METHODS AND MODELS FOR SUSTAINABLE GROUNDWATER PLANNING AND MANAGEMENT

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Abstract: An integrated approach to the sustainable planning and management of groundwater supply is presented. Different sub models describing various physical phenomena (related to agricultural land use, saltwater intrusion, and mountain aquifers) are unified and integrated within decision models that are able to take into account different aspects, like water distribution, agricultural practices, environmental preservation, pollution control. Specifically, two main typology of decision problems are investigated: long term planning and short term management problems. A case study relevant to the optimal exploitation of water supply from a polluted aquifer is presented.

Keywords: Decision Support Systems, Water pollution, Optimization problems, Planning, Management Systems.

1. INTRODUCTION

Modern development and population growth have greatly increased water demands. As a water crisis is forecasted in the near future, the welfare of the world's population is closely tied to a sustainable exploitation of groundwater, surface and coastal water resources in order to prevent their depletion and contamination (Bear, 2000).
Water management includes a wide set of correlated problems that should be taken into account because they strictly interact with water demand, water availability, and water quality. The identification of sustainable pathways for proper land use development is a typical example. In this case, the main trade-off that takes the most problematic decisional aspects is between the anthropic actions and the conservation of natural resources. In this respect, the water system and its quality is taken into account as one of the most important indicators, which affect the sustainability of the agriculture activities on a rural territory. Specifically, groundwater, which saturates in an aquifer and which percolates into the ground from rainfall, snowmelt, rivers, lakes and irrigations, represents a well-defined important indicator of the anthropic activities on a territory, if we take into account their wealth (since they do represent nearly one quarter of freshwater on Earth) and their economic value (e.g., as drinkable and irrigation water). The accurate definition of water quality terms, has been the goal of several regulations (such as in the 2000/60/EC directive). In this respect, several models based on optimization techniques have been developed to determine suitable trade-offs between agricultural activities and resource conservation and maintenance (e.g. Southgate, 1990; Jones and O'Neill, 1992). In general, the decision process, as in other decision processes dealing with the management of environmental systems, is very complex (Wierzbicki and Makowski, 2000), requiring non linear multi-objective setting, and a deep analysis of the territory as well as an integration with geographic information systems.
Evidently, there is the need of an integrated approach that is able to take into account all objectives of the decision problem, supported by simulation models to describe the water system under different viewpoints (hydraulic, chemical, biologic, hydrologic etc...). The common approach to support the so-called integrated water management problem is the design of Decision Support Systems (DSSs), integrating all these aspects (Lombardo et al., 2003). The application of optimization techniques in groundwater quantity and quality management has been clearly investigated by Das and Datta (2001). They present a complete state of the art of the different optimization approaches that have been applied to groundwater management. Specifically, the combined use of simulation and

optimization techniques has been demonstrated to be a powerful and useful approach to determine planning and management strategies for groundwater systems. (Katsifarakis et al., 1999; Psilovikos, 1999; Naji et al., 1999; Shamir and Bear, 1984; Willis and Finney, 1984). In such works, in general, the simulation model component of the management models is generally based upon the partial differential equations of groundwater flow and solute transport or upon multicell models able to consider water and water quality balances. Depending upon the physical processes considered in the management model, either the flow equation, or the solute transport equation, or both equations are used in the simulation. Psilovikos (1999) has analysed two management problems formalized via linear programming and mixed integer linear programming making use of simulation packages like MODFLOW, MODMAN and optimisation tools (LINDO).

As regards saltwater intrusion, Shamir and Bear (1984) have determined optimal annual operation of a coastal aquifer by using a multiple objective linear programming approach based on a multicell model of the aquifer and a network representation of the hydraulic distribution system. Willis and Finney (1988) defined a planning model for the control of seawater intrusion in regional groundwater systems, structuring the management problem as a control problem.

In this paper, a general decision model for IWM, both for planning and management, is proposed. First of all, specific decision variables are described and then the objective functions and the constraints formalized. It is possible to classify the decision variables into two main classes: control variables and state variables. Control variables are those whose value is determined directly by the decision maker; that represents the way by which the overall system is driven by the external. Instead, state variables are used to represent the evolution of the system behaviour (or conditions) over time.

The objectives of the decision problem represent the goals that are pursued by the planning and management strategies, according to the specific exigencies of the decision makers, while the constraints are necessary to represent limits to be respected, requirements to be fulfilled, and can also be used to take into account the various aspects of the problem (environmental, economic, legislative, social, etc.). Besides, it is necessary to point out that the aim of this work is not that of building a model to be used for a detailed simulation precisely representing the reality, but that of developing an overall approach to define groundwater planning and management strategies. In this connection, the use of multicell models seems to be a reasonable choice as it allows representing the physical system at different levels of detail.

2. THE GENERALIZED PHYSICAL MODEL

The characteristics and activities affecting the territory under concern can be easily represented through a schematic partition of the considered territory (typically a single watershed or a union of watersheds) into N cells of different typologies. In the proposed model two main classes of cells are considered, namely:

- the sets M (of the indexes) of mountain/freshwater aquifer cells;
- the set A of agricultural cells.

In the following, the differences among such classes of cells will be highlighted. Two kinds of state equations will be used to represent the dynamics of every cell: the first kind describes the water balance, whereas the second one describes the mass balance of the various pollutant concentrations. To make the model easier to be integrated within an optimisation model, the state equation dynamics will be represented by discretizing the time variable. In addition, for agricultural cells, it is necessary to consider a further class of (algebraic) equations to link crop production with the decision variables.

2.1 Water balance state equations.

For each kind of cells, the state variables appearing in the generalized water balance state equations are:

- H_m^t: the hydraulic head in cell m at time t [m], $m=1,\dots,N$;
- $V_{m,rz}^t$: the volume of water present in the unsaturated sub-cell of the agricultural cell at time t [m^3], defined only for $m \in A$.

The control variables appearing in the water balance state equations are:

- Q_m^t: the water flow pumped from cell m in time interval (t, t+1) [m^{3}s^{-1}], $m=1,\dots,N$.

Some of the variables affecting the behaviour of the state variables relevant to cell m are functions of the state variables of different cells. They are:

- $L_{IN,m}^t$: the overall water flow [m^{3}s^{-1}], entering the generic cell m $m=1,\dots,N$;
- $L_{OUT,m}^t$: the overall water flow [m^{3}s^{-1}] leaving generic cell m, $m=1,\dots,N$;
- R_m^t: the water flow [m^{3}s^{-1}] leaving the unsaturated zone of the agricultural cell m, and entering the saturated zone, $m \in A$.

All flows are considered as referred to time interval (t, t+1).

In Figures 1 and 2, the water flow contributions are represented. Figure 1a represents a cell in which the unsaturated zone is not considered, while Figure 1b represents a cell in which the unsaturated zone is considered.

