DETERMINING MANAGEMENT SCENARIOS FOR THE WATER RESOURCE SYSTEM OF ATHENS

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ABSTRACT

The development process of scenarios used within a decision support system for water resources management is discussed, based on the case of the Athens water resource system. In particular, the schematisation process of the real world hydrosystem into a model representation is analysed, as well as further information consisting a scenario, including hydrological and water demand conditions, operational constraints, targets and their priorities, management objectives, and methodological assumptions used in decision making, is discussed.

1 INTRODUCTION

Uncertainty and risk are central concepts in decisions related to water resources management, as these decisions should be appropriate to the unknown future evolution of several elements of water resource system. The most rational manner to tackle uncertainty and risk is to apply probability concepts. However, this may not be feasible in all elements of the water resource system as in some of them it is difficult or impossible to express uncertainty in terms of probability. Such cases can be tackled in a systematic manner using chains of different alternative hypotheses, whose synthesis composes different scenarios. According to Grigg (1996, p. 21), a scenario is *a concept for a hypothetical or projected chain of events*. Applying this definition in modelling, one can recognise the close relation with simulation, which is a projection of an initial situation (state) to the future. Defining all aspects of the initial state, all system inputs and the operation policies for the system simulation, all intermediate states up to the final one can be predicted. System inputs and policies are uncertain, but in addition, the complexity of the processes taken place introduces further uncertainty in recognising the relation between the cause (initial state) and the effect (final state) and also necessitates simplifying methodological assumptions for the system studied and the processes taken place. According to this point of view, a water resources management (WRM) scenario should be defined in a broader manner, as a set of assumptions (information) needed for modelling and simulating a hydrosystem.

In the following sections, the development process of WRM scenarios will be explained, based on the case of the Athens water resource system (AWRS). Detailed information concerning this case has been published in recent Master Plan Studies for the AWRS (Koutsoyiannis, et al., 2000, 2001).

2 THE DEVELOPMENT PROCESS OF SCENARIOS

The main scenario of a hydrosystem in operation is usually based on the current situation. If the hydrosystem is in planning or under construction, it describes the expected normal operation, according to the technical specifications. Based on this initial scenario, further scenarios may be developed, focusing on other possible situations. Some important alternative scenarios are the following:

- expansion of the hydrosystem, incorporating new watershed areas and new water uses, according to elaborated plans;

- malfunction of certain facilities for a limited time period;
- changes of hydroclimatic conditions;
- modifications of water usage projections, according to a specific water demand policy.

The information needed to formulate a scenario for a hydrosystem may include at least the following categories:

- the model of the hydrosystem;
- hydrological information, such as runoff, precipitation and evaporation data (often called *hydrological scenario*);
- water usage projections for the simulation period (often called *water demand scenario*);
- targets, constraints and priorities imposed by the management policy;
- the management objective, expressed as an objective function; and
- methodological assumptions.

Part of the above information can be provided by mathematical models, requiring additional data and thus becoming part of the scenario. Typical models of this kind are water demand and hydrological models.

