A decision support system for the management of the water resource system of Athens

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Abstract. The main components of a decision support system (DSS) developed to support the management of the water resource system of Athens are presented. The DSS includes information systems that perform data acquisition, management and visualisation, and models that perform simulation and optimisation of the hydrosystem. The models, which are the focus of the present work, are organised into two main modules. The first one is a stochastic hydrological simulator, which, based on the analysis of historical hydrological data, generates simulations and forecasts of the hydrosystem inputs. The second one allows the detailed study of the hydrosystem under alternative management policies implementing the parameterisation-simulation-optimisation methodology. The mathematical framework of this new methodology performs the allocation of the water resources to the different system components, keeping the number of control variables small and thus reducing the computational effort, even for a complex hydrosystem like the one under study. Multiple, competitive targets and constraints with different priorities can be set, which are concerned among others, with the system reliability and risk, the overall average operational cost and the overall guaranteed yield of the system. The DSS is now in the final stage of its development and its results, some of which are summarised in the paper, have been utilised to support the new masterplan of the hydrosystem management.

Keywords Decision support systems; Water resources management; Simulation; Optimisation; Reservoir systems; Athens

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1. Introduction

The term “decision support system” (DSS) has much replaced the term “expert system”, which was in wide use until 10 years ago. Watkins and McKinney (1995) suggest that the two are essentially the same, although they find DSS better in some aspects. However this change, whether terminological or substantial, reflects the fact that our interest has shifted from replacing to assisting expert judgement. The young science of computing has matured from the fear of “artificial intelligence” in the 1960s and 1970s, through heated discussions in the 1980s (see, for example, Dreyfus and Dreyfus, 1986), to today's better balanced attitude towards supportive vs. definitive computing.

This shift in the angle of approach to the problems has resulted in realistic solutions in various fields (Eom et al., 1998; Carver, 1991; Turban and Aronson, 1998), including water resource management (Watknis and McKinney, 1995). However, in order to provide substantial assistance to the expert decision maker, a DSS must provide efficient data gathering, organising, storage, and manipulation capabilities; and it must communicate the resulting information effectively, through proper visualisation, e.g. using geographical information systems (GIS). The development of such large, integrated systems, demands software engineering techniques, which is mainly the domain of software companies, whereas water resource DSS research is conducted primarily in water resource departments of universities and research centres, where computing experience is usually limited to smaller systems and older programming languages. Thus, DSSs in water resources still often lack the flexibility that will make them widely used.

The next chapters describe a DSS, originally developed for the management of the Athens water resource system. The DSS makes use of the latest relational database, networking, telemetric, GIS, and software development technology to provide an integrated, flexible and insightful information system. In addition, it incorporates models that make use of mathematical methods (mainly systems analysis methods, including simulation and optimisation techniques) in order to help seek the optimal management policy (OMP) of the water resource system.

The DSS has been designed to be configurable for any water resource system. Athens can thus be considered as a case study, and a challenging one: four major reservoirs, dozens of boreholes, a network of aqueducts leading to four water treatment plants, and numerous constraints and cost parameters, constitute a complex system described in section 2. In section 3, a general description of the DSS and its components is presented. Section 4 summarises the information systems of the DSS whereas section 5 focuses on the model components of the DSS and the mathematical methods developed. In section 6 few of the results of the application on the Athens water supply system are summarised. Some concluding remarks are contained in section 7.

2. A short description of the hydrosystem

The Athens water resource system shown in Figure 1 is an extensive and complex system that extends over an area of around 4000 km^2 and includes surface water and groundwater resources. It incorporates four reservoirs, 350 km of main aqueducts, 15 pumping stations, more than 100 boreholes and four water treatment plants (WTP). The system is run by the Athens Water Supply and Sewerage Company (EYDAP). Two of the reservoirs, the Mornos reservoir and the natural lake Yliki, hold 88,5 % of the overall storage capacity, which approaches 1400 hm^3. Although the storage capacity of the newly constructed Evinos reservoir is quite small in comparison, inflows to this reservoir are the largest. Therefore, water from the Evinos reservoir is diverted through a tunnel to the neighbouring Mornos reservoir, which stands as the main storage project for the Evinos River flow as well. The smallest reservoir, Marathon, is the oldest and the nearest to the city of Athens. Today the Marathon reservoir is kept at a high water level and it is used only as a backup for emergency situations and as a complement for the peak water demand during the summer season. The water of some aquifers, lying mainly in the northern part of the hydrosystem, is used as a backup resource.

Two main aqueducts transfer water from lake Yliki and from the Mornos reservoir. Interconnections of these allow alternative routes of water to the WTP. Although the Mornos aqueduct carries water via gravity, water is carried through the Yliki aqueduct only via pumping with considerable cost. Another characteristic of lake Yliki is the significant leakage due to its karstic underground. Analysis of historical data established two distinct leakage-elevation relationships, one for the dry period and one for the wet period. It is estimated that about 50% of the overall inflows to the lake end up to the underlying aquifers and finally from there to the sea. Some minor leakage has also been observed from the Mornos reservoir. Moreover, water losses occur along some of the main aqueducts. Projects of EYDAP are under way, which will help specify the exact location and extent of losses and minimise them. Reservoir spills are another significant loss of the system. Due to the several losses, less than 500 hm^3 per annum can be available to the water supply of Athens, although the mean natural inflows are about 840 hm^3 per annum and the groundwater resources in theory can contribute another 90 hm^3.

The system's main objective is to provide water to the Greater Athens area through the four Water Treatment Plants (WTP), which lie in the surroundings of Athens. Each WTP (Kiourka, Menidi, Aspropyrgos, Perissos) serves mainly one sub-area of Athens, but there is a limited possibility of water transfer between the WTPs, which increases the availability and security of the system in case of a malfunction. The annual water demand of Greater Athens had been continuously increasing until the early 1990s. Then, a persistent drought period almost vanished every surface water resource available and forced the government to take severe measures in order to reduce water consumption. A drastic increase in the water price, some administrative measures and a massive water saving campaign reduced water consumption by a third. Today, seven years after the end of the drought period, the construction of the Evinos reservoir has been completed and put into operation, and the annual water demand of Greater Athens has reached again, if not exceeded, the pre-drought period level (386 hm^3 in the year 2000). The water resource system also supplies other uses such as irrigation and water supply of nearby towns and also provides an environmental preservation flow of 1.0 m^3/s in the Evinos River.