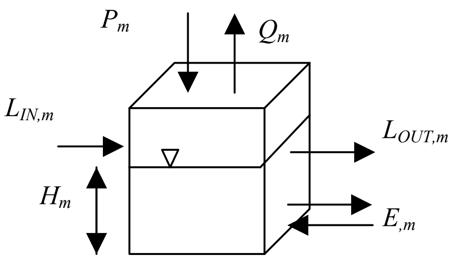

Figure 1. Water flows contribution for a generic cell m when the uunsaturated zone is not taken into account

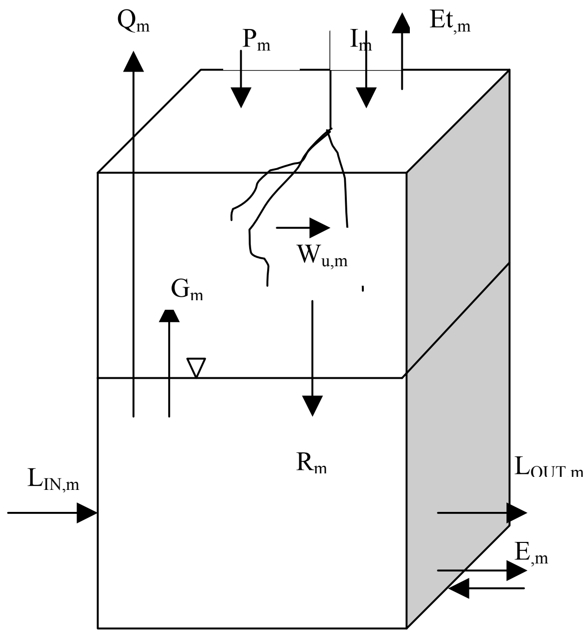

Figure 2. Water flows contribution for a generic cell m when the unsaturated zone is taken into account.

Finally, the following quantities are assumed to be known for every cell m: a parameter ε_m, which is a function of the parameters that describe the geometric characteristics of the cell and soil properties [m^{-2}], and E_m^t, that is the net flow accounting for a set of physical effects (precipitation, evapotranspiration, surface water contributions, etc.) that take place in cell m [m^{3}s^{-1}], within time interval (t,t+1). On these bases, the state equation representing the water balance for a generic cell m can be written as

$$H_m^t = H_m^{t-1} + \\ + \varepsilon_m (L_{IN,m}^{t-1} - L_{OUT,m}^{t-1} - Q_m^{t-1} + R_m^{t-1} + E_m^{t-1})\Delta t$$

$$m=1,\dots,N \qquad t=1,\dots,T \qquad \textbf{(1)}$$

or even, expressing explicitly the terms representing the overall leakages entering (going out from) the cell m,

$$H_m^t = H_m^{t-1} + \varepsilon_m \Big(\sum_{k=1}^{N} \max(\bar{\varepsilon}_{km}\left[H_k^{t-1} - H_m^{t-1}\right],0) + \\ - \sum_{k=1}^{N} \max(\bar{\varepsilon}_{km}\left[H_m^{t-1} - H_k^{t-1}\right],0) - Q_m^{t-1} + \\ + R_m^{t-1} + E_m^{t-1} \Big)\Delta t$$

$$m=1,\dots,N \qquad t=1,\dots,T \qquad \textbf{(2)}$$

where $\bar{\varepsilon}_{km}$ is a parameter, that depends on the geological characteristics of the boundary layer between cell k and m.

It is important to note that the contribution R_m^{t-1} in **(1)** has to be considered only for agricultural cells, i.e. if $m \in A$. Besides, note that, when m is a cell of agricultural type, a further state equation, corresponding to the balance for the unsaturated zone, is needed. Such an equation may be written, for a cell $m \in A$,

$$V_{m,rz}^t = V_{m,rz}^{t-1} + \\ + \left(P_m^{t-1} + I_m^{t-1} - ET_m^{t-1} - WU_m^{t-1} + G_m^{t-1} - R_m^{t-1}\right)\Delta t \qquad \textbf{(3)}$$

where $V_{m,rz}^t$ is the volume of water stored in the root zone [m^3] at time t, P_m^t [m^{3}s^{-1}] is precipitation, I_m^t is the irrigation flow [m^{3}s^{-1}], ET_m^t is the evapotranspiration flow [m^{3}s^{-1}], WU_m^t is the water flow [m^{3}s^{-1}] uptaken by crops, and G_m^t is the water flow [m^{3}s^{-1}] from the saturated subcell, in time interval *(t, t+1)* [m^{3}s^{-1}]. The fraction $\frac{V_{m,rz}^t}{V_v}$ tells how much is far the stored water $V_{m,rz}^t$ from filling completely the available volume among pores V_v, which is a parameter depending on the soil characteristics.

The term R_m^{t-1} may be expressed in different ways as a function of the volume of water stored (see Prajamwong *et al.*,1997; Bear, 1972).

In particular, the model used in this work adopts the following expressions for R_m^t [m^{3}s^{-1}]:

$$R_m^t = 0 \quad if \quad \frac{V_{m,rz}^t}{V_v} < 1 \\ R_m^t = \frac{V_v}{\Delta t} \quad if \quad \frac{V_{m,rz}^t}{V_v} = 1 \qquad \textbf{(4)}$$

Besides, in this work, for the sake of simplicity, the term WU_m^t is considered, for simplicity, as a known fraction α [s^{-1}] of the water stored in the root zone, that is

$$WU_m^t = \alpha V_{m,rz}^t \qquad \textbf{(5)}$$

2.2 Mass balance state equations.

The mass balance equations may be obtained by considering the water balance (state) equations **(2)** and **(3)** and multiplying each water flow appearing in such equations by the corresponding pollutant concentration. This computation has to be carried out for each kind of pollutant, giving rise to a new set of state equations. The state equation representing the water balance for cell *m* (*m=1,…,N*) and pollutant *p* (*p=1,…,P*) can be written as

$$
\begin{aligned}
H_m^t C_{m,p}^t &= H_m^{t-1} C_{m,p}^{t-1} - f(C_{m,p}^{t-1}, H_{m,p}^{t-1}) + \\
&+ \varepsilon_m \Big(\sum_k \max(\bar{\varepsilon}_{km}\left[H_k^{t-1} - H_m^{t-1}\right], 0) C_{k,p}^{t-1} + \\
&- \sum_k \max(\bar{\varepsilon}_{km}\left[H_m^{t-1} - H_k^{t-1}\right], 0) C_{m,p}^{t-1} + \\
&- Q_m^{t-1} C_{m,p}^{t-1} + R_m^{t-1} C_{m,rz,p}^{t-1} + \sum_{y=1}^{YN} \tilde{E}_{m,y}^{t-1} C_{\tilde{E}_{m,y},p}^t + \\
&- S_{out,m}^{t-1} C_{m,p}^t \Big)\Delta t
\end{aligned} \qquad \textbf{(6)}
$$

$$m=1,\dots,N \quad p=1,\dots,P \quad t=1,\dots,T$$

where:

- $C_{m,p}^t$ is the concentration [mg/m^3]of pollutant *p* (*p=1,...P*) in cell *m* at time *t*;
- $C_{m,rz,p}^t$ is the concentration [mg/m^3] of pollutant *p* (*p=1,...P*) in the unsaturated sub-cell of the agricultural cell at time *t* ($m \in A$);
- $\tilde{E}_{m,y}^t$ is a flow [m^{3}s^{-1}] taking into account a set of physical effects (precipitation, evapotranspiration, surface water inflow) that take place in cell *m*, for contribution *y* (*y=1,…,YN*) ;
- $C_{\tilde{E}_{m,y},p}^t$ is the concentration [mg/m^3]of pollutant *p* for contribution *y*;
- $S_{out,m}^t$ is the estimated surface water outflow [m^{3}s^{-1}].