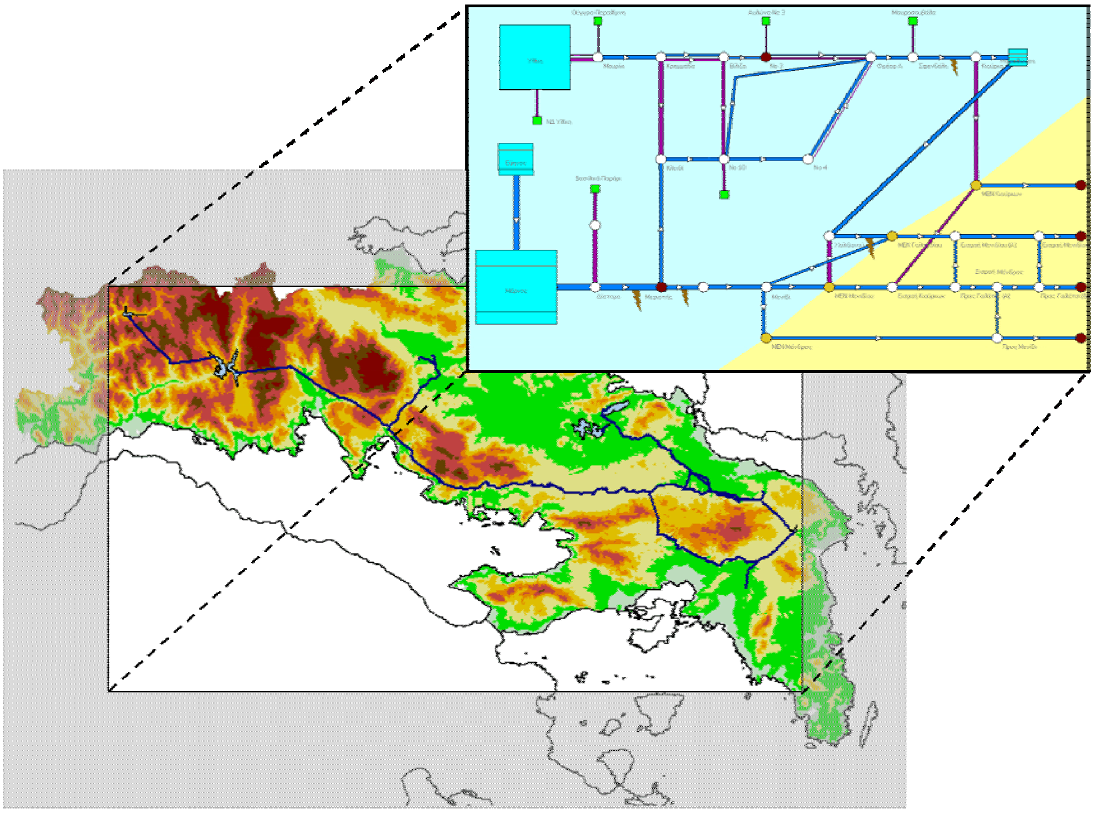
3 THE MODEL SCHEMATISATION OF THE HYDROSYSTEM

The fist step towards simulating the processes of a hydrosystem is to schematise its real-world components into a model representation. Main elements of a schematisation are abstraction, classification and simplification. Abstraction is used to reduce the complexity of the real world to few basic elements that are essential for the description of a situation or a process. It helps eliminate insignificant information and focus on the relevant ones. Since scenarios are based on a model, the exact specification of the information needed to develop a scenario depends on the model itself. More detailed models require more precise information of the hydrosystem or may focus on specific aspects of it, e.g. water quality. The significant information may concern certain objects, their characteristics and interconnections. Objects having same set of characteristics define a class. Classification helps reducing polymorphism and gives a common view and handle of objects. In the field of water resources management the core of most models is a network consisting of nodes and links. Nodes may represent infrastructure facilities such as reservoirs, diversions, junctions, borehole groups, water consumption points and power generation facilities. Aqueducts and rivers that transport water between nodes are represented by links. A network model includes also the attributes of each object and its initial state.

Another important part of the schematisation process is the simplification of the real world lumping many objects of the hydrosystem into one model entity. Today the degree of detail is no longer limited by the memory capacity of the computer. The simplification process serves mainly the saving of valuable resources for the model set-up, since incorporating and maintaining all relevant objects as individual ones would require an enormous and expensive effort and would improve only insignificantly the accuracy of the results. Another motive for simplifying a model may be the limitation of computational effort (in terms of computer time) especially when optimisation is needed. In most applications simplification is used for lumping small irrigation and water consumption areas into one, lumping small river and aqueduct sections into one single branch and grouping a number of boreholes to incorporate them into the model as a single entity.

