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# A software tool for water resources sharing planning problems

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## Abstract

The paper describes the general architecture of a decision support system, designed for the solution of water resources sharing planning problems, taking into account both quantity and quality issues.

The considered system was inspired by a real case study belonging to a general class of problems. The considered planning problem refers to the water resources sharing in a basin having a general topology, with one or more reservoirs, where several users (for irrigation, for hydropower generation, for drinking water supply) compete for the water resources.

The water quality aspects are taken into account by simulating the concentrations of pollutants along the main river trunk, with the objective of checking if pre-specified standards are fulfilled.

The decision support system is composed by modules which interact among themselves and with the decision makers who are involved in the planning process. Each module of the decision support system is described in detail in the paper, and attention is focused on the information flow among the various blocks.

## 1 Introduction

Water resources management problems have received considerable attention in the last three decades, both as regards the quantitative aspect of the management problem, and the necessity of ensuring an adequate quality level of the water. From the quantitative viewpoint, the main approaches reported in the literature ( see, for instance, [1], [2], [3]) regard the deterministic as well the stochastic modelling of optimization problems related to water distribution. More recent literature regarding water resources management, pays a particular attention has been paid to those aspects regarding the application of advanced mathematical programming techniques [4], the multi-objective formalization of water resources distribution [5, 6], or the development of optimal control policies, possibly in an uncertain setting [7].

On the counterpart, in the literature about water quality models (see, for instance [8, 9, 10]), a major emphasis has been put on modelling and analysis rather than on decisional issues. This is mainly due to the really complex nature of the physical system under concern, in which several submodels interact at different time and space scales.

In the literature surveyed the quantity and quality aspects of water resources management have been treated generally as separate problems, even though there are some examples [11, 12] where a unified treatment of these two aspects has been attempted. This separation may be attributed to two types of reasons. First, the models to be used for the two different issues have quite a different structure. Second, the uncertainties affecting the two kinds of models are of different nature: for water quantity management models, the uncertainties generally refer to the random nature of some quantities, such as water stream flows, natural inflows, etc., whereas for water quality models, the uncertainties mostly regard the dynamical structure of the system model.

Actually, the necessity of an integration between the quantitative and the qualitative issues of water resources management cannot be overemphasized, since for instance, in most cases it is the exploitation of the water resources that induces the presence of risky or poor conditions of the water quality.

The objective of the present work is that of presenting the general design of a decision support system for the analysis and solution of water resources management problems of a class which is relatively frequent in northern Italy, and particularly in basins which are close to the Alpine range. Clearly, a modular architecture of the decision support system allows a ready replacement of a submodel with another one, possibly structurally different, which may be considered as more realistic for a new case study.

The decision support system described in this paper is oriented towards the solution of (off-line) planning problems regarding the sharing of the water resources among various possible competitive users. No on-line information is assumed to be available for this purpose, and the objective is that of determining reference values around which an on-line decisional policy should work. In the present formulation, the planning problem is addressed in a completely deterministic version.

## 2 The necessity of a Decision Support System

The solution of water resources sharing problems requires the synthesis and analysis of operating policies for managing water quantity and quality issues. To this end, the use of a computerized system is essential, in order to solve the optimization problems, to simulate the system behaviour, and then to allow the final users, i.e. the decision makers, to efficiently interact with the decision support system, also with a visual display of the performances of the policies. Moreover, the computer support system should assist the decision makers in finding the best compromise among the various competitive water users.

Generally speaking, DSS are computerized systems that assist the decision makers in dealing with ill-structured problems. Such systems facilitate the development and evaluation of alternative courses of action for the decision maker, who is allowed to use an interactive language to combine data from databases with potential models and explore the resulting solutions. Traditional DSSs include a set of tools that supports the storage, manipulation and access

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of data, and the process of fitting these data into formal models; they include also a set of methods and algorithms which are used to solve decision models. Modern DSSs use advances in computing and information technologies to organize and automate the process of alternative evaluation and selection into a flexible fully integrated, interactive, user-friendly computing environment.

