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Abstract: A decision model for groundwater quality preservation in areas affected by intensive agriculture and dairy farming, with specific reference to the Azores islands, is presented. In these islands, the exigency to find appropriate instruments to support decisions in Integrated Water Management (IWM) is particularly felt because the increase of tourism and the dairy farming have increased water demands and depletion of water quality. An optimization problem, in terms of decision variables, objectives, and constraints is formalized. The physical/chemical/ecological models are embedded as constraints in the decision model. Specifically, four types of models (hydraulic model, chemical model, agricultural model, and dairy farming model) are integrated and defined. Hydrological data are used to build the hydraulic model that influences the transport and the dilution of pollutants in the groundwater. The chemical model is influenced by the amount of fertilizers and waste from animals used for yield production in the fields (agricultural model). Finally, the dairy farming model influences the agricultural model because of the presence of animals and at the same time is influenced by the available quantity of food produced in the area. The objective function is the maximization of milk production. The other objectives to be taken into account are transformed into constraints: limits on pollutant concentration in the aquifer, on minimum water demand requirements, on the quantity of used fertilizers. The optimisation problem is non linear with non-linear constraints and continuous decision variables. The decision model has been applied to a case study of Terceira Island.

***Keywords**:* Optimization, Dynamic modelling, Water Quality, Dairy Farming, Agricultural Practices

1. INTRODUCTION

Water resources planning and management is becoming one of the most important issues of the twenty first century because of the treats these are subject to: pollution, increase of water demand, global climatic change, etc. Agriculture is one of the most important human activities with a major impact on water resources because, agricultural activities require huge amounts of water and fertilizers (that affect negatively water quality). New incentives and policies for ensuring the sustainability of agriculture and ecosystem services will be crucial if we are to meet the demands of improving yields without compromising environmental integrity or public health (Tilman et al., 2002). It is important to define planning and management strategies that can satisfy water needs, taking into account environmental, ecological, economic, social and legislative issues. In literature, Decision Support Systems (DSSs) for water resources management are widely recognised as the primary tools that assist decision makers in their judgment (Nalbantis et al., 2002; Lombardo et al., 2003). In this work, specific attention is given to the groundwater system. The main scope is to find appropriate solutions for integrating simulation and optimisation tools, which can support the different decision makers. In regard to the simulation, three categories of models appear in the literature. The first category includes the lumped (one-cell) or semi-distributed (multi-cell) models (Bear, 1979; Todd et al., 1998). The second category includes distributed models and may be divided into two subcategories: models based on the equivalent porous medium (EPM) approach (White, 1999) for aquifers with fractures that are sufficiently interconnected and closely spaced; and models with two distinct flow systems, i.e., a conduit system and a fracture system (Mohrlok and Sauter, 1997; Eisenlohr et al., 1997). In the third model category, there are the statistical methods, essentially of black-box type, with the obvious advantage of simplicity and effectiveness. From an optimisation point of view, previous works to define efficient decision models have been undertaken by Van Calker et al. (2004) that built a dairy farm LP (linear programming) model to analyse the effects of environmental policy and management measures on economic and ecological sustainability on Dutch dairy farms. The aim of this paper is to develop a decision model for the groundwater quality preservation in Terceira Island (Azores), while considering the milk and yield production needs. The equations that describe the state of the various subsystems are embedded as constraints in the optimisation problem. The novelties of the approach lie in a new problem formulation (that integrates several aspects), and in the application to a case study that presents original features. The benefits derive from the integration of different issues in a decision model. Besides, for the specific case study, the attempt of defining planning and management strategies based on optimization is an improvement for local IWM.

2. THE SYSTEM DESCRIPTION: THE CHEMICAL, PHYSICAL, AND ECOLOGICAL MODELS

Different types of models have been considered: the hydraulic model, the chemical model, the agricultural model, and the dairy farming model. Figure 1 represents the interactions among these four subsystems. Hydrological data are used to build the hydraulic model that, influences the transport and the dilution of pollutants in the groundwater. The chemical model is influenced by two main contributions of pollutants: the amount of fertilizers used for crop yield production, and the waste of animals grazing in the area. The yield production (that is calculated by the agricultural model) is function of the nutrient input (both fertilizers and waste from animals), of the soil characteristics, and of the area climatic conditions. Finally, the dairy farming model (determining the amount of milk produced and the number of cows in the territory) influences the chemical model.