The everyday normal operation of the hydrosystem relies upon several decisions, which are concerned with the allocation of withdrawals to the different reservoirs or groundwater resources and the conveyance of water through the different aqueduct branches. In emergency situations, other issues such as activation of backup resources and storages, and measures to restrict consumption are also considered.

3. Characteristics of the DSS

The DSS for the management of the Athens water resources system consists of several components (modules), some of which can operate as stand alone systems. Figure 2 shows the basic scheme of the DSS. Three of the basic components of the DSS, namely the database, the GIS, and the telemetric system compose the information subsystem of the DSS. Two other components, the stochastic hydrologic simulator *Castalia* and the hydrosystem simulator and optimiser *Hydronomeas*, contain the models of the DSS. All software has been developed from scratch in *Object Pascal* under the software development environment *Delphi*[2], also using the relational database system *Oracle*. *ArcInfo* and *ArcView* are used for the GIS. The system operates under Windows NT.

Although the DSS is already in use as the main decision support tool of the water resource system of Athens, it is yet not fully operational. The telemetric system and the peripheral telemetric stations are expected to operate in the beginning of 2002. The interoperability of the components and the system integration is scheduled for 2003. The DSS is scheduled to go online by the end of 2003. The present configuration of the DSS is designed to operate with a minimal time step of one month. Therefore, the system management for shorter time periods, e.g. the optimal daily distribution of the monthly-allocated water or even the distribution of water over the period of one day, is not currently supported.

Although the DSS was developed for the hydrosystem of Athens, its design is general enough so that it can be ported to other complex multipurpose reservoir systems. Thus, it can be applied to a wide range of hydrosystems with conflicting water usages, incorporating all

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[2] In ancient Greece, *Delphi* was presumed to be the middle of the earth. The prophecies made by the famous Oracle of Delphi have been respected all over the ancient world. Delphi with its famous Castalia spring of purifying water lies not far from the Mornos reservoir, the biggest of the reservoirs supplying Athens with water.

natural, operational, environmental and other restrictions. End users are able to define the operation targets according to a specified scenario, give them priorities and weighting factors.

4. Information system components of the DSS

An information system consists of software and hardware that is organized to perform some or all of the following functions: collection, processing, storage, transmitting, and dissemination of data that represent user information. In the case of DSS for water resources management, information systems usually are based on GIS that combine the functionality of a powerful database with the ability of visualising geographical information.

The core of the DSS is its database, which is designed so that it is flexible and easily extensible. Currently it consists of more than 130 relational tables, which store measured and synthetic time series, stage-discharge curves, sediment discharge curves, measuring stations and instruments, reservoirs, dams, boreholes, irrigation and water demand data, aqueducts, water treatment plants, pumps, basins and rivers, multimedia for all these entities, synthetic data generation parameters, simulation scenarios, and numerous other types of information. The integration of all data used by the DSS components in a single database facilitates the exchange of information between them and enables the rapid development of future applications.

The GIS is used in many ways such as storing and visualising spatial data and developing spatial software applications. The information that is presented concern the following categories:

- the water resource system, including among others information about reservoirs, dams, aqueducts, pumping stations and water treatment plants;
- surface and groundwater hydrology, such as general topographic information, digital elevation models, watershed areas, hydrological measuring stations, aquifers, wells and boreholes;
- geographical information related to water quality;
- other useful geographical information of the area, not directly related to the Athens hydrosystem.

By the end of DSS development all components of the DSS will be able to use the GIS as a user interface, entering data and representing simulation results with a geographical dimension. The GIS component is important for an additional reason: Although not every participant in the decision-making process can delve in the theoretical background of the methodologies applied, it is very important that the level of acceptance to the methodologies and the confidence to the results is high. GIS is able to present data and results in a comprehensive way that facilitates the understanding of their meaning.

The automated telemetric system is used in the DSS, because it can provide data of high reliability, without delay, and less costly than conventionally measured data. During the current phase of the project, peripheral telemetric stations are to be located near the main reservoirs and transfer automatically or semi-automatically important hydrological data to the central system. The new telemetric system will also help EYDAP to build a modern measuring system that will replace older prone to malfunction measuring stations. The data collected will include stage and discharge data from the main stream of each river basin, water level data in the reservoirs, rainfall data and meteorological data. The data collection procedure is to be initiated periodically by the central telemetric system. All data will be stored in the database for immediate use by other systems.

5. Model components of the DSS

5.1 Stochastic simulation and forecasting of hydrologic inputs

The overyear regulation capability of the hydrosystem demands that the system simulations must be carried out for time horizons of many years. For such horizons, deterministic forecasts of hydrological variables such as reservoir inflows, rainfall and evaporation are impossible and only a probabilistic approach is meaningful. The methodology followed implies the use of a comprehensive stochastic framework that generates synthetic series either in simulation or forecast mode. The synthetic time series have to be statistically consistent with the historical ones. They are generated by the *Castalia* model based on an integrated mathematical background, involving the combination of novel stochastic techniques.

A two-level, multivariate stochastic simulation scheme is assumed. Each variable refers to a specific hydrological process (rainfall, runoff, evaporation), at a specific location. The higher level refers to coarse time-scale (annual) whereas the lower level refers to finer time-scale (e.g., monthly). The developed scheme is appropriate to preserve all essential statistical characteristics of the historic time series (Matalas and Wallis, 1976); these are the marginal statistics up to the third order (mean, standard deviation, skewness), and the joint second order statistics (auto- and cross-correlations). It is also appropriate for the preservation of long-term persistence, in order to reproduce the particular patterns observed in the recent severe drought that lasted about six years.