Decision makers are frequently overwhelmed by the vast amounts of information which they must consider. Often, they are forced to make partially informed decisions which ignore critical issues because of the complexity of the situation being analyzed, and thus they are unable to identify actual optimal outcomes.

DSSs can play a crucial role in the decision making process by allowing the decision maker to navigate large amounts of information quickly and to explore interrelationships between factors which may influence the decision.

## 3 The Architecture of the proposed Decision Support System

For the particular class of problems under concern, the conceptual architecture in Figure 1 is proposed. Let us proceed starting from the 'external' level, i. e., that concerning the interaction with the user, and then moving towards the 'inner' modules, which are not directly accessible to the user.

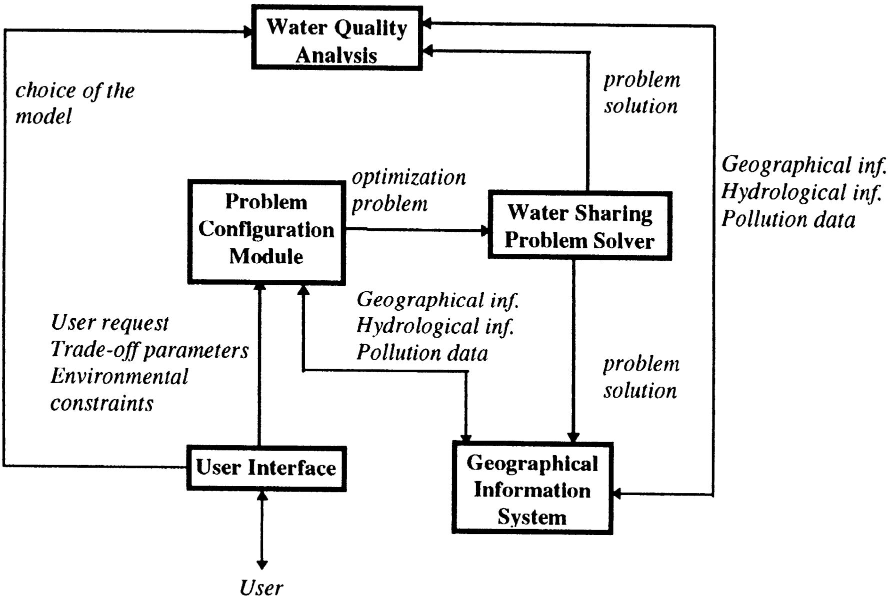

Figure 1 - The conceptual structure of the Decision Support System

The User Interface has the function of providing a user-friendly access to all the various modules of the system. The interaction with the user interaction takes place via a menu-driven command system.

As it has already been remarked, the considered class of problems is characterized by the necessity of taking into account several, generally conflicting, optimization objectives. In this connection, it has to be noted that most of the effective multi-objective analysis techniques require some form of interaction between the decision maker(s) and the mathematical procedure for the problem solution. This interaction may consist in an iterative presentation of solutions to the decision maker, who is then requested to express his/her evaluation in relation to each of such solutions. Each solution is modified in light of the concerns of the decision maker(s), and the process is repeated until a solution is obtained, which can be considered satisfactory.

In the evaluation of the solutions successively provided by the decision support system, it may be necessary to correlate the information used by the mathematical decision procedure (which has generated the solutions) with some other pieces of information, which cannot be used from the above procedure.

In this connection, the use of a Geographical Information System (GIS) turns out to be essential. Generally speaking, a GIS has the main function of storing, manipulating, and displaying geographical data. Besides, the GIS has the essential function of storing and making accessible all information needed to formalize the decisional problem, apart from the information coming directly from the system users. Essentially, such information refers to geographical aspects of the basin under concern, as well as to the hydrology of the basin (river flows, etc.) and to the location, type and size of the pollutant sources along the river.

