A Decision Support Tool for the Management of Multi-reservoir Systems

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Abstract: A decision support tool is developed for the management of water resources, focusing on multipurpose reservoir systems. This software tool has been designed in such a way that it can be suitable to hydrosystems with multiple water uses and operating goals, calculating complex multi-reservoir systems as a whole. The mathematical framework is based on the parameterization-simulation-optimization scheme. The main idea consists of a parametric formulation of the operating rules for reservoirs and other projects (i.e. hydropower plants). This methodology enables the radical decrease of the number of decision variables, making feasible the location of the optimal management policy, which maximizes the system yield and the overall operational benefit and minimizes the risk for the management decisions. The program was developed using advanced software engineering techniques. It is adaptable in a wide range of water resources systems and its purpose is to support water and power supply companies and related authorities. It was already applied to two of the most complicated hydrosystems of Greece, the first time as a planning tool and the second time as a management tool.

Introduction

The design and operation of surface water systems are the most typical watershed management problems. The fundamental components that make up surface water systems include reservoirs and their withdrawal structures and spillways as well as pipelines, irrigation channels and hydropower units. They also include the watershed as a source of water as well as the physical aquatic environment and the associated ecosystems.

Water resources management requires system-wide decision-making and control that considers an integrated viewpoint (Grigg, 1996). It is a scientific area rich in problems and challenges. The large number of variables involved, the nonlinearity of dynamics, the stochastic nature of future inflows and other uncertainties of water resources systems render their management a difficult but imperative task. Complexity further increases when desiring to combine multiple benefits arising from reservoir system operation (e.g., hydropower, irrigation, etc.), frequently competitive or even conflicting, together with the reduction of natural risks (e.g., flood control) and the environmental requirements. Many times, the management of large hydrosystems, especially when they lie on more than one watershed, raises conflicts between authorities or organizations with different interests (e.g., water supply companies, farmers' leagues, ecologists).

The problem of planning and managing multipurpose reservoir systems, most often stated as an optimal control problem, has been and continues to be the subject of extensive research work. A plethora of mathematical models, based on systems analysis techniques, have been proposed during the past decades, offering a wide range of choices and solutions. Most researchers group them in two large categories: optimization and simulation methods. Mays and Tung (1996) make an exhaustive overview of typical optimization techniques used in water resources systems analysis.

Due to the stochastic aspect of water resources systems, deterministic optimization methods, such as linear and dynamic programming (Loucks et al., 1981; ReVelle, 1999), cannot provide optimal solutions or, more accurately, cannot estimate the reliability of the proposed solutions. On the other hand, stochastic dynamic programming, which has been repeatedly used by many researchers (e.g., Su and

Deininger, 1972, 1974; Askew, 1974a, b; Sniedovich, 1979, 1980a, b; Bras et al., 1983; Stedinger et al., 1984; Karamouz and Vasiliadis, 1992; Tejada-Guibert et al., 1995; Kim and Palmer, 1997), is subject to the "curse of dimensionality", requiring excessive amounts of computer time and storage. To increase the efficiency of the solution algorithm, some researchers have treated the inflows uncertainty in an analytic way without state-space discretization (Wasimi and Kitanidis, 1983; Georgakakos and Marks, 1987). The latter represented the reservoir system dynamics in a state-space form and proposed an extension of stochastic control theory, which they termed extended linear quadratic Gaussian (ELQG). In this way they obtained a very efficient algorithm at the expense of accurate representation of the stochastic structure of inflows, which was tackled in later studies (Georgakakos, 1989; Georgakakos et al., 1997, 1998). Other researchers continued their studies in the direction of stochastic dynamic programming, with the purpose of remedying errors due to the discretization (Kitanidis and Foufoula-Georgiou, 1987; Johnson et al., 1993). Another approach, the so-called principal component dynamic programming, identifies the major components of the reservoir system's operation applying statistical analysis of deterministic optimization results, to diminish the number of state variables of the mathematical model (Saad and Turzeon, 1988; Saad et al., 1992).