In brief, the model does the following: First, the statistical characteristics of the historical series are computed and through them all model parameters are estimated. At the annual timescale, a parametric autocovariance function is formulated, which is appropriate for preserving both short-term and long-term persistence (and the Hurst coefficients) in different locations. The autocovariance function is implemented in a generalised symmetric moving average scheme for the generation of annual series (see section 5.1.1). The annual time series are then disaggregated into monthly series using a multivariate disaggregation scheme that is able to couple stochastic models of different timescales (see section 5.1.2). The whole scheme can operate in two different modes. In steady-state simulations long time series (e.g. several thousands of years) are generated irrespectively of any initial conditions. In terminating simulations the model operates in forecast mode for a time horizon of several years, and the observed past and present values of the hydrological values are introduced as initial conditions to the generation schemes, in order to obtain statistical predictions of their future values (see section 5.1.3).

5.1.1 The annual generating scheme

A specific requirement of annual synthetic series is the good reproduction of persistent droughts. Long-term persistence (also known as Hurst phenomenon) is the property of hydrological (and other geophysical) processes that dry periods tend to follow dry periods or wet periods follow wet periods. Long lasting droughts or wet periods can be regarded as the result of large timescale random fluctuations of climate. Such fluctuations can be equivalently modelled by means of stationary stochastic processes with a specified autocorrelation structure, such as the one proposed by Koutsoyiannis (2000). This structure is expressed by

$$\gamma_j = \gamma_0 \, [1 + \kappa \, \beta \, j]^{-1/\beta} \tag{1}$$

where γ_j is the autocovariance of the higher-level (annual) stochastic process for lag j, γ_0 is its variance and κ, β are parameters that are related to the persistence of the process. By adjusting the values of parameters κ and β, one can take a wide range of feasible autocovariance structures to represent short-term (ARMA-type) as well as long-term persistence.

The autocovariance function (1) is implemented in a generalised moving average scheme for annual series generation. This is an extension of the well-known backward moving average (MA) scheme (Box and Jenkins, 1970), introduced by Koutsoyiannis (2000), which has the symmetric form

$$Z_i = \sum_{j=-s}^{s} \alpha_{|j|} \, V_{i+j} = \alpha_s \, V_{i-s} + \ldots + \alpha_1 \, V_{i-1} + \alpha_0 \, V_i + \alpha_1 \, V_{i+1} + \ldots \alpha_s \, V_{i+s} \tag{2}$$

where Z_i denotes a stochastic process in discrete time i, V_i denotes independent identically distributed innovations, and α_j are numerical coefficients that can be determined from the sequence of γ_j. Equation (2) is the mathematical expression of the so-called symmetric moving average (SMA) scheme, which is used in *Castalia* for the annual time series generation. The SMA scheme has several advantages over the backward MA. Among them, it allows a closed solution for numerical coefficients α_j

$$s_\alpha(\omega) = \sqrt{2 s_\gamma(\omega)} \tag{3}$$

where $s_\alpha(\omega)$ and $s_\gamma(\omega)$ are the discrete Fourier transformations of the series α_j and γ_j respectively. One of the key advantages of the above method is that it can be directly extended to generate multivariate time series, a feature that is absolutely necessary to model multi-reservoir systems.

5.1.2 The monthly generating scheme

Since the long-term persistence of hydrologic processes is reproduced by the higher-level (annual) model, the emphasis for the lower-level model is to the reproduction of periodicity. We begin with a periodic lag-one autocorrelation model PAR(1):

$$\widetilde{\mathbf{X}}_\tau = \mathbf{a}_\tau \widetilde{\mathbf{X}}_{\tau-1} + \mathbf{b}_\tau \mathbf{V}_\tau \tag{4}$$

where $\widetilde{\mathbf{X}}_\tau$ is a vector of n stochastic processes in discrete time step (month) τ; $\mathbf{a}_\tau$ and $\mathbf{b}_\tau$ are matrices of coefficients and $\mathbf{V}_\tau$ is a vector of innovation variables with unit variance, independent both in time and location. The model parameters $\mathbf{a}_\tau$ and $\mathbf{b}_\tau$ are determined from the joint second order statistics of the monthly historic sample. For the calculation of matrix $\mathbf{b}$ (which is a typical matrix decomposition problem, often met in several stochastic hydrology applications), a novel methodology is applied, based on advanced numerical analysis techniques (Koutsoyiannis, 1999). On the other hand, random variables $\mathbf{V}_\tau$ are assumed to be gamma-distributed and their properties depend on the marginal statistics of the historical samples.

Provided that data series are known on the annual time scale denoted by i and the monthly synthetic series are generated from (4), an adjusting technique is applied to modify the latter so as to make them consistent with the annual ones (Koutsoyiannis and Manetas, 1996; Koutsoyiannis, 2001). This technique implements a linear transformation defined by

$$\mathbf{X}_\tau = \widetilde{\mathbf{X}}_\tau + \boldsymbol{h}\left(\mathbf{Z}_i - \widetilde{\mathbf{Z}}_i\right) \tag{5}$$

where $\widetilde{\mathbf{X}}_\tau$ and $\mathbf{X}_\tau$ denote the initial and adjusted series, respectively, $\widetilde{\mathbf{Z}}_i$ is the sum of $\widetilde{\mathbf{X}}_\tau$ for the ith period, $\mathbf{Z}_i$ is the corresponding annual vector, already generated via the multivariate SMA scheme, and $\mathbf{h}$ is the adjusting matrix. By appropriate determination of the matrix $\mathbf{h}$ (Koutsoyiannis, 2001), (5) preserves the vectors of means, the variance-covariance matrix and any linear relationship between $\mathbf{X}_\tau$ and $\mathbf{Z}_i$, but it cannot preserve the skewness coefficients of variables. In order to improve the approximations of statistics that are not explicitly preserved by the adjusting procedure, such as the skewness, a simple repetitive scheme is adopted, aiming at minimising the departures between $\widetilde{\mathbf{Z}}_i$ and $\mathbf{Z}_i$.

5.1.3 Generation scheme in forecast mode

In terminating simulations of the hydrosystem, the observed values of the hydrological series in the past and present must condition the future. This is attainable using a two-step algorithm. First, future time series are generated without reference to the known present and past values, and then a linear adjusting algorithm is applied in order to correct them (Koutsoyiannis, 2000). The algorithm is similar to (5) with $\mathbf{Z}_i$ and $\tilde{\mathbf{Z}}_i$ denoting the actual and generated values, respectively, of past and present times. If the adjusting matrix h is appropriately determined in terms of covariances among variables, the algorithm can preserve exactly the mean values and the autocovariance structure of the simulated process.