Figure 1 visualises the schematisation of the network of the AWRS. It includes three artificial reservoirs, Evinos, Mornos and Marathon, and the natural lake Yliki. Two main aqueducts (Mornos and Yliki aqueducts) transfer water to the four Water Treatment Plants (WTP) Galatsi, Menidi, Kiourka and Aspropyrgos, located at the suburbs of Athens. Although the Mornos aqueduct carries water via gravity, water is carried through the Yliki aqueduct only via pumping with considerable cost. Interconnections of the main aqueducts allow alternative routes of water to the WTP. A number of borehole groups, most of which are located along the Yliki aqueduct, are used as auxiliary resource.

Figure 1: Schematisation of the Athens Water Resource System



4 HYDROLOGICAL SCENARIOS

Generally, two totally different approaches are applied to simulate the variability of water resources availability in a hydrosystem and the uncertainty caused by this variability. The first and simplest one formulates hydrological scenarios that are based on historical time series, either by using the full series or by selecting specific patterns, which represent certain typical or extreme conditions (e.g., dry, mean, wet periods). The second approach is the stochastic one. Instead of historical series, long-term synthetic series are used, which are consistent with the historical ones. Consistency may refer to statistical characteristics as well special properties of hydrological processes, such as persistence (also known as the Hurst phenomenon).

In all cases, the reliability of hydrological scenarios is strongly depended on the accuracy of the historical data. However, this data is often characterised by errors that are due to false, incomplete or insufficient measurements. The application of rainfall-runoff models, meteorological analysis and other tools may enhance the quantity of the available data. Moreover, in order to improve the quality of the data, tabular, graphical, computational or statistical validation and filling-in techniques can also be used.

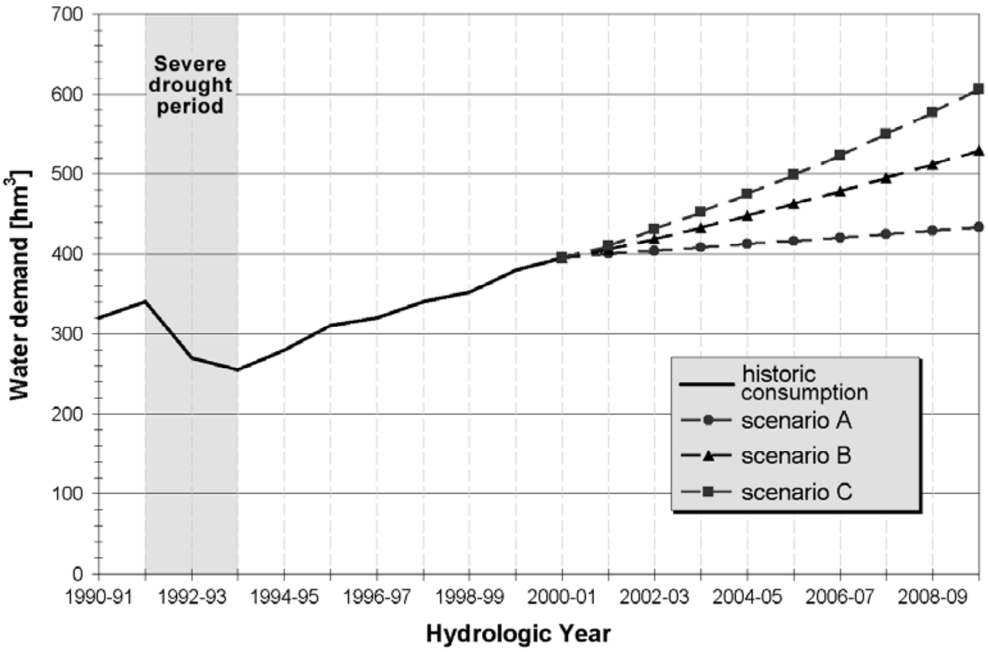
To simulate the AWRS, synthetic hydrological scenarios are used, which are generated through state-of-the-art stochastic models (Efstratiadis and Koutsoyiannis, 2000). Especially in this case, the stochastic approach is strongly required, because of the need to study the impacts of low-probability events, given that the acceptable failure rate for the water supply of Athens is only 1% on an annual basis.