All the above information is made available to the problem configuration module which has the function of formalizing mathematically the water sharing optimization problem; such a formalization requires also the use of the information provided directly from the decision maker. The latter information is relevant, for instance, to the requests of the water resources expressed by the various users, and to the weight coefficients (trade-offs parameters) that the decision maker assigns to such requests (taking into account the relative importance of the water users). Such information may also refer to environmental constraints coming from laws and regulations.

The problem configuration module formalizes an optimization problem which is then solved by the water sharing problem solver. This is simply a mathematical programming problem (more specifically, a linear programming one, as it will be shown later on), which has to be solved via the use of a suitable software package. Actually, the reason why it is convenient to think of the problem configuration and the water sharing problem solver as two separate modules, is just that of separating the problem formalization from the problem solution, which can be accomplished by means of one among a set of linear programming codes which are commercially available (for instance the LINDO or CPLEX tools).

The solution of the water sharing problem is provided to the GIS and to the water quality analysis modules. The latter includes one or more water quality models, which can be used to evaluate the environmental impact on the basin of the decisions taken about the water resources sharing. The choice about the models to be used is made by the decision maker, through the user interface; the evaluation of the water quality in the river (or, more generally, in the basin)

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takes place mainly by simulation and needs the use of information provided from the GIS module and from the water sharing problem solver module.

The final evaluation, from the environmental and from the "economical" point of view, of the solution obtained is made by the decision maker, by using the interface module. To this end, the graphical facilities of the GIS module are essential. There is also the possibility that such a module integrates the information embedded in the obtained solution with information which has not been used in the problem formalization (for example, information regarding the land use or the location of settlements of particular relevance).

The user interface has to be provided with all features necessary to allow an easy navigation in the overall system. In the following, three of the modules represented in Figure 1, namely the problem configuration module, the water quality analysis module, and the GIS, will receive particular attention.

## 4 The Problem Configuration Module

As already pointed out, the function of this module is that of assembly all information necessary to the formalization of the water resources sharing problem. Such information is then provided to the problem solver module, which is simply a mathematical programming tool.

Given the generality of the structure of the proposed DSS, the problem configuration module can be applied to formalize problems referring to basins having different topologies and complexity, e.g., as regards the number of water streams, of reservoirs, of water users. In the following, for the sake of clarity we explicitly refer to a specific case study, presently under development at our Department, and referring to a pre-Alpine basin in the north of Italy, in the Piemonte region. Such a case study can be considered representative of water resources planning problems which are common in northern Italy.

The considered basin consists of the main trunk of a river flows from a reservoir, which has also a second separate outflow intended for drinkable water supply and hydropower generation. The river is characterized by a single space variable y, ranging from 0 to L. The flow of the river is considered piecewise constant, over the river length. That is, a given set of sections of N points $y_i$, i=1,...,N ($y_0$=0 and $y_N$=L), are fixed a priori, each one corresponding to variations of the river flow. Such variations are due to: either a) the confluence of other minor natural water streams or of sewerage water coming from industrial plants or civil settlements $y_i \in \Lambda$ or b) the water withdrawal for irrigation, industrial or other uses $y_i \in \Phi$.

The confluence sections may be furtherly partitioned into four different subsets, namely:

-$\Lambda_a$ including the sections $y_i$ which correspond to the confluence of water streams whose quantity and quality are not controllable;

- $\Lambda_b$ including the sections $y_i$ which correspond to the confluence of water streams whose quantity is controllable and quality is not;
- $\Lambda_c$ including the sections $y_i$ which correspond to the confluence of water streams whose quality is controllable and quantity is not;
- $\Lambda_d$ including the sections $y_i$ which correspond to the confluence of water streams whose quantity and quality are both controllable;

As regards the withdrawal points, they also will be partitioned in two sets:

- $\Phi_a$ including the sections $y_i$ for which the water withdrawn is not returned to the river (irrigation uses);

- $\Phi_b$ including the sections $y_i$ for which the water withdrawn is (totally or partially) returned to the river (industrial uses); the returned water is in general characterized by pollutant concentrations different from those of the water withdrawn.