5.2 Simulation and optimisation of the hydrosystem

Some of the most important management decisions made in the field of water resources have long-term impact. Years after the decision time, false or even non-optimal decisions may imply the reduction of the system reliability, the inability to serve new regions and meet increased water demand and great economic losses. *Hydronomeas* is a software system appropriate for simulating complex multipurpose reservoir systems and for determining the optimal water resources management policy. It is applicable to a wide range of hydrosystems, incorporating natural, operational, environmental and other restrictions and giving answers to questions such as the following:

- What is the maximum total withdrawal from the hydrosystem, for a given hydrologic regime and a given reliability level?
- What is the minimum failure probability in achieving a given set of operational goals, for a given hydrologic regime?
- What is the minimum cost to achieve a given set of operational goals, for a given hydrologic regime and a given reliability level?
- What are the consequences of modifications in the hydrosystem (e.g., construction of new projects), and the impacts of different management policies or hydroclimatic scenarios?
- How could the system respond to unusual events such as aqueduct damages or an intense increase of water demand for a specific period?

The theoretical foundation of the software lies mainly on recent research work. It implements a new methodology in the field of water resources management named parameterisation-simulation-optimisation.

5.2.1 Parameterisation of operating rules

The management of the hydrosystem follows an operation rule. An operation rule is a law (equation or chart) that specifies the amount to be released for various purposes as a function of system states and parameters (ReVelle, 1999).

A convenient and efficient mathematical expression for the operation rules of a system of N reservoirs is (Nalbantis and Koutsoyiannis, 1997)

$$S_i^* = K_i - a_i K + b_i V \tag{6}$$

where K_i is the net storage capacity of the ith reservoir ($1 \le i \le N$), K is the total storage capacity of the system, V is the total active storage of the system (i.e., the total water availability), S_i* is the target storage for the ith reservoir at the end of each time step, and a_i, b_i are unknown parameters ($0 \le a_i, b_i \le 1$). In order to satisfy the reservoir capacity constraints, the initial rules are corrected according to an adjusting procedure (Nalbantis and Koutsoyiannis, 1997), which makes the final operating rules nonlinear. Nevertheless, the final operating rule is completely determined by the set of parameters a_i, b_i, irrespectively of all corrections. Examples of the graphical representation of the operating rules are shown in Figure 5 and Figure 6. This methodology does not use step-by-step releases of the reservoirs as control variables, thus avoiding an extremely large number of control variables. The above formulation determines the target storage of each reservoir of the system as a function of the total active storage. This reduces the total number of control variables of the system to 2N and becomes independent of the simulation length. Another advantage of this methodology is that once an operating rule has been determined, the reservoirs of the hydrosystem can be operated even without running the model whereas conventional methods need continuous runs with updated hydrological data.

5.2.2 Simulation

The simulation model represents the operations of the hydrosystem in an accurate manner, handling all physical constraints and trying to satisfy the operational targets that are imposed from the manager of the system. Applying *Hydronomeas*, a number of operational targets can be defined by the user from one of the following categories:

- water consumption targets (water supply, irrigation etc.);
- minimum flow preservation and maximum flow in selected aqueducts and time periods;
- minimum and maximum reservoir storage.

Assuming that the operating rule and consequently all parameters a_i and b_i are known, according to equation (6) the desired storages S_i^* and releases from each reservoir i will also be known at the beginning of each time step. Knowing the desired release values may not be sufficient for the specification of all system's state variables (i.e., the actual releases and discharges) because of at least one of the reasons below:

- due to discharge capacity constraints, the actual releases may differ from the desired ones;
- the flows in the network can be conveyed via multiple paths, each one having a different cost;
- multiple and contradictory operational targets have to be satisfied simultaneously;
- the total water availability may be less than the total demand.

Therefore, a flow allocation problem arises, demanding to strictly satisfy all the physical constraints of the system, handling all the operational targets according to a predefined priority series and minimise the total water conveyance cost and system's losses that are due to spill. At the same time the deviations between the actual and the desired releases have to be minimised in order to satisfy (or, if not possible, approach) the operation rules of the system. This is done by formulating the mathematical model of the system as a network optimisation problem, which is solved at each time step, assuming that the system's components and attributes are represented in a digraph form, as shown in Figure 3. In the digraph each reservoir is replaced by three nodes, an "inflow" (a), a "storage" (b) and a "release" node (c). Virtual arcs are used to represent each variable of the water balance equation and the sum of water that is stored, spilled or consumed is diverted to a "dummy" node. At each arc of the digraph two attributes are imposed, the conveyance capacity u_{ij} and the unit cost c_{ij}. Some of the costs are actual monetary costs whereas some others are artificially introduced to enforce satisfaction of restrictions and priorities.

The objective of the problem is the identification of the appropriate flow values x_{ij} in the network that minimise the total transportation cost, namely:

$$\text{minimise } \mathbf{c}\,\mathbf{x} = \sum c_{ij}\, x_{ij} \tag{7}$$

The mathematical constraints are (a) the continuity equations at each node of the digraph and (b) the capacity constraints at each arc of the digraph. The above optimisation model, also known as the transshipment problem, can be very easily and quickly solved via linear programming methods like the simplex and the network simplex. Thus the simulation procedure at each time step can be described by the following steps:

> Step 1: The total net storage of the system is estimated and the target releases from each reservoir are calculated according to the parametric operating rules.
>
> Step 2: System's components are transformed into digraph components and the values of the digraph attributes (inflows, capacities and unit costs) are specified.
>
> Step 3: The flow allocation (transshipment) problem is formulated and solved.
>
> Step 4: The optimal flow values are assigned to the variables of the mathematical model of the hydrosystem, in order to express the actual flow quantities.

It must be emphasised that the flow allocation problem, which is a linear optimisation problem, is solved separately in each simulation step (e.g. month). In other words, the system simulation embraces a linear optimisation routine, which is executed a vast number of times. Fortunately, the linear character of the flow allocation problem enables a very fast execution of simulation.