For agricultural cells, it is necessary to take into account the influence of pollutant concentrations in irrigation water, of fertilizers use, and of crop uptake. As regards the last issue, it is supposed that the required mass flow of nutrients (entering the water volume in time interval *(t, t+1)* and corresponding to the generic compound p), that is subtracted to the concentration in the unsaturated zone, is a non manipulable time-varying quantity namely, $N_{REQ,p}^{t-1}$ [mg/s]).

Besides, it is assumed that the nutrients income [mg/s] due to fertilizer application, in time interval *(t, t+1)* is given by

$$N_{Fert,m,p}^t = \sum_{c=1}^{C} \sum_{k=1}^{K} F_{m,k,c}^t \tilde{A}_{m,c} \alpha_{k,p} \qquad [mg/s],$$

where $F_{m,k,c}^t$ [mgm^{-2}s^{-1}] is the quantity of fertilizer k applied in cell $m \in A$ per unit time and unit area, as regards crop typology c in time interval *(t,t+1)*, $\tilde{A}_{m,c}$ is the area dedicated to crop c in cell $m \in A$, and $\alpha_{k,p}$ is the percentage of compound p that is present in fertilizer k and that actually reaches the soil. On the basis of such notations, the following state equations may be written ($m \in A$)

$$
\begin{aligned}
V_{m,rz}^t C_{m,rz,p}^t &= V_{m,rz}^{t-1} C_{m,rz,p}^{t-1} + \Big(P_m^{t-1} C_{Pm,p}^{t-1} + \\
&+ I_m^{t-1} CI_{m,p}^{t-1} - N_{REQ,p}^{t-1} + N_{Fert,m,p}^{t-1} + G_m^{t-1} C_{m,p}^{t-1} + \\
&- R_m^{t-1} C_{m,rz,p}^{t-1} \Big)\Delta t
\end{aligned} \qquad \textbf{(7)}
$$

$$m=1,\dots,N \quad p=1,\dots,P \quad t=1,\dots,T$$

2.1 Crop production equation

When analysing an agricultural cell, it is necessary to take into account the yield production for every crop type. In fact, nutrients (present in soil or applied as fertilizers) contribute to yield production in a measure that depends on the water provided, the fertilizer quantity, and the presence of specific compounds that can influence the crop growth. More specifically, according to Reid (2002), there is a quantity of fertilizer for which the yield is maximum, while, for higher or lower quantities, the yield production decreases. The extent to which it decreases for an equal addition or subtraction is dependent on the crop and soil types. In addition, the influences of water and other compounds, such as salinity (Feinerman and Yarow, 1983), on yield have to be considered. In the presented work, the yield is considered to be a function of the water flow and the amounts of nutrients provided (both from natural - such as precipitation or soil chemical content- and non natural sources -such as fertilizers and irrigation practices), and of those compounds, such as salinity, that influence crop growth. The yield is usually expressed as an adimensional fraction *Y** between the actual yield *Y* (per unit area) and the maximum yield, namely $Y^* = \dfrac{Y}{Y_{\max}}$, where Y_{max} (Reid, 2002) is a function of the water content present in the soil and of the characteristics of the cell. Actually, *Y** may be evaluated on the basis of the limiting factors due to the amount of available fertilizer, to the PH, to salinity, etc. For the sake of simplicity, in the following, only limiting factors related to the availability of fertilizers are taken into account.

More specifically, the yield $Y_{m,c}^t$ is function of the crop water uptake $W_{u,m}^t$ and of the quantity of applied fertilizers $F_{m,c,k}^{t-1}$, whereas harvested yield

$HY_{m,c}^{t}$ is proportional to the produced yield $Y_{m,c}^{t}$ through parameter $\beta_{m,c}$; namely

$$Y_{m,c}^{t} = f_{m,c}(W_{u,m}^{t-1}, F_{m,c,k}^{t-1}) \quad \textbf{(8)}$$

$$HY_{m,c}^{t} = \beta_{m,c} Y_{m,c}{}^{t} \quad \textbf{(9)}$$

$$m \in A \quad c=1,\dots C \quad t=1,\dots,T$$

3. PLANNING PROBLEMS

Planning problems mainly regard decisions relevant to the choice of technologies, infrastructures, and to the definition of specific land uses. Such a kind of problems refers to long term decisions and their position does not require the use of real time information. Possible decisions that have to be considered within a planning framework are: where to install a pump (that is to say, the choice of the water body to exploit), which pump kind/size to use, how much money to allocate for specific tasks, where to install treatment plants (which size, kind, etc.), where to perform monitoring campaigns and networks. In the next subsections decision variables, constraints and objectives relevant to planning problems will be introduced.

3.1 The model equations

In this problem formulation, state equations are not present in the model formulation. However, it is necessary to relate the various decision variables and the model parameters through algebraic equation representing water and mass balances. Such algebraic equations may be obtained by **(2)**, **(3)**, **(6)** and **(7)**, respectively, by eliminating the dependence on time variable *t*. As an example, consider the following algebraic equation obtained from **(2)**

$$\sum_{k=1}^{N} \max(\bar{\varepsilon}_{km}\left[H_k - H_m\right], 0) + \\ -\sum_{k=1}^{N} \max(\bar{\varepsilon}_{km}\left[H_m - H_k\right], 0) + \\ -Q_m + R_m + E_m = 0 \quad \textbf{(2a)}$$

$$m=1,\dots N$$

3.2 The decision variables

The water pumped from a specific cell *m* is one of the main decision variables to be taken into account, and the values of such variables have to be selected in order to ensure a sustainable exploitation of the various water bodies. Let Q_m be the overall pumped water flow [m^3/s] in cell *m.* The extracted water can be used for different purposes. The destination use is indicated with *z* (irrigation, drinking water, etc.) and the pumped water can be used either in the same cell in which it is extracted or in other cells. $Q_{k,m,z}$ is the water flow that, after extraction in cell *k,* is used in the generic cell *m* for use *z.*

The pumping wells that can be used to extract water can be of different sizes and kinds (related to the depth). Then, it is necessary to introduce binary variables indicating the presence of a pumping well (of a specific kind) in a specific cell. Let δ_m be a variable whose value is equal to 1 when there is a well in cell m, and equal to 0 otherwise.