The time variable is discretized by considering a set of time intervals (whose length is, for example, equal to one month) $(t_j, t_{j+1})$, j=0,..., T-1, being $t_0=0$ and $t_T$ the last instant in which the system is observed. The length of such time intervals may be fixed by the system user. Then, $\overline{Q}_i(t_j)$ represents the river flow, in the time interval $(t_j, t_{j+1})$, in the reach $(y_i, y_{i+1})$. $\overline{B}_i(t_j)$ is the variation of flow (positive for $y_i \in \Lambda$, nonpositive for $y_i \in \Phi$) in the time interval $(t_j, t_{j+1})$, at the section $y_i$. $\overline{D}_i(t_j)$ is the water flow withdrawn and $\overline{E}_i(t_j)$ is the water flow returned at sections $y_i \in \Phi_b$ in the time interval $(t_j, t_{j+1})$. It is assumed that $\overline{E}_i(t_j)=\eta_i \overline{D}_i(t_j)$ being $\eta_i \leq 1$ a fixed nonnegative parameter. Obviously, $\overline{B}_i(t_j)=\overline{E}_i(t_j)-\overline{D}_i(t_j)$, for $y_i \in \Phi_b$.

Finally each variable $\overline{B}_i(t_j)$, for $y_i \in \Lambda_b \cup \Lambda_d$ may be decomposed as $\overline{B}_i(t_j)=\overline{B}'_i(t_j)-\overline{B}''_i(t_j)$, where $\overline{B}'_i(t_j)$ represents the value of the inflow in absence of water withdrawals, and $\overline{B}''_i(t_j)$ is the value of the overall water withdrawals before the confluence into the main river trunk.

As previously mentioned, there are two water outflows from the reservoir, namely $\overline{Q}_0(t_j)$, which is the river initial flow, and $\overline{Z}(t_j)$, which is the flow of the water which is withdrawn from the reservoir and not returned to the river; finally, $\overline{S}(t_j)$ is the volumetric content of the reservoir in the time interval $(t_j, t_{j+1})$.

Any formalization of water resources sharing planning problem must have the objective of optimizing the compromise among the various possible uses of water. Such a problem which is essentially a multi-objective one. In the designed structure for the module under concern, the original problem is reduced to a single objective formalization through the so called "goal programming" method [13] based on the proper specification of the aspiration levels and the asymmetric weights for the various water resources users.

More specifically, the above formalization leads to the following mathematical programming problem:

$$\min_{\xi} \sum_{j=0}^{T-1} \left\{ \begin{aligned} &\tau_j \max\left[Z_j^* - \overline{Z}(t_j), 0\right] + \sum_{i:y_i \in \Phi_a} \left\{\beta_{i,j} \max\left[B_{i,j}^* - \overline{B}_i(t_j), 0\right]\right\} + \\ &+ \sum_{i:y_i \in \Phi_b} \left\{\gamma_{i,j} \max\left[D_{i,j}^* - \overline{D}_i(t_j), 0\right]\right\} + \sum_{i:y_i \in \Lambda_b \cup \Lambda_d} \left\{\delta_{i,j} \max\left[\left(B''_{i,j}\right)^* - \overline{B}''_i(t_j), 0\right]\right\} \end{aligned} \right\}$$

(1)

s.t.

$$S(t_{j+1}) = S(t_j) - \overline{Q}_0(t_j)(t_{j+1} - t_j) - \overline{Z}(t_j)(t_{j+1} - t_j) + P(t_j) \qquad (2)$$

$$\overline{Q}_i(t_j) = \overline{Q}_{i-1}(t_j) + \overline{B}(t_j) \qquad (3)$$

$$\overline{Q}_i(t_j) \geq Q_i^{\min}(t_j) \qquad i=1,\dots,N,\ j=0,1,\dots,T-1 \qquad (4)$$

$$\overline{B}''_i(t_j) \le \nu_i \overline{B}'_i(t_j) \qquad i: y_i \in \Lambda_b \cup \Lambda_d,\ j=0,1,\ldots,T-1 \tag{5}$$