5.2.3 Optimisation

An advantage of the parametric formulation of problems is that simulation procedures can be driven by optimisation algorithms whereas conventional non-parametric simulation methods cannot. A performance index of the system is introduced as a measure of the efficiency of a particular policy management. It is defined in terms of reliability, yield or economy and mathematically expressed in terms of the (unknown) parameters of the operating rules. The objective function can have one of the following formulations:

- minimisation of the mean failure probability of the system, for a given set of operational targets;
- maximisation of the total annual withdrawal, for a given reliability level;
- minimisation of the mean water conveyance cost, for a given set of operational targets and a given reliability level.

The objective function is evaluated via the simulation process as shown in Figure 4. Thus, simulation is driven by an external optimisation procedure, which is totally different from the internal flow optimisation procedure discussed in section 5.2.2. Specifically, this optimisation problem is strongly nonlinear; advanced techniques are used, particularly the multi-start downhill simplex method (Nelder and Mead, 1965) and the shuffled complex evolution method (Duan et al., 1992).

6. DSS application

During the last year, the model of the hydrosystem has been successively improved, in order to represent in the best possible way the characteristics of the real world. Many scenarios of several hypothetical situations for the water supply system of Athens have been examined. These scenarios cover different assumptions for the future water demand, incorporate the expected improvements in the water conveyance capability of the network and reflect some realistic hydrological situations. They also cover different management objectives. Two of the implemented scenarios are discussed below.

6.1 Scenario 1: Theoretical potential of the water resources system

The objective of Scenario 1 was to calculate the theoretical potential of the water resources system regardless of any restrictions imposed by conveyance capacity limits of aqueducts and regardless of any costs due to the conveyance of the water through the network. The adopted reliability level was set to 99% on an annual basis (only 1 failure of the system to meet the target is allowed in 100 years), a value that provides a high level of safety. A particular management policy was considered for groundwater resources, which are considered as backup resources. Two thresholds were imposed, the upper one to forbid the usage of groundwater if the active storage of the system is more than 40% of the total active capacity, and the lower one to enforce their usage if the storage is less than 25% of the capacity. Between these thresholds, the usage of groundwater depends on economic criteria. The conveyance cost was introduced in terms of energy consumption (kWh/m^3). After optimisation based on steady state simulations with a synthetic inflow series of 2000 years length, the safe yield of the system, estimated at the location of WTPs, is about 480 hm^3 per year for the above described policy of groundwater abstractions.

The OMP is described in terms of parametric operating rules for each reservoir of the system. The graphical representation of these rules, shown in Figure 5, describes the target reservoir storage as a function of the total system storage. Since the reservoir of Marathon is kept at given stages, it has been excluded from the optimisation process. An analysis of the results indicates that under Scenario 1, water has to be allocated preferably from the Evinos reservoir and from lake Yliki. This management policy minimises the water spillage from the relatively small Evinos reservoir and at the same time it increases the yield of the lake Yliki by keeping the stored water at a low level and thus reduces the water leakage rates.

6.2 Scenario 2: Actual potential of the present water supply system

The objective of Scenario 2 was to evaluate the real potential of the present hydrosystem configuration and to determine the OMP, which ensures an average annual 99% reliability level for the next 10 years and at the same time minimises the total pumping energy. Thus, the discharge capacity values of the aqueducts were set to their actual values and the values of losses of each branch of the network were set according to estimations and earlier studies. The overall water losses from aqueducts (from sources to the WTPs) are estimated to about 10% of the total withdrawal.

During the simulation period, the water demand increase is assumed to be moderate, starting at 400 hm^3 in the first year and reaching 420 hm^3 in the last year. The terminating simulations were based on 200 synthetic inflow data sets, each of them having a length of 10 years.

Figure 6 shows the graphical representation of the OMP for the three main reservoirs of Athens. In this scenario and according to the calculated rules, the water from lake Yliki is used only to ensure the predefined reliability level. If this condition is satisfied, the operating rule tends to save the water in the lake Yliki and use water primarily from the two other reservoirs, because of the pumping cost related to the water transportation through the Yliki aqueduct.

Figure 7 shows the surface water resources storage prediction for the water supply system of Athens, calculated on 1 December 2001. The prediction is represented by curves, which gives the system storage against time with a given exceedance probability. *Hydronomeas* makes similar probability-based predictions for all quantities related to the hydrosystem, such as releases, pumping energies, and failures of user-defined targets.

The current operating rules for the reservoirs of the water supply system of Athens are based on the statistical properties of more than twenty years (since 1979) hydrological records. In case there is no particular reason to do otherwise (e.g. modification of the initial scenario), it is estimated that a reconsideration and eventually an update of the operating rules, after optimisation, every three months, based on newer hydrological, storage, and water use data would be adequate. This rough estimation should however be verified in further stages of DSS application.

7. Concluding remarks

It has been a common practice in the development of DSSs to use existing tools that are linked together into an integrated system. This however, it was not the case in the development of the DSS for the Athens hydrosystem. The peculiarities of the hydrosystem (e.g., high reservoir leakage), the high level of specifications (e.g., 99% reliability) and the experience from its operation so far (e.g., the 6-year drought of the 1990s), dictated the development of novel methodologies, which had to be programmed into a totally new system. These methodologies are mainly concerned with the prediction of reservoir inflows in a manner that the historically observed long-term hydrologic persistence is preserved on multiple sites simultaneously, and with the optimisation of the system management in such a manner that the water leakages, the conveyance cost, and the failure risk are minimised. In this way the system's risk in satisfying its targets is being studied in a holistic manner, avoiding empirical considerations like the separate study of isolated dry, normal and wet years, which has been a common practice in similar situations.

Although the paper focuses on the modelling issues of the DSS, like the hydrologic and system simulation and optimisation, from a mathematical point of view, it cannot be too strongly emphasized that the tool would not be successful were it not for the administrative tasks it performs, such as data storage, visualisations, and report creation. It is especially important that a network of automatic measuring stations has been designed as a part of the DSS. Too much attention is often given to data processing techniques, easily overlooking the problem of shortage of reliable data.