Another important issue that influences the environment and the economics of a territorial system is land use, because different land uses (grazing, woodland, residential area, industrial area, dumpsite, etc.) produce different incomes, have different management costs, and different impacts on the environment. In this framework, let us indicate as $\widetilde{A}_{m,L_x}$ the area [hectares] in cell m that is dedicated to land use/activity L_x ($x=1,\dots X$).

One of the human activities having the strongest impact on aquifers is agriculture. In this connection, different decision variables can be used in order to represent the feasible choices concerning agricultural land use, especially as regards the adoption of sustainable farming practices for food production, considering different types of crops. Let $F_{m,k,c}$ be the quantity of fertilizer [kg/m^2] and/or pesticide k given to crop type c, and $\widetilde{A}_{m,c}$ be the area [m^2] disposed for crop of kind c (olive, vineyard, rice, wheat, soybean, cotton, etc.) in cell m.

Another important decision variable is the water flow that is assigned to a specific crop.

Let $I_{m,c}$ [m^3s^{-1}/m^2] be the water flow per unit area provided for crop type c in cell m, and $HY_{m,c}$ the harvested yield [kg/m^2year] for crop type *c* in cell *m.* Moreover, it is possible to define an economic decision variable related to the possibility of reducing the attitude of the farmers to use certain types of fertilizers and pesticides to increase crop production. More specifically, let $IF_{m,k,c}$ [€/m^2year] be the incentive given to farmers for not using fertilizers/pesticide *k* in crop *c* in cell m. A similar class of decision variables is that relevant to the price of water for the different water uses. Let P_z [€/m^2year] the price for water use *z.*

3.3 The objectives

Several objectives should be taken into account when planning water resources exploitation within an integrated framework. Such objectives are:

1. minimizing the economical costs and maximizing the benefits;

2. minimizing water demand dissatisfaction (with respect to the expressed aspiration levels);
3. minimizing the overall concentration of pollutant p in the aquifer;
4. minimizing concentration of pollutant p in the pumped water;
5. maximizing agricultural productivity.

All such objectives may be expressed by using the above introduced decision variables.

Objective 1: minimizing the costs and maximizing benefits. The costs and benefits to be considered are:

- water distribution costs and benefits from water sales;
- pumping costs;
- farming costs (costs of fertilizers/pesticides, irrigation costs, harvesting costs, etc.);
- farmers incentives for not using fertilizers/pesticides;
- land use costs and benefits;

Water distribution costs may be partitioned into different (additive) terms. The first one ($FC_{k,m}$) represents the fixed costs [€/year] (for example personnel and instruments for maintenance, energy for pumps, installation costs) for tubes, pumps and reservoirs necessary to transport and store water from cell k to cell m. The second one ($C^u_{k,m}Q_k$) represents the proportional cost [€/year], which can be assumed to depend linearly on the water flow (because different water flow amounts require infrastructures having different sizes). Finally, it is necessary to take into account also the benefits deriving from water sales. Namely, being P_z the price of water [€/m³], the net water distribution costs are

$$CW = \sum_{k}^{N}\sum_{m}^{N}(FC_{k,m} + C^u_{k,m}Q_k) - \sum_{z=1}^{Z}P_z\sum_{m=1}^{N}\sum_{k=1}^{N}Q_{k,m,z} \quad \textbf{(10)}$$

Pumping costs include fixed costs CPT_m for the installation of pumping wells (that vary depending on the type of pumping well w) and the costs due to the energy used to lift water from the well. In fact, the water level H_m [m] in the well , that depends on the quantity of water stored in the aquifer, must be lifted to the surface of elevation in order to be extracted. To this end, it is necessary to use a certain amount of energy. It is reasonable to represent the overall pumping cost CP_m [€/year] in cell m as

$$CP_m = CPu_m Q_m(\overline{H}_m - H_m)K_e + CPT_m\delta_m \qquad m=1,\dots,N \quad \textbf{(11)}$$

where:

- $\overline{H}_m$ is the height of ground level above an impermeable soil layer;
- Q_m is pumped water [m³/s] in cell m;
- CPu_m is unit cost for energy used to lift water in cell m [€/KWh];
- H_m is the piezometric head [m] of cell m;
- K_e is a constant [KWh/(m⁴/s)];
- CPT_m is the fixed cost for the installation of a well of type w in cell m;
- δ_m is the binary decision that indicates the presence of pumping well in cell m ($\delta_m = 1$), or not.

Farming costs are mainly due to irrigation, fertilizers/pesticides use, and harvesting. Recall that every agricultural cell is characterized by different crops. The typologies of crops are indicated with $c=1,\dots,C$, and each of them is characterized by specific fertilizer and irrigation strategies.
Specifically, it is possible to take into account the following costs:

- irrigation costs, which are proportional to the irrigation water flow $I_{m,c}$ [m³s⁻¹/m²] that is used for every crop c, whose unit cost is $C_{I,m}$ [€/m³s⁻¹year];
- fertilizing costs, which depend on the type and on the quantity of fertilizer k ($F_{k,c,m}$, [kg/m²year]) used for a specific crop c in cell m and on their unit costs $C_{Fu,k}$ [€/kg];
- harvesting costs, which are given by the product of the harvested quantity in crop c, $HY_{c,m}$, [kg/m²year], the crop area $\widetilde{A}_{m,c}$ [m²] and a unit cost Cu_c [€/kg];
- harvesting benefits, which can be expressed as the product of the area dedicated to crop c ($\widetilde{A}_{(i,j),c}$) times a coefficient B_c [€/m²year];
- fixed costs, which can be evaluated for every crop and can be globally expressed by terms $C_{FI,m,c}$, for each cell.

On the whole, the overall farming costs can be expressed as

$$CC = \sum_{m=1}^{N}\sum_{c=1}^{C}((\sum_{k=1}^{K} F_{k,c,m}C_{Fu,k}\widetilde{A}_{m,c}) + C_{I,m}I_{m,c}\widetilde{A}_{m,c} + Cu_c HY_{c,m}\widetilde{A}_{m,c} - B_c\widetilde{A}_{m,c}) + \sum_{c=1}^{C}C_{FI,m,c} \quad \textbf{(12)}$$

One of the main problems regarding agriculture is that the use of certain fertilizers and/or pesticides may lead to problems for water quality. However, these chemical compounds are used to increase the crop yields, thus providing a higher income from the sale of agricultural products. In this connection, one of the interventions that may be considered to be undertaken is the introduction of specific incentives to farmers in order to induce them not to make use of an excessive amount of fertilizers. The following structure can be selected, or regards the expression of the overall incentive to farmers CI [€/year]

$$CI = \sum_{m=1}^{N}\sum_{c=1}^{C}\sum_{k=1}^{K} IF_{m,c,k}\left(\max\left(\left(\frac{a_{m,c,k}}{b_{m,c,k}+F_{m,c,k}}\right), d\right) - d\right) \quad \textbf{(13)}$$

where:

- $IF_{m,c,k}$ [€/m^{2}year] is the incentive given for not using a certain fertilizer *k* for crop *c* in cell *m*;
- $F_{m,c,k}$ [kg/m^{2}year] is the amount of used fertilizer;
- $a_{m,c,k}$ [kg/m^{2}year], *b*[kg/m^{2}year], and *d* [€/m^{2}year] are suitable coefficients .