$$\overline{B}_i(t_j) \le \chi_i \overline{Q}_{i-1}(t_j) \qquad i: y_i \in \Phi_a,\ j=0,1,\ldots,T-1 \tag{6}$$

$$\overline{D}_i(t_j) \le \pi_i \overline{Q}_{i-1}(t_j) \qquad i: y_i \in \Phi_b,\ j=0,1,\ldots,T-1 \tag{7}$$

$$\overline{B}_i(t_j) = (1-\eta_i)\overline{D}_i(t_j) \qquad i: y_i \in \Phi_b,\ j=0,1,\ldots,T-1 \tag{8}$$

$$S(t_j) \ge S^{min}(t_j) \qquad j=0,1,\ldots,T-1 \tag{9}$$

$$S(t_T) = S(t_0) \qquad j=0,1,\ldots,T-1 \tag{10}$$

$$\underline{\xi} \ge 0 \tag{11}$$

where
$S(t_0)$ may be considered known; $P(t_j)$ represents the amount of water entering the reservoir during the time interval $(t_j, t_{j+1})$, $j=0,1,\ldots,T-1$;
$Z^*_i$, $B^*_{i,j}$, $D^*_{i,j}$, $(B''_{i,j})^*$ are the aspiration level respectively of the average flow delivered for drinkable water and/or hydropower generation uses , for withdrawals in sections $y_i \in \Phi_a$, for withdrawals in sections $y_i \in \Phi_b$, and for the overall water flow withdrawn for each $y_i \in \Lambda_b \cup \Lambda_d$ ;
$Q_i^{min}(t_j)$ and $S^{min}(t_j)$ are respectively the "vitality minimum" for the river flow and the minimum allowed reservoir content;
the quantities $\nu_i$, $\chi_i$, $\pi_i$, $\eta_i$ are coefficients fixed and known;
the quantities $\tau_j$, $\beta_{i,j}$, $\gamma_{i,j}$, $\delta_{i,j}$ are constants which have the function of taking into account the importance of the various water users as well as their determination in specifying their aspiration levels;
$\underline{\xi}$ is the decisional vector defined as

$$\underline{\xi} = \mathrm{col}\left[\begin{array}{l} Z(t_j), j=0,\ldots,T-1; \\ \overline{Q}_i(t_j), i=0,\ldots,N-1; \\ -\overline{B}_i(t_j), i: y_i \in \Phi_a, j=0,\ldots,T-1 \\ \overline{D}_i(t_j), i: y_i \in \Phi_b, j=0,\ldots,T-1 \\ \overline{B}''_i(t_j), i: y_i \in \Lambda_b \cup \Lambda_d, j=0,\ldots,T-1 \\ S(t_j), j=0,\ldots,T-1 \end{array}\right] \tag{12}$$

At this point, it is sufficient to note that, by using standard mathematical programming devices, it is possible to convert the cost to be minimized into a linear one, thus making the overall optimization problem become a linear programming one.

## 5 Water Quality Analysis

As regards the water quality models, a variety of choices are possible, different for the mathematical complexity of the involved differential equations as well as for the chemical compounds taken into account [8, 9, 10]. As the proposed system is intended to be applied to solve planning problems, the models we are interested in are those describing the system in a time-stationary setting. As regards the chemical compounds, attention is presently moving from the traditional Biochemical Oxygen Demand (BOD) Dixolved Oxygen (DO) analysis towards more complex models taking into account also toxic metals and mutagenic compounds. In any case, the modular architecture mentioned in the introduction will allow the choice of the water quality sub-model most suitable for the particular case study under concern.

A series of computer packages have been made available for easy configuration and calibration of water quality sub-models; among them, one can cite the QUAL2EU [14], the MIKE 11 [15], the WODA [16] packages.