A well-known problem in development and application of a DSS is the general lack of communication between analysts/developers and decision makers (or their technical support staff). Therefore, emphasis has been given from the initial steps of the development to the attainment of a good communication level through interviews with experience personnel, joint seminars, workshops and education programmes. So far the situation is encouraging since the new masterplan of the hydrosystem management has been totally based on the DSS and simultaneously, the decisions of the system management in the last year, which was a difficult one due to drought conditions, were harmonised with the suggestions of the DSS.

Although the DSS has been developed for the management of the Athens hydrosystem, a great effort was done to make the methodologies and the software as general as possible, in order to be adaptable to other complex reservoir systems. For example, although the hydropower generation capabilities in the Athens hydrosystem are limited and rather marginal (a few small hydropower projects are foreseen along the aqueducts), the methodology is applicable to complex reservoir systems with large hydropower projects.

The DSS has been designed to operate on a monthly time step, which is crucial for the management of the Athens hydrosystem. An extension for daily or sub-daily time step is one of the main tasks of future developments.

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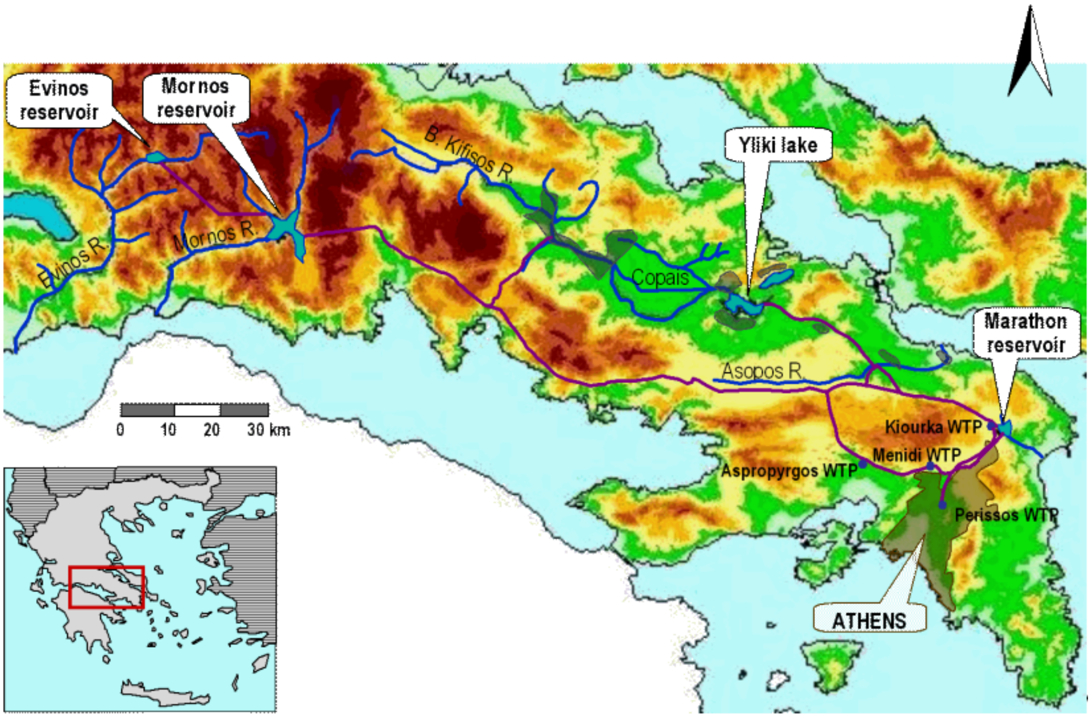


Figure 1: The Athens Water Supply System.

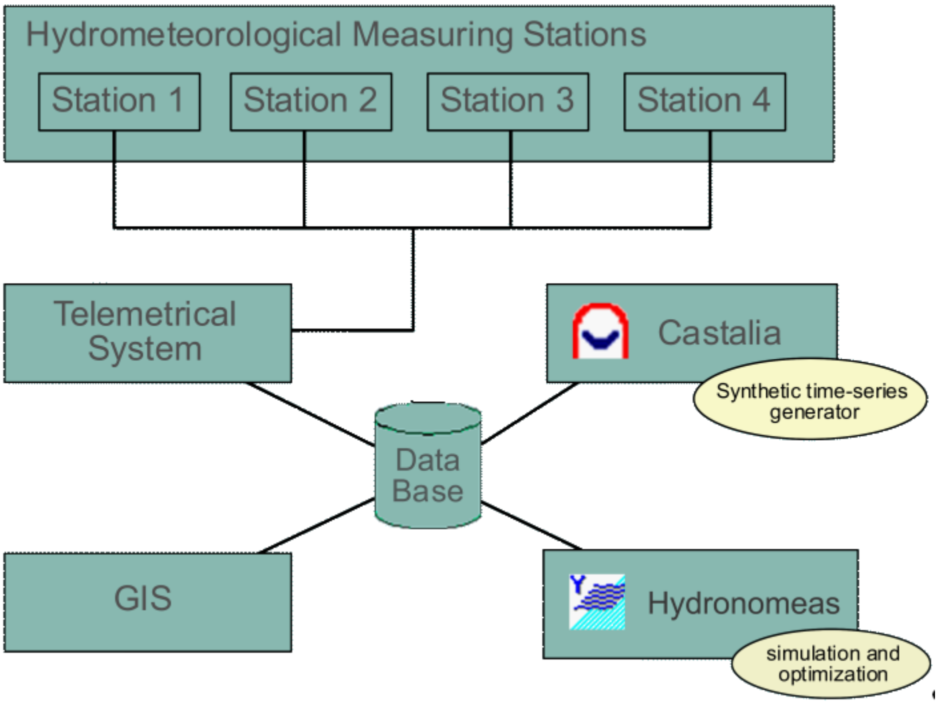
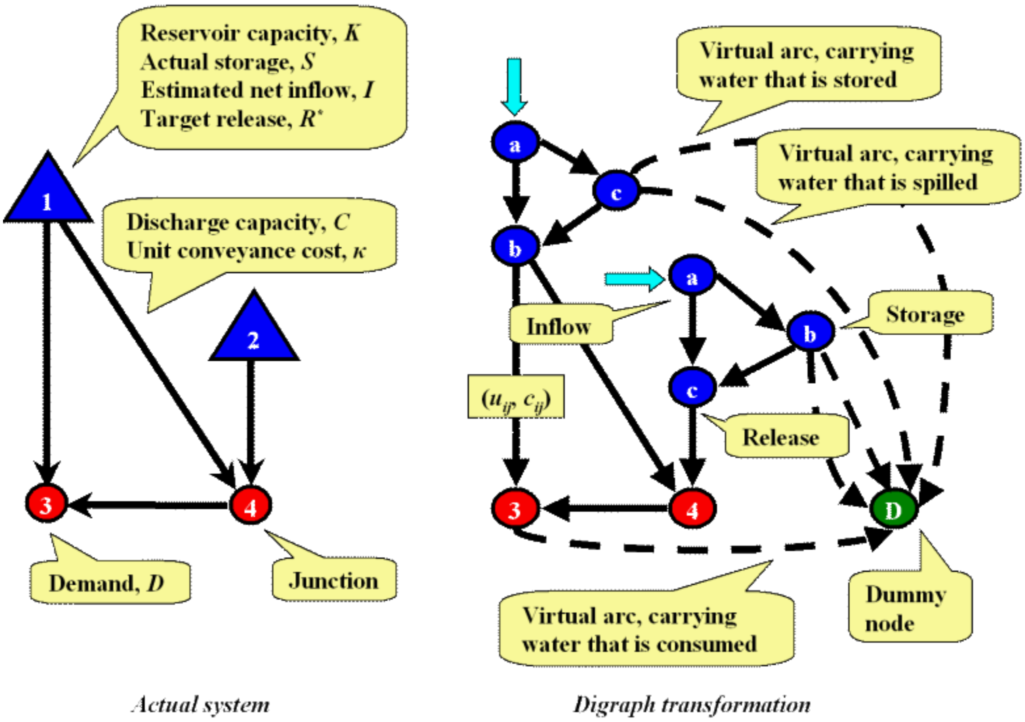