Note that when $F_{m,c,k} = 0$ (i.e., no fertilizer is used at all, the contribution of cell *k* to the overall cost CI, for fertilizer *k*, and crop *c*, corresponds to $\frac{a_{m,c,k}}{b_{m,c,k}}$. Instead, when $F_{m,c,k} \to +\infty$, then such a contribution is zero.

A specific land use (agriculture, industry, grazing, residential area, etc.) may produce costs and benefits in proportion to the area disposed for the specific land use. Indicating with $\tilde{A}_{m,L_x}$ the area disposed for land use *x (x=1,...,X)* and with B_x and C_x benefits and costs, respectively, per unit area for land use *x*, the following expression for land use cost can be adopted

$$CL = \sum_{m=1}^{N}\sum_{x=1}^{X} \tilde{A}_{m,L_x}(-B_x + C_x) \quad \textbf{(14)}$$

The overall cost expression J_1 is given by the sum of the previous listed contributions.

Objective 2: minimizing water demand dissatisfaction. The main kinds of water demand to be satisfied regard irrigation, drinking water and industrial/public use. The target is to satisfy, as far as possible, the water demands, estimated on the basis of the exposed local exigencies. Specifically, let us use the notation $D_{m,z}$ for the water demand in cell *m* for water use *z* (irrigation, drinking water, other uses). The overall pumped water Q_m [m^3/s] in cell m can be used in the same cell or can be used in other cells for different purposes. The decision variable $Q_{k,m,z}$ is the flow of water that, after extraction in cell *m* is used in the generic cell *m* for destination use *z* (irrigation, drinking water, etc.). The water demand dissatisfaction is given, by

$$J_2 = \sum_{z=1}^{Z}\sum_{m=1}^{N} \alpha_z \max\left(D_{m,z} - \sum_{k=1}^{K} Q_{k,m,z}, 0\right) \quad \textbf{(15)}$$

where α_z are weight coefficients regarding water use and water demand of a specific cell.

Objective 3: minimizing the overall pollutant concentration in the aquifer. Each part of the aquifer can be affected by different kinds of pollutant. In order to take into account the various pollutants, it is possible to consider a reference value for the concentration of the various pollutants. Then, a possible structure for this kind of cost to be minimized is

$$J_3 = \sum_{m=1}^{N}\sum_{p=1}^{P} \max\left\{ \frac{C_{m,p}}{\overline{C}_p} - 1, 0 \right\} \quad \textbf{(16)}$$

where*:*

- $C_{m,p}$ is the pollutant concentration in aquifer cell *m* [mg/m^3];
- $\overline{C}_p$ is a value considered as a reference value for the specific pollutant *p* (*p=1,...,P*).

Objective 4: minimizing concentration of pollutant p in the pumped water. Another objective of the optimization problem is to minimize the concentration of pollutant in the water extracted from wells. Let $C_{m,p}$ be the concentration of pollutant *p*, expressed in mg/l, of the water extracted from cells where pumping wells are present. The considered objective can be represented as follows

$$J_4 = \sum_{m=1}^{N} Q_m F\left[\frac{C_{m,p}}{\overline{C}_p}\right] \quad \textbf{(17)}$$

where $F\left[\frac{C_{m,p}}{\overline{C}_p}\right]$ is a function of pollutant concentration.

Objective 5: maximizing agricultural efficiencies. The yield that is produced from the different crops *c (c=1,...,C)* in cell m, $HY_{m,c}$, should be characterized by a pre-defined efficiency $\tilde{Y}_c$. Then, a sensible goal is that of maximizing the fraction between the produced yield and the expected yield, and thus the objective function to be minimized is

$$J_5 = \sum_{m \in A}\sum_{c=1}^{C} \frac{\tilde{Y}_c}{HY_{m,c}\tilde{A}_{m,c}} \quad \textbf{(18)}$$

The overall objective function. The overall objective function is given by the weighted objectives previously formalized. Specifically, the overall objective function to be minimized is

$$Min \quad \sum_{i=1}^{5} \gamma_i J_i \qquad \textbf{(19)}$$

where:

- γ_i is the weight for the *i-th* objective;
- J_i is the i-th objective, where J_1, J_2, J_3, J_4, and J_5

3.4 The constraints

The constraints that are necessary to build up a decision model for planning purposes belong to different classes: the land use constraints, based on territorial considerations, chemical constraints (about the pollutant concentration), the constraints represented by the state equations, water demand constraints, legislative, technological, and economic constraints. In the following, all the mentioned classes of constraints are explained and formalized.

Land use constraints state that the area disposed for every land use can not exceed a predefined value $\widetilde{A}_{L_x}$. Obviously, among the various land uses, there is also the area disposed for agricultural use (given by the sum of the areas disposed for every crop in every cell). These constraints are formalized as follows

$$\widetilde{A}_{m,L_x} \le \widetilde{A}_{L_x} \quad x=1,\dots,X \quad m \in A \qquad \textbf{(20)}$$

For concentration there are different types of constraints that can be formalized in order to reduce and control pollution in the aquifer system. First of all, it can be stated that the pollutant concentration in every aquifer cell is less or equal to a pre-defined value $C^*_{m,p}$, that is to say

$$C_{m,p} \le C^*_{m,p} \qquad p=1,\dots,P \quad m=1,\dots,N \qquad \textbf{(21)}$$

Then, it is necessary to limit the pollutant concentration in the pumped water. Specifically, depending on the water use, the extracted water must not exceed specific levels imposed by regulation. Then, such constraints can be expressed as

$$C_{m,p} Q_{k,m,z} \le \overline{C}_{z,p} Q_{k,m,z} \qquad \textbf{(22)}$$
$$p=1,\dots,P \quad z=1,\dots,Z \quad m=1,\dots,N$$

and, of course, have effect only for non zero flows $Q_{k,m,z}$. Then, it is important to remind that the variables $Q_{k,m,z}$ are related to the variables Q_m by the following expression

$$Q_m = \sum_{k=1}^{N} \sum_{z=1}^{Z} Q_{k,m,z} \qquad m=1,\dots,N \qquad \textbf{(23)}$$

Three main kinds of water demand constraints can be formalized: the satisfaction of a minimum water request for the different uses, the relation between the amount of irrigation water and the pumped water, and the satisfaction of plant water requirements.