In spite of the development and growing use of optimization techniques, simulation models remain the primary tool for reservoir planning and management studies in practice. Simulation allows a more detailed and faithful representation of a real-world system's performance than optimization models do (Loucks and Sigvaldason, 1982). Moreover, they can be easily combined with synthetically generated inflow sequences (Loucks et al., 1981). The main drawback of simulation is that it requires prior specification of the system operating policy. In consequence, the only way to locate an optimal policy is through subsequent trials. Many researchers have employed optimization methods within simulation models (Evenson and Moseley, 1970; Sigvaldason, 1976; Ginn and Houck, 1989; Johnson et al., 1991; Tejada-Guibert et al., 1993). These techniques do not result in optimal solution but rather facilitate compliance with the predefined operating rules (Oliveira and Loucks, 1997).

Such rules are often heuristic and define the desired storage and release targets in terms of some state variables. Among them are the well-known space rule (Bower et al., 1962) and the relative New York Rule (NYC) (Clark, 1950, 1956), both applied in water supply systems, whose aim is to reduce losses due to spills. These heuristic rules are applicable only to ideal systems with no constraints relative to storage capacities or water withdrawals. In real-world applications they are accompanied by special algorithms that regulate storage and release targets so as to be consistent with physical and operating constraints (Stedinger et al., 1983; Loucks and Sigvaldason, 1982; Yeh, 1985; Johnson et al., 1991; Lund and Guzman, 1999).

Recently, Nalbantis and Koutsoyiannis (1997) proposed a framework that combines simulation and optimization in quite a different scheme. Their methodology does not use the step-by-step releases of the reservoirs as control variables thus avoiding an extremely large number of variables. Instead, it introduces simple parametric rules describing their operation policy using a few parameters (system parameterization). The unknown parameters are estimated by nonlinear optimization, employing stochastic simulation to evaluate the objective function value for each trial set of parameter values. In that manner, the physical constraints of the system are handled by the simulation procedure and the control variables of the problem, namely the parameters, do not depend on inflow series but rather on their statistical properties.

A decision support tool, which implements the parameterization-simulation-optimization methodology, has been developed and applied to two of the most complex hydrosystems in Greece, particularly diverse in terms of their structure and purposes. The program can be adapted to a plethora of hydrosystems with a variety of goals and constraints, such as consumptive (e.g., irrigation, water supply) and non-consumptive uses (e.g., hydropower, reservoir storage control, minimum flow preservation).

This paper is organized in five sections. First, the basics of the proposed mathematical framework are presented. Next the parameterization-simulation-optimization methodology is explained. Some information concerning the software tool and its capabilities is included in the following section. Then, two applications to real-world reservoir systems are examined to assess the reliability and efficiency of the proposed methodology. The last section summarizes the conclusions and discusses future prospects.

Mathematical framework

A system of N reservoirs, each having a storage capacity K_i, is assumed for which an operating policy is sought. The policy is focused on various water uses such as consumptive uses, hydropower generation, environmental preservation or storage control (for flood prevention). The reservoirs are connected in series or in parallel, forming a network with any topology. Water is withdrawn from some or all of them in order to meet either downstream target water demands or energy generation targets.

System dynamics at any time step t are described by a set of mass conservation (water balance) equations:

$$S_i(t + 1) = S_i(t) + I_i(t) - L_i(t) - R_i(t) \qquad (1)$$

where $S_i(t)$ is the storage for reservoir i; $I_i(t)$ is the inflow from the upstream system, including the catchment runoff; $L_i(t)$ includes various losses due to net evaporation (evaporation minus rainfall), seepage and spillway operation; and $R_i(t)$ is the controlled release rate. Since the release $R_i(t)$ of each reservoir is unknown, the system has a large number of degrees of freedom, more precisely $N \times T$, where T is the total number of simulated time steps (e.g., years or months). To reduce this number, the idea of parameterization is introduced.

Let V denote the total active storage (excluding dead volume) in the system at the end of a time period of interest and S_i be the respective active storage for reservoir i. Reference to the time interval is omitted for convenience. Apparently,

$$\sum_{i=1}^{N} S_i = V \qquad (2)$$

The actual problem is to determine the releases from all reservoirs so that their sum equals the total water demand. Equivalently, the problem is to distribute V into the N reservoirs such that the latter constraint is satisfied. This can be done in numerous ways, as the problem has several degrees of freedom. A specific way to perform this distribution is termed an operating rule. Nalbantis and Koutsoyiannis (1997) introduced a parametric linear rule, whose a slightly modified form is:

$$S_i^* = K_i - a_i K + b_i V \tag{3}$$

where K is the total capacity of the system, a_i and b_i, $i \in \{1,\ldots, N\}$, are unknown parameters ($0 \le a_i, b_i \le 1$) and S_i^* stands for the target storage for the reservoir i at the end of the period, which generally differs from the real storage S_i due to the physical constraints that were not considered in this stage. After extensive analysis, Nalbantis and Koutsoyiannis (1997) concluded that the operating rule in the linear form of (3) is a convenient and efficient parameterization of the problem. Moreover, they found that the parameterization is still efficient even if we omit the constant term of (3), by setting parameters a_i equal to K_i / K. Generally, the parameters can be considered constant in time or, alternatively, they may be different for the refill (wet) and the drawdown (dry) season.

Subsequently, because (3) ignores the physical constraint that the storage cannot be negative nor can it exceed the capacity K_i, they modified (3) so that:

$$S_i'^* = \begin{cases} 0 & K_i - a_i K + b_i V < 0 \\ K_i - a_i K + b_i V & 0 \le K_i - a_i K + b_i V \le K_i \\ K_i & K_i - a_i K + b_i V > K_i \end{cases} \tag{4}$$

Then, a nonlinear adjusting procedure is applied in order to re-establish the additive property (2). This makes the final operating rule nonlinear, yet being completely determined by the initial parameters a_i and b_i, irrespective of all corrections. Therefore the total number of control variables in the system reduces to $2N$ and becomes independent of the number of simulated time steps, T. In Figure 1 the parametric operational rules for three hypothetical reservoirs are plotted; thin lines represent the initial linear rules (equation 3) whereas thick lines represent the adjusted ones.

Only the fundamental principles of the methodology have been mentioned here. For more details, including justification of the parametric rule's form, the reader may refer to Nalbantis and Koutsoyiannis (1997).

In addition to the parameters of the operating rule other control variables may be introduced depending on the specific problem examined each time. Such variables could be the target withdrawal of the system or the target energy production from the system, etc. In any case the number of control variables in this formulation remains very limited and obviously the problem is essentially nonlinear.

The parameterization-simulation-optimization scheme

A flowchart representation of the parameterization-simulation-optimization scheme is given in Figure 2. Input data are a) the hydrosystem structure, namely the system components and their attributes, and the topology; b) the hydrologic data series, either taken from historical records or generated synthetically. The system is parameterized using the parametric operation rule described above. Parameters of the operating rule and, on occasion, a target withdrawal or target power production are considered as control variables of the problem to be determined by optimization. The objectives of the management are expressed mathematically as the performance index of the system. The operational constraints of the system are incorporated into the performance index as penalty terms.

Assuming that parameters a_i and b_i are known, the target releases from each reservoir will also be known at each time step. Due to the physical constraints of the hydrosystem (e.g., discharge capacity of pipes, channels and penstokes), the actual releases may differ from the desired ones and their estimation is done via simulation. Within simulation, an internal optimization procedure may be necessary. That case arises when flows in the network can be conducted via multiple paths. A flow allocation, also known as transshipment, problem is formulated and the hydrosystem's layout is represented in a digraph form [Figure 3]. Three nodes, a "source" node, a "sink" node and a "storage" node represent each reservoir. Each link (pipe or channel) corresponds to an edge for which a unit transportation "cost" is introduced, expressing either the real water transportation price or a penalty value, depending on the deviation of the actual flow from the desired one. The transshipment problem is easily formulated and solved within each simulation step using typical linear programming algorithms (simplex, network simplex).

Because parameters are not known, but rather are to be optimized, simulation is driven by an external optimization procedure. The method is applied in the form of successive steps or iterations. Trial values are assigned to the parameters and the performance index (objective function) of the system is evaluated, by performing a simulation of the system operation for the whole operation period. New parameter values are chosen according to an iterative nonlinear optimization method (see next section) and the algorithm proceeds in this way for a number of iterations until convergence to an optimal solution. The results of the model are the values of parameters of the operating rules and other control variables that optimize the performance index of the system.