Figure 2: The components of the DSS for the management of the Athens water resource system.



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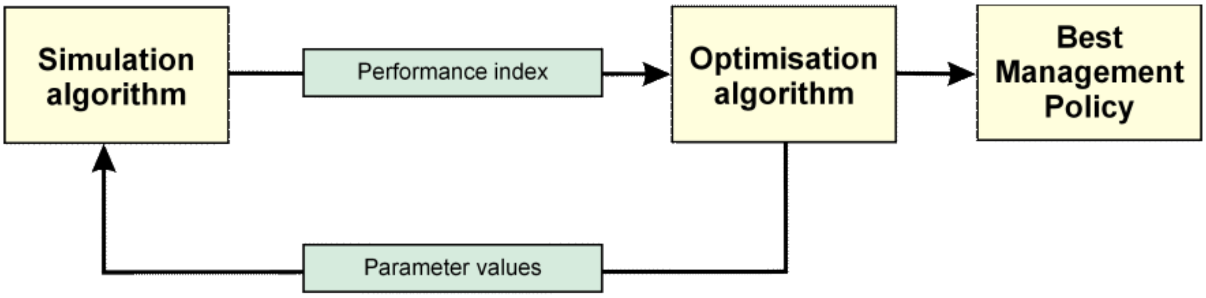

Figure 4: Flow chart of the optimisation process.

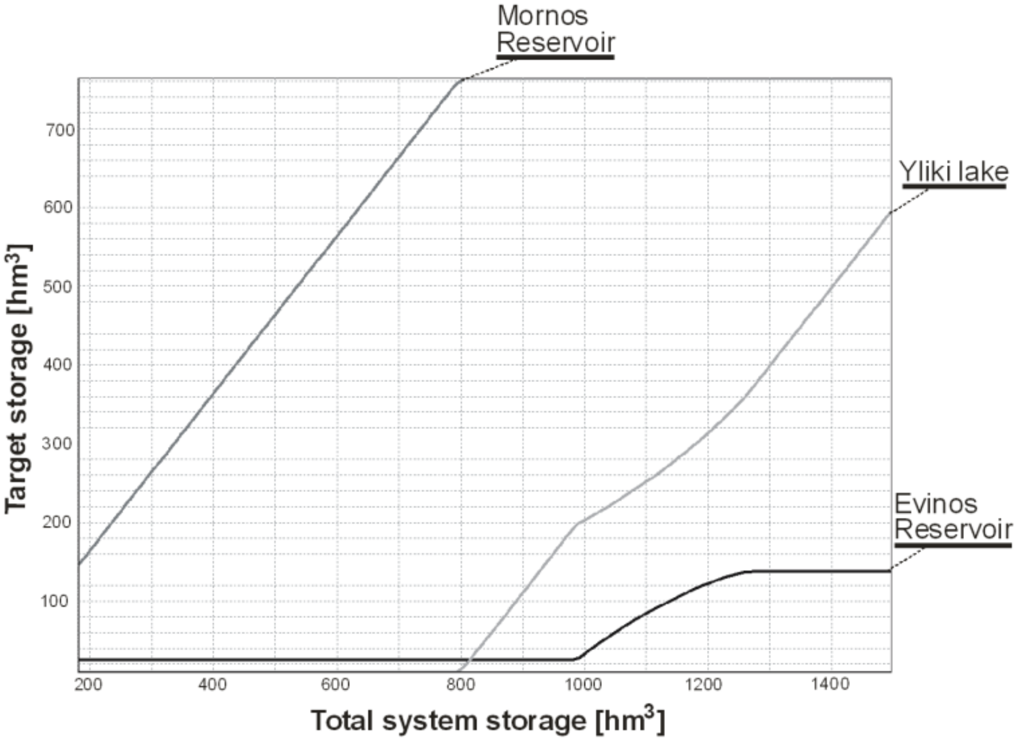

Figure 5: Graphical representation of the optimal operation rules of the three main reservoirs of the Athens hydrosystem for Scenario 1.