Indicating with $D_{z,m}^{\min}$ the minimum water demand to be satisfied for use *z* (agriculture, industry, drinking water, etc.) in cell *m*, the following constraints can be formalized,

$$\sum_{k=1}^{N} Q_{k,m,z} \ge D_{z,m}^{\min} \qquad z=1,\dots,Z \qquad m=1,\dots,N \qquad \textbf{(24)}$$

The water that is extracted and that is dedicated for agricultural use ($Q_{k,m,z}$, $z=A$) has to be related to the decision variable that represents the quantity of irrigation water that is provided to a certain crop type ($I_{m,c}$). In this work, it is supposed that all the water used for irrigation comes from the aquifer system. That is to say, the total amount of water disposed of agricultural use should be greater than or equal to the water effectively used for irrigation,

$$\sum_{k=1}^{K} Q_{k,m,z} \ge I_m \qquad z = A \qquad m \in A \qquad \textbf{(25)}$$

where

$$I_m = \sum_{c=1}^{C} I_{m,c} \widetilde{A}_{m,c} \qquad m \in A \qquad \textbf{(26)}$$

Finally, the irrigation water should be sufficient for plant life and crop growth, considering the climatic conditions of the area. Specifically, the irrigation water given to a specific crop ($I_{m,c}\widetilde{A}_{m,c}$) plus the contribution of precipitation ($\frac{P_m \widetilde{A}_{m,c}}{\widetilde{A}_m}$) minus the water that evaporates ($ET_{m,c}\widetilde{A}_{m,c}$) must be greater that or equal to the required amount of water $W_{m,c}^{REQ}$ for the specific crop. This constraint is expressed as

$$I_{m,c}\widetilde{A}_{m,c} + \frac{P_m \widetilde{A}_{m,c}}{\widetilde{A}_m} - ET_{m,c}\widetilde{A}_{m,c} \ge W_{m,c}^{REQ}$$
$$c=1,\dots,C \qquad m \in A \qquad \textbf{(27)}$$

Technological constraints and energy constraints allow considering technological characteristics of the treatment plants and the pumps. Specifically, for the pump-sizing, it can be stated that the pumped water must lie within a range of values,

$$\overline{Q}^{\min} \le Q_m \le \overline{Q}^{\max} \qquad m=1,\ldots,N \qquad \textbf{(28)}$$

where $\overline{Q}^{\min}$ and $\overline{Q}^{\max}$ represent, respectively, the minimum and the maximum allowable pumping rates. It is important to note that in every cell m, there must be at maximum only one well (of any kind), i.e.

$$\delta_m \in \{0,1\} \qquad m=1,\ldots,N \qquad \textbf{(29)}$$

Economic constraints are relevant to the limitations of water price and incentives to farmers between a lower and an upper bound. That is to say,

$$P^{\min} \le P_z \le P^{\max} \qquad z=1,\ldots,Z \qquad \textbf{(30)}$$

$$IF_c^{\min} \le IF_{c,m} \le IF_c^{\max} \quad c=1,\ldots C \quad m=1,\ldots,N \qquad \textbf{(31)}$$

Finally, the algebraic equations deriving from the state equations must be included as constraints. Finally, crop growth equations have to be included in the problem formulation.

4. MANAGEMENT PROBLEMS

Management problems are relevant to those classes of decisions that should be taken by using also real time information, and with reference to a certain optimisation horizon. Specifically, management decisions are: the definition of the pumping pattern, the definition of the irrigation schedule, the application of fertilizers, crop rotation, plume containment for polluted aquifers.

The main difference between planning and management problems is that the decision variables are here time-dependent.

The physical model is characterized by equations **(2-7)** . Moreover, crop growth equations **(8)** and **(9)** have to be included as constraints in the optimisation problems. The decision variables are: H_m^t, $V_{m,rz}^t$, $C_{m,p}^t$, $C_{m,rz,p}^t$, S_m^t, Q_m^t, $Q_{k,m,z}^t$, $F_{m,k,c}^t$, $\widetilde{A}_{m,c}$, $I_{m,c}^t$, $HY_{m,c}$, all already defined.

The typologies of objectives for the Management problems have exactly the same contributions as for Planning problems. The formalization of the objectives (and constraints) in Management problems differs for the necessity of taking into account the time dependence. As a consequence, there is the necessity of a summation over time. The different classes of constraints relevant to Management problems are similar to those considered for Planning problems.

5. AN APPLICATION: POLLUTION CONTROL

In this case, the aim is that of developing a management model that is able to define the optimal pumping pattern for *p* (*p=1, P*) wells that withdraw water from an aquifer, characterized by pollutant contamination, with the objective of satisfying the requested water demand while satisfying pollution containment objectives.

5.1 The physical chemical model

The overall model of the considered system may be decomposed into a hydraulic component and a chemical one. As regards the hydraulic component, the adopted model is drawn by Schwartz (2002) and particularly focuses on the behaviour of the piezometric head at local scale, and specifically on the interaction among the various wells. The pollutant mass transport equation is solved using a finite difference scheme. The hypotheses under which our model is applied are:

1. confined, homogeneous and isotropic aquifer;
2. source terms represented by pumping wells with given pumping pattern $Q_p(t)$ for $p=1,\ldots P$;
3. wells completely penetrating and located in (x_p, y_p), $p=1,\ldots P$.

It is possible to evaluate (Schwartz, 2002) the piezometric head, in stationary condition, as follows

$$h(x,y,t) = H + \sum_{p=1}^{P} \frac{Q_P(t)}{2\pi T} \ln \frac{\sqrt{(x-x_P)^2 + (y-y_P)^2}}{R} \qquad \textbf{(32)}$$

where $T=KB$ is the trasmissivity of the homogeneous aquifer and B is its thickness. Using Darcy's law, it is possible to write an analytical expression for the velocity field due to P pumping wells spread in the domain and having different pumping rates Q_p. Let n be the soil porosity, and u and v the components of the velocity of the fluid flowing in the aquifer along x and y directions, respectively. Such velocities can be expressed as follows

$$u(x,y,t) = \frac{-1}{2n\pi B} \sum_{p=1}^{P} \frac{Q_p(t) \quad (x-x_p)}{(x-x_p)^2 + (y-y_p)^2} \qquad \textbf{(33)}$$

$$v(x,y,t) = \frac{-1}{2n\pi B} \sum_{p=1}^{P} \frac{Q_p(t) \quad (y-y_p)}{(x-x_p)^2 + (y-y_p)^2} \qquad \textbf{(34)}$$

The knowledge of the velocity field is needed in order to solve the mass transport equation. To this end, a contaminant transport numerical model is used, which is able to predict the concentration behaviour in the aquifer for a biodegradable pollutant. Since in many application concerning the monitoring of groundwater

quality, the only concentration measures that are often available are the mean value over the thickness of the sampling well, the averaged mass transport equation is taken into account in this work. These equations can be obtained by vertically averaging the classical advection-dispersion equation over the thickness of the aquifer system (Willis et al.,1998; Bear, 1972).
The mass transport equation can be solved by using the classical central finite difference scheme in space, and an implicit method in time (Fletcher, 1991). The stability of the methods is related to the dispersion and advection Currant numbers, defined as

$$C_{adv} = \frac{v\,\Delta t}{\Delta L} \quad \text{and} \quad C_{disp} = \frac{D\,\Delta t}{\Delta L^2}.$$