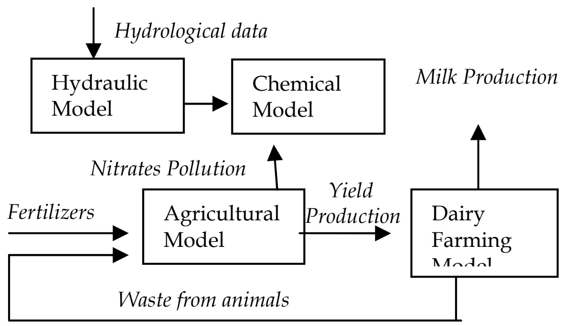

Figure 1. The different subsystems.

2.1 Hydraulic and chemical models

The hydraulic and chemical models are formalized as multi-cell models. The hydraulic model has been built considering the water balance of every cell, and the leakage among cells (governed by Darcy's law). The water balance of the generic cell *i* at instant *t* is given by the sum of the different inputs, minus the sum of the outputs. Specifically, the hydraulic head H_i^t in every cell is given by

$$H_i^t = H_i^{t-1} + \varepsilon_{ij}\left(P_i^{t-1} + FOG_i^{t-1} - WU_i^{t-1} - E_i^{t-1} + \right. \\ \left. - Q_i^{t-1} - W_i^{t-1} - R_i^{t-1} - L_{i,j}^{t-1} \right)\cdot \Delta t$$

$$i=1,\ldots,I \quad \ldots\ldots t=1,\ldots,T \qquad \textbf{(1)}$$

where:

- P_i^{t-1} is net precipitation;
- FOG_i^{t-1} is fog interception, a typical characteristic of the Azores Islands;
- E_i^{t-1} is evapotranspiration;
- Q_i^{t-1} is flow from the springs;
- W_i^{t-1} is water pumped from wells;
- R_i^{t-1} is percolation from the cell;
- WU_i^{t-1} is crop water uptake;
- $L_{i,j}^{t-1}$ is flow going to (or coming from) the adjacent cells, governed by Darcy's law;
- ε_i is a parameter that depends on the geological and geometric characteristics of the cell *i*.

The flow of water from the cell *i* to the cell *j* for phreatic aquifers is given by the Darcy law:

$$L_{ij}^t = K_{i,j} W_{i,j} \frac{H_i^{t-1} - H_j^{t-1}}{l_{ij}} \frac{H_i^{t-1} + H_j^{t-1}}{2} \qquad \textbf{(2)}$$

$$i=1,\ldots,I \quad j=1,\ldots,I \quad t=1,\ldots,T$$

where $K_{i,j}$ is the hydraulic conductivity, $W_{i,j}$ the width, and $l_{i,j}$ is the distance between the two cells.

The WU_i^t contribution is relevant to the water that is taken by the different typologies of crops. Specifically,

$$WU_i^t = \sum_{c=1}^{C} \alpha_{i,c}^t A_{c,i}^t \quad i=1,\ldots,I \quad t=1,\ldots,T \qquad \textbf{(3)}$$

where $\alpha_{i,c}^t$ is crop water uptake per unit area, and $A_{i,c}^t$ is area dedicated to crop *c* (corn, maize and pasture) in cell *i*. In the chemical model, under a simplified hypothesis, nitrates (NO_3^-) are the only pollutants that are taken into account. The mass balance equation for nitrates is almost equal to the water balance equation, with the exception that in this equation, for each component, the concentration of nitrates in the aquifer (C^t_i), has been added at time *t* and for cell *i*. The other new elements are the reaction and adsorption term for the nitrates (*Kn*), and amount of nitrogen (F^t_i) that is deposited in the cell *i*. The final result is equation **(4)**, which relates the amount of nitrates in the aquifer at time *t* and *t-1*. Please, note that, in this work, diffusive and dispersive phenomena have not been taken into account.