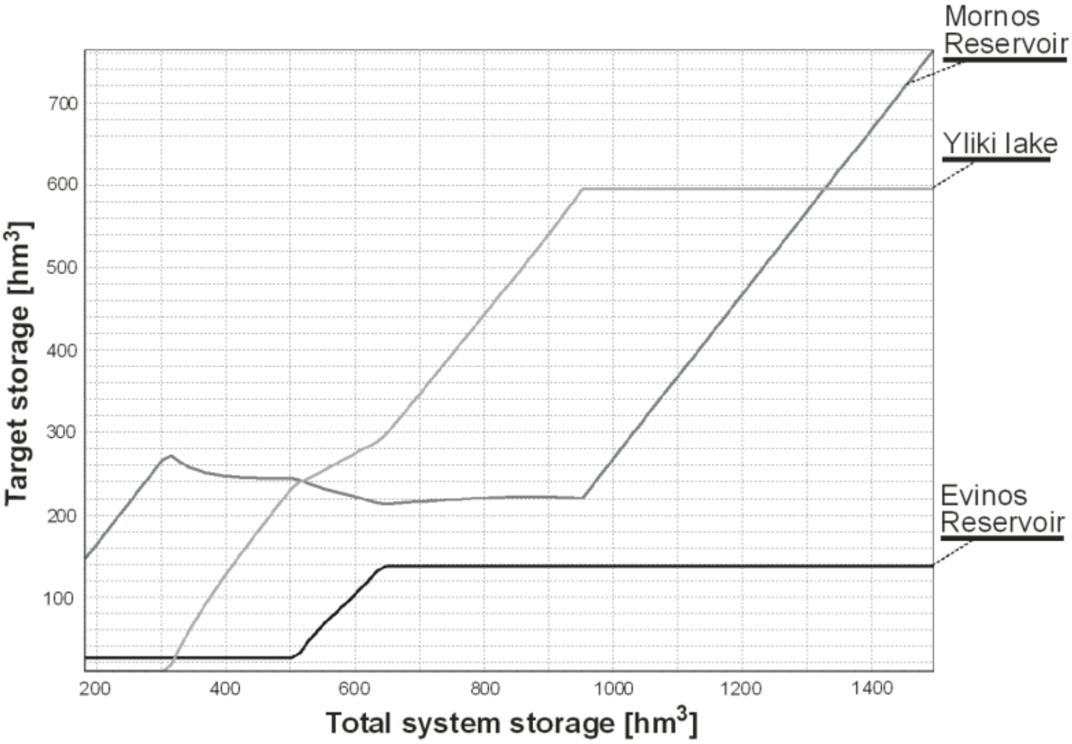

Figure 6: Graphical representation of the optimal operation rules of the three main reservoirs of the Athens hydrosystem for Scenario 2.

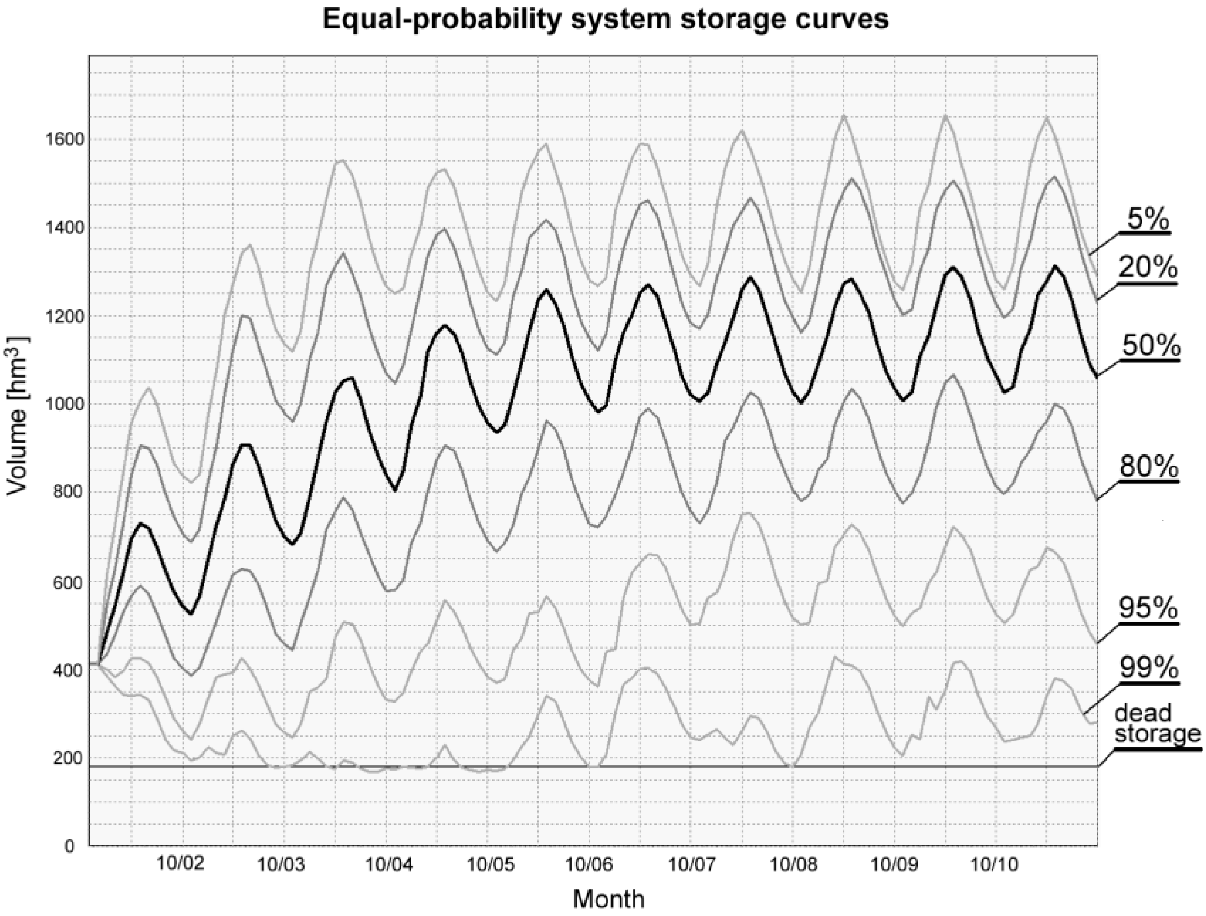

Figure 7: Surface water resources storage prediction for the water resource system of Athens, calculated on 1 December 2001.