HYDRUS 1D and 2D) using Richards equation, convection-dispersion equation and van Genuchten algorithm and considering half-life decay of pesticides.

In the end of this task, an evaluation of the effects of different land use scenarios in the concentration of pollutants (nitrates, phosphates, and some applied pesticides) in the soils and the vadose zone will be done. This will be made by using the field data and by interpreting it using deterministic models for nitrate and pesticides transport.

The results are expected to be obtained through the following actions:

• Determination of seasonal variations of soil moisture over unsaturated zone profile and fertiliser leaching. This will be supported by automatic soil moisture probes and appropriate ceramic blocks during 2 years for major pollutants (nitrates, phosphates, and some applied pesticides).

• Measurement of agro-meteorological data (rainfall, ET0, soil moisture, groundwater level, etc.) for soil and unsaturated zone.

• Determination of seasonal water balance using deterministic models supported by field calibration.

• Evaluation of different land use scenarios in the concentration of pollutants (nitrates, phosphates, and some applied pesticides) in the soils and the vadose zone taking account specific conditions of the study area. This will be done by using deterministic models for nitrate and pesticides (HYDRUS 1D and 2D).

3.3 Task 3

Under this task the development and calibration of flow and transport models (MODFLOW and QUAL2K) for saturated media and river quality will be done. The input parameters results obtained in the previous task, for unsaturated zone modelling, will be used.

Groundwater quality modelling in order to ascertain the correspondence between the land use and water composition and to calculate geochemical mass balances will be made using PHREEQ2C model. Also the study of main interactions between groundwater and surface water, recharge assessment and seasonal monitoring of pollutants (nitrates, pesticides, phosphorous) and water level will be carried out.

The results are expected to be obtained through the following actions:

• Soil and water samples will be collected and analysed for major elements and common pesticides. All information will be stored in Database and user-friendly GIS.

• Groundwater and surface water quality modelling in order to ascertain the correspondence between the land use and water composition and to calculate geochemical mass balances will be made using PHREEQ2C model.

• Hydrogeological and stochastic modelling including:

i) Definition of the hydrogeological conceptual model at the site.

ii) Determination of the spatial distribution of the main hydrogeologic parameters using stochastic models for further incorporation on deterministic models.

iii) Flow and transport modelling using the appropriate deterministic models.

iv) Simulation of different pollution scenarios for different land uses and soils.

This task intends to help interpreting the field and lab results carried out for the 6 different scenarios (2 soils and 3 crops). For the field experiments, the following tasks will be done:

• Definition of the hydrogeological conceptual model at the site (partially already done in previous work at the site, although needing to be adapted to the small watershed basin area to be selected).

• Determination of the spatial distribution of the main hydrogeologic parameters using stochastic models for further incorporation on deterministic models (also using some previous data for the permeability values, dispersivity, etc.).

• Flow and transport modelling of the vadose zone using the appropriate deterministic models (possibly HYDRUS-2D).

• Flow and transport groundwater modelling using the appropriate deterministic models (possibly MT3D); some previous modelling of the site was done and the values of recharge calculated will also be used.

• Simulation of different pollution scenarios for different land uses and soils.

For the laboratory experiments, the following tasks will be done:

• Modelling flow and transport for each crop at laboratory scale for the 2 different soils (possibly using CANALT model). The relevance of the physical properties, namely the permeability and the porosity of the media, as well as the chemical properties like cation exchange capacity, adsorption capacity as well as the conditions of temperature and pH, will be analysed.

4 Conclusions

An integrated framework for a sustainable agriculture land use and production practices is presented. Diffuse pollution is among the major environmental concerns in terms of prevention of further deterioration and restoration of water to a "good status" in terms of ecological and chemical parameters. The importance of building a decision model is enhanced and the different tasks to be accomplished in the scope of a multidisciplinary approach, for such purposes, are systematized. These kind of models are very important to tackle the challenge of an integrated river basin management, thus fulfilling the objectives of the Water Framework Directive.

The results achieved until now within this project are presented in [11] and [12].

Acknowledgement

The authors gratefully acknowledge support received from the Fundação para a Ciência e a Tecnologia through grant POCTI/AGR/57719/2004.

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