$$H_i^t C_i^t = H_i^{t-1} C_i^{t-1} + \varepsilon_{ij}(-WU_i^{t-1} C_i^{t-1} + F_i^{t-1} - Q_i^{t-1} C_i^{t-1} - W_i^{t-1} C_i^{t-1} - R_i^{t-1} C_i^{t-1} - L_{i,j}^{t-1} C_i^{t-1})\Delta t \quad i=1,\dots,I \quad t=1,\dots,T \qquad \textbf{(4)}$$

It is important to note that the amount of nitrogen is given by the sum of fertilizers that are used in the various crops of cell *i* at time *t* $Fert^t_{i,c}$ and of the input of waste from animals I_i^{t-1} at time *t-1* in the area dedicated to pasture. Then:

$$F_i^t = \left(I_i^{t-1} A_{i,c=pasture}^{t-1} + \sum_c Fert_{i,c}^t A_{i,c}^t \right) \quad i=1,\dots,I \quad t=1,\dots,T \qquad \textbf{(5)}$$

with:

$$I_i^t = D_{i,c=pasture}^t \alpha \quad i=1,\dots,I \quad t=1,\dots,T \qquad \textbf{(6)}$$

where α is the specific coefficient of nitrogen excretion and $D^t_{i,c}$ is the density of animals in the area of crop *c=pasture*, in cell *i*, at time *t*.

2.2 The agricultural model

Three major types of yield (and food sources for the dairy animals) are considered in this work: maize silage, grass silage, and pasture.

The yield equations for the different type of food sources were constructed in the form of equation **(7)** The coefficients have been calculated using the available data for the case study.

$$Y_{i,c}^t = \frac{a_c}{1 + e^{-Fert_{i,c}^{t-t_c} - x_{0,c}}} \quad i=1,\dots,I \quad c=1,\dots,C \quad t=1,\dots,T \qquad \textbf{(7)}$$

where:

- $Y^t_{i,c}$ is the yield produced by crop *c* in cell *i* at time *t*;
- a_c and $x_{0,c}$ are parameters of the logistic equation;
- t_c is the time in which crop *c* grows.

Then, it is necessary to calculate the useful content ($Crop_{i,c}$)of crop *c*, in cell *i*, utilized by the animals in kg, that results from the harvested yield, versus the dry matter content of the crop (DMC_c), versus the area of the crop *c* in cell *i* ($A^t_{i,c}$), at time *t* and an harvest coefficient for each kind of crop (β_c) multiplied by the yield ($Y^t_{i,c}$).

$$Crop_{i,c}^t = \beta_c Y_{i,c}^t DMC_c A_{i,c}^t \quad i=1,\dots,I \quad c=1,\dots,C \quad t=1,\dots,T \qquad \textbf{(8)}$$

The main simplification reported in the present work is that it is assumed that among farmers there is not competition. As a consequence, the conceptual formalization of the available quantity of food of typology *c* at time *t* M_c^t is given by

$$M_c^t = M_c^{t-1} + \sum_{i=1}^{I} Crop_{i,c}^t - \sum_{i=1}^{I} FOOD_{i,c}^t \quad c=1,\dots,C \quad t=1,\dots,T \qquad \textbf{(9)}$$

where $FOOD^t_{i,c}$ is food of typology *c* given to animals in cell *i* at time *t*.

2.3 The dairy farming model

The dairy farming model regards the feeding needs of the animals and the milk produced. It is based on the concept of the Metabolized Energy (*ME*) (Agnew & Newbold, 2002) in order to assess the nutritional needs of the defined farm. Using defined unit values for the different feeds, it is possible to know the energy value of an amount of a specific feed.

$$AE_i^t = \sum_{c=1}^{C} Food_{i,c}^t \varepsilon_c \quad i=1,\dots,I \quad t=1,\dots,T \qquad \textbf{(10)}$$

where ε_c is a coefficient able to transform the quantity of every typology of food in energy.

The *ME* required by the animals, that should be satisfied by the different kinds of food, is divided in different components: the metabolized energy required for the maintenance of the animals ME_m[MJ], the metabolized energy required for growth ME_g [MJ], and the metabolized energy required for the milk production ME_l [MJ]

The term ME_l can be expressed as function of the energy in a liter of milk (E_l) divided by the efficiency factor of conversion of energy into milk (k_l), versus the amount of milk per animal (*M*).