The finite difference representation of the equation is for any point *i,j,* (a generic point (*x,y*) on the grid) at any time *t*) is :

$$\frac{\overline{C}_{i,j}^{t+1} - \overline{C}_{i,j}^{t}}{\Delta t} + u_{i,j}^{t+1}\frac{(\overline{C}_{i+1,j}^{t+1} - \overline{C}_{i-1,j}^{t+1})}{2\Delta x} + v_{i,j}^{t+1}\frac{(\overline{C}_{i,j+1}^{t+1} - \overline{C}_{i,j-1}^{t+1})}{2\Delta x}$$
$$= D\frac{(\overline{C}_{i+1,j}^{t+1} - 2\,\overline{C}_{i,j}^{t+1} + \overline{C}_{i-1,j}^{t+1})}{\Delta x^2} + D\frac{(\overline{C}_{i,j+1}^{t+1} - 2\,\overline{C}_{i,j}^{t+1} + \overline{C}_{i,j-1}^{t+1})}{\Delta y^2}$$
$$-\sum_{p=1}^{P}\frac{\overline{C}_{i,j}^{t+1}\,Q_p^{t+1}}{B\,\Delta x\,\Delta y}\delta^*(i - i_p, j - j_{p,}) - k\,\overline{C}_{i,j}^{t+1} \quad \textbf{(35)}$$

where (i_p, j_p) is the location of the generic well on the grid.

5.2 The management model

The control variables that characterize the system are the quantity of water that is extracted in each well p in time interval t. These quantities influence both the hydraulic head and the concentration distributions in the aquifer. The state variables of the system correspond to the pollutant concentrations and to the hydraulic heads in the aquifer. Let $Q_{p,t}$ be the control variable that represents the quantity of water that is extracted in each well *p* in time interval (*t,t+1*). These quantities influence both the hydraulic heads and the concentration distributions in the aquifer. Moreover let $\overline{C}_{i,j,t}$ represent the pollutant concentration in the aquifer at time *t* in point (*i,j*). Clearly, the pollutant concentration in the extracted water from wells corresponds to the pollutant concentration $\overline{C}_{i,j,t}$ in the nodes of the grid where the wells are located. Specifically, $\overline{C}_{i,p}$ represents the pollutant concentration in well *p* (*p=1,...,P*) at time t (*t=1,...,T*), where $p=(i_p,j_p)$.
The objective function (to be minimized) considered in connection with this case study is composed by three terms: water demand dissatisfaction, pollutant concentration in extracted water, pollutant concentration in all nodes of the discretized aquifer. Every term of the objective function is weighted by specific coefficients.

Minimization of water demand dissatisfaction. The water demand dissatisfaction corresponds to the difference between the requested water and the extracted water from the wells, when such a difference is positive or zero. Thus this objective function (to be minimized) can be expressed as

$$\max\left[\left(Q_{REQ} - \sum_{p=1}^{N}\sum_{t=0}^{T-1} Q(p,t)\right), 0\right] \quad \textbf{(36)}$$

where:

- Q_{REQ} represents the overall requested water flow, expressed in l/s, over the whole decision horizon;
- *N* is the number of available wells;
- *T* is the planning horizon.

Minimization of pollutant presence in extracted water. Another objective of the optimization problem is to minimize the impact of the pollutant in the water extracted from wells. Let $\overline{C}(p,t)$ be the pollutant concentration, expressed in mg/l, of the water extracted from well *p* in the *t-th* time interval. This objective function can be formalized as follows

$$\sum_{p=1}^{N}\sum_{t=1}^{T} Q(p,t)F\left[\overline{C}(p,t)\right] \quad \textbf{(37)}$$

where $F\left[\overline{C}(p,t)\right]$ is a function of the pollutant concentration and has been taken as

$$F\left[\overline{C}(p,t)\right] = \overline{C}(p,t)^2 \quad \textbf{(53)}$$

Minimization of pollutant concentration in the aquifer. The aquifer pollution should be limited for two important reasons: the preservation of the water resource and the possibility to satisfy water demand for a longer time in the future. Denoting by $\overline{C}(i,j,T)$ the pollutant concentration [mg/l] at node *(i,j)* at the end of the optimisation period, the objective function to be minimized is

$$\sum_{i=0}^{I}\sum_{j=0}^{J}\overline{C}(i,j,T) \quad \textbf{(38)}$$

where *i* and *j* are the coordinates of the nodes of the grid representing the aquifer.
Then, the overall objective function to be minimized is obtained through the weighted sum of the above introduced functions, each one multiplied by a specific weighting factor. Then, the following minimization has to be carried out

$$\min\left\{ \alpha \cdot \max\left[\left(Q_{REQ} - \sum_{p=1}^{N}\sum_{t=0}^{T-1} Q(p,t)\right), 0\right] + \beta \cdot \sum_{p=1}^{N}\sum_{t=0}^{T-1} Q(p,t) F\left[\overline{C}(p,t)\right] + \gamma \cdot \sum_{i=0}^{I}\sum_{j=0}^{J} \overline{C}(i,j,T) \right\} \quad \textbf{(39)}$$

where α, β, and γ are suitable weighting coefficients.

The constraints. There are different kinds of constraints that should be considered in the model. The first class of constraints represents the state equations that represent the dynamics of the pollutant concentrations and of the hydraulic head, as driven by the control variables.

The other constraints are: the hydraulic head limitations due to hydraulic conditions that must be respected, the capacities of the wells, and the constraints that prevent to extract water from wells when the pollutant concentration exceeds the one imposed by regulations.

Besides, one can impose the physical conditions that ensure the consistency of some hypothesis. One of them is that the aquifer is "in pressure", that is to say

$$h(i,j,t) > B \quad \textbf{(40)}$$

where B is the aquifer thickness.

Moreover, the water flow extracted from a well must be less or equal to its capacity, namely

$$Q_{p,t} \le W_p \qquad p = 1,\dots,P \qquad t = 1,\dots,T \quad \textbf{(41)}$$

Finally, the water extracted must have a concentration of pollutant not exceeding a specific bound defined by regulations. In other words, this means that:

$$\overline{C}_{p,t} > C^* \Rightarrow Q_{p,t} = 0 \quad p=1,\dots,P \;\; t=1,\dots,T \quad \textbf{(42)}$$

where C^* is the maximum pollutant concentration allowed by regulation.