5 WATER DEMAND SCENARIOS

Water demand scenarios describe any possible water usage in the future. For this reason historical data may provide a good starting point. Furthermore, for the estimation of the water consumption in urban and industrial areas, the scenarios should take into account forecasts about the population and industrial growth, the living standard, the water charging policy and other parameters.

Figure 2 shows the historical urban water demand and future water demand scenarios elaborated for the metropolitan area of Athens (Koutsoyiannis, et al., 2000, 2001). Water demand scenarios for irrigation are based on the extent of the irrigation area, the land use, as well as other agricultural developments affecting water consumption. In the hydrosystem, the most significant irrigation area is the Kopaida plain, which is supplied by the Boeoticos Kephisos River, by underground resources and eventually by the lake Yliki. As there are no exact measurements for agricultural water needs, are estimated by typical hydrological models. In addition to the above, some areas require a minimum discharge level for environmental preservation.

Figure 2: Urban water demand scenarios for the metropolitan area of Athens (Koutsoyiannis, et al., 2001).



6 TARGETS, CONSTRAINTS AND PRIORITIES

By definition, multipurpose hydrosystems serve a variety of water uses. In order to implement a management policy, a number of related targets have to be specified. These targets may be classified in one of the following categories:

- water consumption (water supply, irrigation, etc.);
- discharge control (minimum, maximum or defined flow preservation in aqueducts);

- storage control (minimum or maximum water storage level in reservoirs).

Due to hydrological uncertainties, the fulfilment of these targets cannot be guaranteed. Hence, apart from their values, an acceptable reliability level for the each target may also be specified, thus making a probabilistic constraint.

Moreover, physical constraints imposed from the hydrosystem may prohibit the realisation of all predefined targets simultaneously. Typical reasons for this are the exhaustion of water resources or the exhaustion of the system discharge capacity. Water resources managers are asked to create a priority list of all specified targets. Those targets who are first in this priority list are served first. Lower prioritised uses are allowed to use resources only if all other higher positioned uses are fully served. Targets, which aim to allocate water in reservoirs, allow the release of water only to serve higher prioritised targets.

For the management of the AWRS, the following priority list has been applied for all elaborated scenarios:

1. A maximum storage target of 25 hm^3 during the winter season and 30 hm^3 during the rest of the year for the Marathon reservoir imposes a very low probability of water spill from the reservoir. This target has the highest priority due to significant damages, which could be caused by the spill in downstream and coastal areas.
2. Four water supply targets have been defined that correspond to the water demand in the four main districts of the Athens metropolitan area, each served by one of the four water treatment plants of Athens. The reliability level for these targets was set to 99%, which means only one failure of the system to meet the target in 100 simulated years would be acceptable.
3. A minimum storage target for the Marathon reservoir, which is the only one located close to Athens, slightly below the maximum storage target, aims at maintaining as much water as possible in the reservoir for backup during the summer season and in case of malfunction of other parts of the system. In the last few yews this target is often violated during the summer season by the higher prioritised water supply target, because the water demand in Athens exceeds the current discharge capacity of aqueducts, through which water is transferred from lake Yliki and the Mornos reservoir. Nevertheless the target prevents taking water from the Marathon reservoir if other resources are available.
4. Maximum storage levels in the Evinos and Mornos reservoirs help reduce water losses due to spill. Because of the significant water transportation cost from the lake Yliki to the downstream system, due to pumping stations, no such target is defined for this reservoir.
5. An environmental preservation flow of 1 m^3/s in the Evinos River is imposed.
6. During April to August, up to 35 hm^3 can be withdrawn from the lake Yliki to irrigate the Kopais plain.

7 THE MANAGEMENT OBJECTIVE

It is widely recognised that water resources planning and management serves two general objectives, which is the national economic development and the environmental quality. Beneficial and adverse effects of any project or plan may also be displayed in the accounts of regional development and the social well-being (Haith and Loucks, 1976). The E.U. Water Framework Directive 2000, clarifies the objectives of water resources management, with emphasis on the sustainable water use, the improvement of surface and underground water quality and the conservation, protection and recreation of ecosystems (E.U., 2000).