Specifically, *ME* required (ME_{req}) for one animal is given by

$$ME_{req}^t = ME_m^t + ME_g^t + \frac{E_l}{k_l} M \quad t=1,\dots,T \qquad \textbf{(11)}$$

The produced milk in cell i is given by

$$Milk_i^t = (AE_i^t + -(ME_m^t + ME_g^t)D_{i,c=pasture}^t A_{i,c=pasture}^t)\frac{k_l}{E_l M} \quad \textbf{(12)}$$

3. The optimization problem

The formalization of the decision model is characterized by the mathematical definition of state and control variables, objectives and constraints. State variables represent the state of the system, while control variables represent the enthities on which it is possible to operate when planning or managing. For the specific case study, considering $i=1,...,I$ cells, $c=1....C$ crop types, $t=1,...,T$ time intervals, the state variables are:

1. H_i^t : hydraulic head in cell i at time t
2. C_i^t : concentration of nitrates in cell i at time t
3. $Y_{i,c}^t$: yield produced in cell i for crop c at time t
4. $Milk_i^t$:milk produced in cell i at time t
5. M_c^t : quantity of food c stored in the magazine at time t

The control variables are:

1. $FOOD_{i,c}^t$:food of typology c provided to animals present in cell i at time t
2. $D_{c,i}^t$ density of animals at time t in crop area c in cell i
3. $A_{c,i}^t$ area dedicated to land use c in cell i at time t
4. Q_i^t water pumped from cell i at time t

3.1 The objective function

The considered objective function regards the maximization of total milk production. The other issues of the problem can be considered through the formulation of specific constraints, as it is explained further on. The objective function of the optimization problem is

$$\text{Max} = \sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{t=1}^{T} Milk_{i,c}^t \quad \textbf{(13)}$$

3.2 The constraints

The constraints in the mathematical formalization of specific limitations are (concentration limits imposed by regulation, technological requirements, environmental limitations). Different classes of constraints are formalized. The first class of constraints is given by the chemical/physical/ecological systems expressed by equations **(1)-(12)**. The second class of constraints regard water quality preservation constraints. Water demand satisfaction constraints represent the third class of constraints. Finally, the fourth and the fifth classes of constraints are represented by a limit on the number of animals and specific limits on the crop areas.

Water quality preservation constraints
Water quality preservation can be taken into account by posing a limit on fertilizers' quantity, and over pollutant concentration. That is,

$$Fert_{i,c}^t <= \overline{F} \qquad i=1,\dots,I \;\; c=1,\dots,C \;\; t=1,...,T \quad \textbf{(14)}$$

$$C_i^t \le C^* \qquad i=1,\dots,I \;\; t=1,...,T \quad \textbf{(15)}$$

Water demand constraints
A minimum water demand for each time interval is fixed:

$$\sum_{i=1}^{I} W_i^t \ge \overline{W}^t \qquad t=1,...,T \quad \textbf{(16)}$$

Limits on the number of animals
Being that the total number of animals is given by

$$N_A^t = \sum_{i=1}^{I} D_{i,c=pasture}^t A_{i,c=pasture}^t \qquad t=1,...,T \quad \textbf{(17)}$$

the following constraint is given

$$Na_{\min} \le N_A^t \le Na_{\max} \;\dots\; t=1,...,T \quad \textbf{.(18)}$$

Limits on crop areas
Different constraints for the land use have to be formalized. First of all, the total area dedicated to crops should not exceed a given value. Thus

$$\sum_{c=1}^{C} A_{i,c}^t \le A\max_i^t \qquad t=1,...,T \quad i=1,...,I \quad \textbf{(19)}$$

Then, it is necessary to consider that there are some areas where a specific crop can not be cultivated due to altitude. That is,

$$A_{i,c}^t \le A\max_{i,c}^t \qquad i=1,\dots,I \quad c=1,...,C \quad t=1,...,T \quad \textbf{(20)}$$

where $A\max_{i,c}^t$ is maximum area that can be dedicated to a specific crop in the generic cell in the different time intervals. Other constraints arise from the consideration that crops can be cultivated only in specific time periods during the year.

$$A_{i,c}^{\bar{t}} = 0 \qquad i=1,\dots,I \qquad c=1,\dots,C \qquad \textbf{(21)}$$