5.3 Results

The model has been applied to a study area of 50mx50m in which three wells pump water from a confined aquifer that is affected by nitrate pollution. As regards the spatial location of the pumping wells, with respect to the source of pollution, well 1 is the nearest to the pollutant source, while well 3 is the most far. The case study is located within the Ceriale Municipality (Savona, Italy), and the confined aquifer is affected by nitrate pollution due to agricultural practices. The well field is used to extract water for drinking use, but it is periodically closed because of the pollution due to nitrates infiltration. The application of the optimisation model allows finding the optimal pumping pattern in order to satisfy the water demand needs and to control the advancing of the pollutants in the aquifer.

The optimisation problem has been solved over a three months period. The aquifer has been discretized in space (1 m), and in time (10 hours). The total water demand is 600 l/min, while the pollutant concentration in the polluting source is 150 mg/l. The initial value of the hydraulic head over the whole considered area is 20 m, while the aquifer thickness is equal to 15 m. Moreover, each well is able to pump the total amount of the water demand, that is 10 l/s. According to the experts, the optimisation problem has been solved for two different cases in which there are specific technical configurations of the pumping wells. Specifically, in Case 1, each well is hypothetically able to pump the total amount of the water demand, that is 10 l/s, while in Case 2 each well is able to pump 3.3 l/s.

The management problem formalized in the previous section has been solved over a time horizon of three months for the two cases, and the weight coefficients are imposed equal to one.

Case1-results. In the optimal solution, only well 1 (the nearest to the pollution source) overcomes the law limit (50 mg/l) reaching a concentration value of about 106 mg/l. Well 2 and well 3 (the farthest from the pollution source) reach a maximum concentration of 40 and 21 mg/l, respectively, far below the threshold for the whole length of time horizon. Figure 3 shows the pattern of the concentration over time, for the three wells.

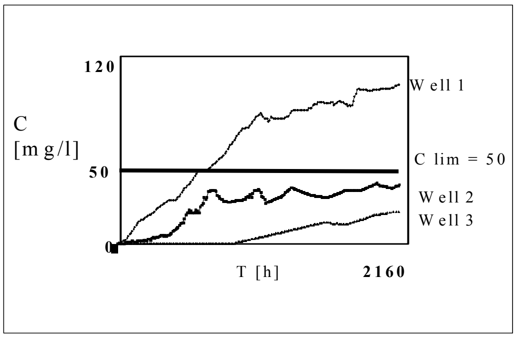

Figure 3. Pollutant concentration in the extracted water

The water demand is completely satisfied. As it is evident in Figure 4, that shows the pumping pattern in the first 120 hours, all the necessary water is taken from well 3 because it is the most far from the pollutant source.

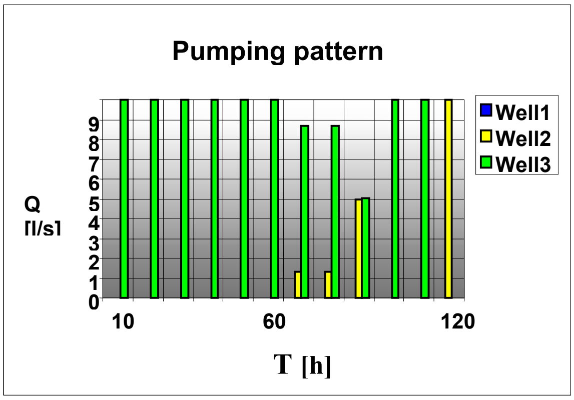

Figure 4. The pumping pattern in the first 120 hours

Case2-results. The results for Case 2 are reported in Figure 5. As it is evident from the pumping pattern, the water demand is not satisfied after 410 hours because well 1 stops pumping. This is due to the fact that well 1 very soon reaches the limit concentration (see Figure 6).

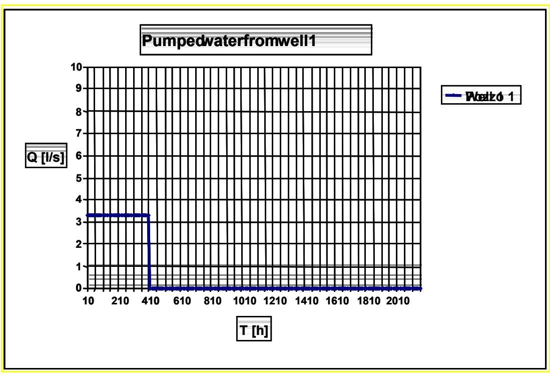

Figure5. The pumping pattern for well 1 in Case 2

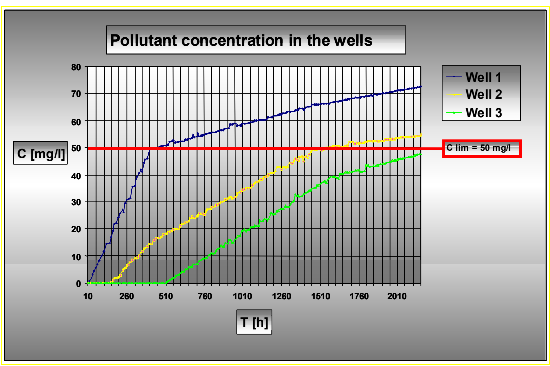

Figure 6. The concentration of pollutants in Case 2

6. CONCLUSIONS

The aim of this work is the definition of methods and models for the sustainable planning and management of groundwater resources. Specifically, attention is focused on the definition of decision models able to integrate the modelling tools made available by hydrology, hydraulics, chemistry, etc. In particular, the main pressures on groundwater quality have been represented in order to be used in the models for the planning and management of groundwater resources: agricultural practices effects, aquifer over-exploitation, saltwater intrusion in coastal aquifers.
The physical/chemical models are based on water and mass balances, considering a multicell scheme, with rectangular cells, following a general formalization approach that provides the opportunity of choosing the degree of accuracy of the discretization.
Two kinds of decision problems are studied: long term planning and short term management. Planning problems mainly regard decisions relevant to the choice of technologies, infrastructures, and to the definition of specific land uses. Management (control) problems are relevant to decisions that specifically require the use of real time information, at least for the position of the problems. For instance, management decisions may regard: the definition of a pumping pattern, the definition of an irrigation schedule, the quantity of fertilizers to be used, crop rotation, plume containment for polluted aquifers.
A specific case study has been presented.
On the whole, the present work may represent a first effort towards the definition of a comprehensive methodological framework for Integrated Water Management. Clearly, a lot of work has still to be done before effective tools may become relevant for practical use. First of all, a careful investigation about the accuracy of the used models (expecially as compared with those relevant to common simulation tools) has to be carried out.
In particular, the validity of several simplifying assumptions in the developed models has to be evaluated. Moreover, and more important, the integration of the developed methodologies tools with GIS requires a deep analysis of the class of problems investigated and of the available data about the considered territory.
Finally, a further possibility to explore is that of integrating the proposed methodology approach, based on the formalization of optimal decision problems, with commercially available simulation tools and GIS platforms. This is actually matter of current activity.

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