In modelling, the general management goals must be specified, quantified and incorporated in a unified numerical expression, known as performance measure of the system. This measure helps assess the response of the system and compare different management policies. Using system analysis terminology, the performance measure corresponds to an objective function, which is evaluated via the simulation process. Simulation may be driven by an external optimisation procedure, which finally results to the optimal management policy.

In the AWRS, the following alternative management objectives have been used:

- The first option is the maximisation of the total annual withdrawal of the AWRS, for a given reliability level. This has been used to calculate the operation policy for two theoretical scenarios that define the limits of the hydrosystem. Firstly, the theoretical potential of the water resource system regardless of the limitations imposed by the discharge capacity of aqueducts and secondly the actual potential of the water resource system.
- An alternative option is the minimisation of the water supply failure probability (risk) for a given set of targets. Applied to the AWRS, this objective function calculates the management policy, which ensures the supply of water to the metropolitan area of Athens with the highest reliability level, regardless of any operational cost. It is applied in order to find out if certain scenarios, such as crisis and emergency scenarios, can achieve the specified targets with a feasible management policy.
- A realistic approach for the normal operation policy gives a third objective, which is the minimisation of the total operational cost for a given set of operational goals and for a given acceptable (very low) water supply failure probability.

Regardless of the specific management objective adopted, all targets specified in section 6 (e.g., environmental flow, irrigation, etc.) are also entered into the model in the form of constraints that must be fulfilled.

8 METHODOLOGICAL ASSUMPTIONS

According to the requirements that are imposed from the scenario, the appropriate mathematical methodologies as well as the software modules that implement them have to be selected. The main model components of a decision support system (DSS) for the management of water resources are simulation and optimisation tools.

The management policy of the AWRS is expressed in terms of parametric reservoir operation rules, which aim to distribute the current surface water resources to the three main reservoirs of the system (Evinos, Mornos and Yliki). The rules determine the target storage of each reservoir as a function of the total active storage (Nalbantis and Koutsoyiannis, 1997). The Marathon reservoir is excluded from the above rule, since its storage target is defined by very tight upper and lower limits (see section 6).

Furthermore, a step-by-step flow allocation methodology is applied to allocate the available water resources through the hydrosystem, in order to satisfy the system's targets. For this purpose, a network optimisation model is formulated, taking into account the physical constraints of the hydrosystem, the priorities of the targets, the operation rules, the alternative paths through the aqueduct network and the pumping cost (Karavokiros et al., 2000).

Special rules regulate the operation of boreholes, which are clustered in borehole groups, in order to simulate the real use of underground water as auxiliary resource. More specifically, groundwater releases are regulated according to the ratio V / K, where V is the estimated active storage of the reservoir system and K is its total active capacity. For each borehole group two thresholds are defined, the upper one to forbid the usage of groundwater if the active storage of the system exceeds this upper threshold (to avoid unnecessary exploitation of aquifers when there is abundance of surface water), and the lower one to enforce their usage if the storage falls below it. Between these thresholds, the usage of groundwater depends on economic criteria.

Finally, the simulation procedure is driven by an optimisation algorithm, which determines the optimal parameters of reservoir operation rules and aquifer exploitation, according to the predefined objective function (section 7).

9 CONCLUDING REMARKS

The development of management scenarios is an important part of water resources planning and management. Each scenario should be carefully planned and include information concerning the hydrosystem model, the hydrological conditions, the water demand evolution, the management objectives and the targets of the system, along with operating rules. The latter can be determined by a simulation/optimisation procedure. Defining scenarios for the management of a hydrosystem and calculating the results of the alternative scenarios facilitates the decision making process by providing to decision makers, planners, local authorities and the public, detailed information of the impacts of the different policies.

For the management of the AWRS a number of scenarios have been elaborated, which include the present operation, modifications to the hydrosystem model according to construction plans and possible emergency situations. The presentation of these scenarios and their results is out of the scope of this paper; the interested reader is referenced to Koutsoyiannis et al. (2000, 2001).

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