4. Application to a case study: Terceira Island

The decision model has been applied to Terceira Island (Azores). The Azores are a group of nine volcanic islands situated in the confluence of the African, American and European tectonic plates, over the Atlantic Ocean Rift. With a population of 250 thousand inhabitants, the larger island (São Miguel), has an area of approximately 750 square km, and a population of 125 thousand inhabitants, and the smallest (Corvo), only 17 square km, and 400 inhabitants. Of the nine islands, São Miguel, and Terceira (with its 55 thousand inhabitants), are the most important, having more than 70% of the total population of the Azores, and being responsible by almost 80% of all the income of the islands. In geological terms the islands are fairly recent, with active volcanic in most islands, being some hot springs, and emissions of gases the most visible demonstration. From the hydrological point of view, there isn't a real developed superficial network of streams and lagoons, being that most of these are not of permanent nature. Most of the water resources of these islands are of underground nature, and conditioned by the complex geology. Considering the nature of the water resources that these islands possess, there are many springs that result from the intersection of suspended aquifers with the surface. Then, there are some wells that in general are used to complement the insufficient water supplied by the springs. Nowadays the main agricultural production of these islands is dairy farming, which is more intense in the islands of São Miguel, and Terceira. The produced milk is used to make dairy products, such has butter, cheese, powder milk, and other, or it is simply pasteurized and sold that way. The intensification of the agricultural practices leads to a decrease in the quality of the groundwater, due to an increase of the nitrogen concentration in drinking water. The practice of dairy farming is well connected with changes in the land use of these islands, as feeding of the animals is in great part done with grass and corn. During the winter, when there is enough grass in the fields, the animals are kept in this, normally at low altitudes, feeding on available grass, with supplements of rations to increase productivity. In summer, the animals are moved to higher locations, and the fields can be use to grow corn, and grass (that are stored for times of need). To guarantee the productivity of the fields, there is a substantial use of fertilizers. Then, it is necessary to consider the high density in which the animals occur, that causes a discharge of large amounts of nitrogen in a small area. The case study area is divided into three major cells, with two sub cells each. The six cells are characterized by homogeneous characteristics and have at least an outgoing source of water, well or spring. For the location and delimitation of the cells, the major hydrologic units defined in *Plano Regional da Água* (Direcção Regional de Ordenamento do Território e dos Recursos Hídricos & Instituto da Água, 2001) was considered, and the location of the different springs and wells, forming homogenous hydrological areas was also considered. Figure 2 highlights the six cells considered in this work. Each cell is characterized by an upper phreatic aquifer and by a basal aquifer. Both of them have been modeled. Please, note that the unsaturated zone modeling is not considered in this work.

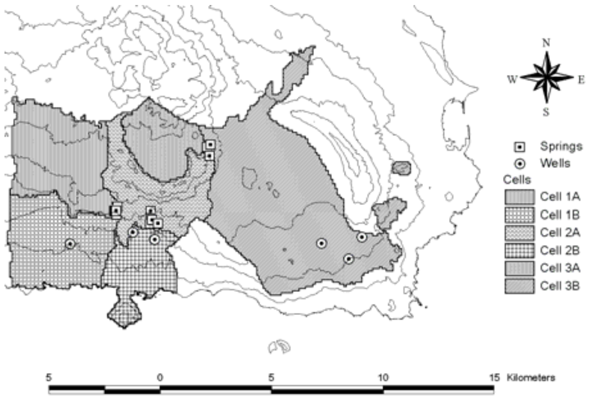

Figure 2. The cells of the study area.

All data, such as the available infiltration, have been provided by the Municipal Water Services (SMAH). The parameters used in the yield equations (7) were calculated on the basis of the data of produced yield, available for the case study.. Regarding infiltration, in certain time periods and in certain areas it is equal to zero because the evapotranspiration overcomes the available rain and fog water. In general, this is not common in areas with a high altitude. The initial conditions for the hydraulic and chemical models were taken by investigations on the study area, as well as all the hydro-geological parameters.

The optimization problem is non linear with continuous decision variables and non-linear constraints. The time horizon is one year while the time discretization is three months. It is solved through mathematical programming techniques, and, in particular, with the use of Lingo 8.0 (Lindo Systems inc.). Produced milk [tonnes] during the four time intervals (three months each) is reported in Table 1. The sum of the reported quantities correspond to the optimal value of the objective function expressed by equation (13).