In the proposed decision support system the US. EPA QUAL2E tool has been selected for the simulation of water quality along the river. QUAL2E is a comprehensive and versatile stream water quality model . It can simulate up to 15 water quality constituents in any combination desired by the user. The model is applicable to dendritic streams that are well mixed. It assumes that the major transport mechanism, advection and dispersion, are significant only along the main direction of flow (longitudinal axis of the stream). It allows for multiple waste discharges, withdrawals, tributary flows, and incremental inflow and outflow. QUAL2EU can operate either as a steady-state or as a dynamic model, making it a very helpful water quality planning tool. In steady-state analysis, QUAL2 performs the system simulation over time periods during which both the stream flow in river basins and input waste loads may be considered constant. In this case, it can be used to study the impact of waste loads (i.e., of their magnitude, quality and location) on instream water quality.

## 6 Geographical Information Systems

Geographical Information Systems (GIS) are computerized (software and hardware) systems aiming at providing a number of tools to code, store and retrieve data about aspects of the earth's surface. GIS have the ability to display and graphically summarize both the input data for the analytical models and the results of application of management models using those data. Generally, GIS are composed by several hardware components (scanner, plotter, Personal Computer, etc.) and software tools to manage data provided by external devices.

Because the data can be accessed, transformed, and manipulated interactively in GIS, they can serve as a test bed for studying environmental processes, for analyzing the results of trends, or for forecasting the possible results of planning decisions. Using GIS in such a manner, it is possible for planners and decision makers to explore a range of possible scenarios and to obtain an idea of the consequences of a course of action.

The ability to display the results graphically improves the man-machine interaction which is generally accepted as being an integral part of multi-objective water resources analysis. GIS should not be considered as a means of providing final answers to complex water resources planning issues, but they should be seen as an important tool of Decision Support Systems by which information on the basin issues is transferred to the decision-maker for his/her considerations. Within this framework, GIS or any computer aided system should not be considered as a means of obtaining the answers, but more properly as a means for identifying objectives or goals, constraints, etc. of problems which are not well defined. In [17, 18, 19] examples may be found of the application of GIS to water resources management problems.

A primary role of a GIS is to facilitate the whole process by upgrading data input, improving data accessibility, allowing a better interpretation of results. A comprehensive analysis of the water resources in a particular river basin will require the consideration of all aspects regarding the water resources.

An important tool for the decision maker is the map of the region of interest. In particular, there are two types of map that can be treated by GIS: thematic maps and Digital Elevation Models.

A thematic map can be defined as a set of points, lines, and areas that are defined both by their location in space with reference to a coordinate system and by their non-spatial attributes. The map legend is the key linking the non-spatial attributes to the spatial entities. Non-spatial attributes may be indicated visually by colors, symbols or shading, the meaning of which is defined by the legend. The non-spatial attributes of a region could represent the different uses of the land, different types of land/water users, etc., associated to different colors, or shaded regions, on the map.

On the counterpart, unlike land-use, the landform is usually perceived as a continually varying surface that cannot be modelled appropriately only by the thematic maps. Any digital representation of the continuous variation of relief over space is known as a Digital Elevation Model, whose most important uses are the storage of elevation data for digital topographic maps and three dimensional display of landforms for design and planning the location of dams, waste water treatment plants, etc.. Besides it can also serve as background for displaying thematic information or for combining relief data with thematic data such as soils, land-use or vegetation. A DEM can also provide data for image simulation models of landscapes.

The integration of the GIS with the decisional architecture described in this paper is useful to provide the possibility of evaluating the impact of the outcomes of the planning procedure over the territorial area under concern, taking into account issues which cannot be modelled in the quantitative decisional procedure. To this end, the most reasonable choice seems that of using the ARC/INFO version for PC.

## 7 Conclusions

This paper reports the general guidelines for the development of a computerized Decision Support System designed to assist in decisions regarding water resources management in basins having a certain degree of complexity. The novelty of the proposed system is in the attempt to combine quantity and quality issues, and to integrate advanced software tools for the solution of mathematical programming problems with established codes for the simulation of water quality in rivers.

The whole system is presently under development; in the same time, the application to a specific case study is carried out. The objective is to obtain a fully integrated system which can be operational for a large class of water resources management problems.

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