Milk	1	2	3	4
1a	527	2108	2108	2108
1b	704	2818	2818	2818

Table 1. Produced milk in Cell 1a and Cell 1b

To the objective function value corresponds the optimal values of the control variables previously defined. As an example, Table 2 shows the different crop areas [hectares] in cells 1a and 1b.

Crop Area (ha)	1	2	3	4
Pasture-1a	1386	1386	1386	1386
Pasture-1b	1665	1665	1665	1665
Grass -1a°	0	396	396	396
Grass-1b	0	0	18	18
Maize-1a°	0	0	0	0
Maize-1b	0	0	0	0

Table 2. Crop areas in Cell 1a and Cell 1b

6. Conclusions

The complexity of water resources planning and management depends on the different aspects to be taken into account, on the integration of physical/chemical/ecological models, on the presence of various actors involved in the decision process, on the exigency of integrating qualitative and quantitative considerations. The aim of this work is to present a decision model for water resources management in Terceira Island, where the exigency to find instruments for IWM is particularly felt. The main economic activity is dairy farming, that is well connected with changes in the land use, as feeding of the animals is mainly done with grass and corn. The intensification of the agricultural practices leads to a decrease in the quality of the groundwater. The problem statement necessitates four sub-models for the representation of the system (the hydraulic model, the chemical model, the agricultural model, and the dairy farming model), embedded as constraints in the optimization problem. The decision model is characterized by control variables (i.e. land use areas, pumped water, animals' density, food to animals), state variables (hydraulic head, pollutant concentration, yield production), objectives, and constraints. The optimization problem is non linear with continuous variables and non-linear constraints and is solved through the use of Lingo 8.0 (Lindo Systems inc.). The main simplification in the optimization problem formalization lies in the neglecting of competition phenomena among farmers. Future developments regard a careful calibration and validation of the system models and on the implementation of the presented model in a DSS based on GIS (Geographic Information System) support.

7. References

Agnew, Rosemary E. & Newbold, John R., Nutritional Standarts for Dairy Cattle. *Report of the British Society of Animal Science Nutritional Standards Working Group: Dairy Cows*, 2002.

Bear, J., *Hydraulics of groundwater*, McGraw-Hill, Publishing Company, 1979.

Eisenlohr, L., L. Kiraly, M. Bouzelboudjen, and Y. Rossier, Numerical simulation as a tool for checking the interpretation of karst spring hydrographs, *Journal of Hydrology*, 193:306–315, 1997.

Lombardo C., R. Minciardi, M. Robba, and R Sacile. Decision support systems for integrated water management, In Integrated Water Management (Lombardo C., Coenen M., Sacile R., and Meire P.), vol. 5 p. 159-167, Ambasciata d'Italia Editions, Brussels, Belgium, 2003.

Mohrlok, U., and M. Sauter, Modelling groundwater flow in a karst terrain using discrete and double-continuum approaches. Importance of spatial and temporal distribution of recharge, *Proceedings of the 12th International Congress on Speleology*, La Chaux-de-Fonds, Switzerland, 2:167, 1997.

Nalbantis, I., Rozos, E., Tentes, G., Efstratiadis, A. and Koutsoyiannis, D.. *Integrating Groundwater Models within a Decision Support System.* Athens: European Water Resources Association, 2002.

Tilman, D., Cassman K.G., Matson P.A., Naylor, R., and S. Polasky, Agricultural sustainability and intensive production practices. *Nature*, volume 418, p. 671-677, 2002.

Todd, H., M. Carol, and M. Wicks, Modeling of storm responses in conduit flowaquifers with reservoirs, *Journal of Hydrology*, 208:82–91, 1998.

Van Calker, K.J., Berentsen, P.B.M., de Boer, I.M.J., Giesen, G.W.J. and Huirne, R.B.M.. "An LP-model to analyse economic and ecological sustainability on Dutch dairy farms: model presentation and application for experimental farm "de Marke"." *Agricultural Systems*, 2004, 82pp. 139-160.

White, W. B., Groundwater flow in karstic systems, *The Handbook of Groundwater Engineering* (Delleur. J. W., editor-in-chief), CRC Press, New York, 18-1–18-34, 1999.