Attempting a comparison between the proposed, low-dimensional methodology and a conventional, non parametric optimization we can distinguish four advantages of the former:

1. Due to parameterization, the number of control variables is small, reducing the computational effort of optimization.
2. Parametric optimization can be combined with simulation procedures whereas conventional optimization techniques (e.g., linear and dynamic programming) cannot and, thus, in the latter case all physical constraints of the system must be introduced as mathematical constraints in the optimization procedure.
3. In most optimization methods, the optimal solution depends on inflow series, whereas in the parametric methodology the optimum depends only on their statistical properties (this is also true for stochastic dynamic programming models). Within stochastic simulation, the reliability of the management policy can be estimated.
4. Optimization models need continuous runs with updated hydrological data, whereas a hydrosystem optimized via the parametric rule based procedure can be operated without running the model again.

A disadvantage of the method is that the form of the operation rules is predefined; notwithstanding several trials proved that the differences between the linear rule given by (3) and other mathematical expressions (e.g., quadratic) are not significant (Nalbantis and Koutsoyiannis, 1997).

Program description

The parameterization-simulation-optimization scheme described above has been implemented in *Hydronomeas* (a Greek term meaning the "distributor of water"), a software application for planning and management of multi-reservoir multipurpose hydrosystems. The source code is in Object Pascal programming language, designed for the Windows environment [Figure 4]. A first version of the program was developed for academic purposes (Karavokiros et al., 1999; Efstratiadis and Zervos, 1999) and its improved, operational version is in progress (Karavokiros et al., 2000).

The decision support system gives answers to several questions, about:

- the maximized annual total withdrawal (or firm energy) from the hydrosystem, for a given hydrologic regime and a given reliability;
- the minimized failure probability for a given set of operational goals and a given hydrologic regime;
- the minimized cost for a given set of operational goals, a given hydrologic regime and a given reliability;
- the optimal management policy that assures the above objectives;
- the consequences of modifications in the hydrosystem (e.g., construction of new projects), and the impacts of different management policies or hydroclimatic scenarios.

A brief representation of the software system structure and relations between its modules is given in Figure 5. *Hydronomeas* is supported by a database where all information concerning the hydrosystem is stored. Database architecture is based on the entity-relationship (E/R) model, described by Sommerville (1998). The components of the real system are replaced by five entities, namely nodes, aqueducts, energy conversion units, hydrologic time series and (operational) targets [Figure 6]. More specifically:

1. A *node* can be a source (e.g., reservoir, aquifer) or sink (e.g. consumption area) of water or simply an intermediate point (junction) of the network. A node is assigned some attributes. For example, the attributes of a reservoir are the river basin area, the dead volume, the storage capacity, the storage-elevation-area function, the seepage equation, the inflow series file, etc.

2. An *aqueduct* refers to a natural or artificial channel connecting two nodes and the flow direction is defined from the corresponding hydraulic heads. Some of the attributes of an aqueduct are the discharge capacity, the head-discharge relationship, the leakage function, the unit transportation price, etc. Special restrictions can be imposed on aqueducts, permitting their use only for specific reasons, i.e. reservoir evacuation, and limiting their time-use availability (e.g., to provide for maintenance and repairing works). Natural channels (e.g., rivers) do not have capacity or time-usage limits.
3. An *energy conversion unit* is either a turbine station or a pumping station or a pumped storage station, referred to a unique aqueduct. Pumping facilities may permit bi-directional flow through aqueducts. The fundamental attributes of an energy conversion unit are the power capacity and the discharge-power relationship.
4. *Time series* are referred to reservoirs and contain runoff, rainfall and evaporation data for the simulated period, all expressed as equivalent depths. Hydrologic data can either be obtained from historical records or generated. For this purpose, a two-level (annual and monthly) multivariate stochastic model is linked to *Hydronomeas*. The generation of annual series is performed via a generalized long-memory scheme (Koutsoyiannis, 2000), whereas monthly series are generated by disaggregation (Koutsoyiannis and Manetas, 1996; Koutsoyiannis, 1999).
5. A *target* is an operational goal or system constraint, referred to a unique component of the network. Multipurpose hydrosystems need to serve (by definition) a large number of water uses that are usually unrelated or even competitive. *Hydronomeas* supports a variety of such uses that can be classified in four major categories a) water consumption, b) minimum flow preservation either in aqueducts or in natural channels to satisfy environmental requirements, c) energy generation in hydroelectric plants, and d) reservoir storage control, either to ensure the existence of a minimum safety storage or to prevent overrun of a maximum storage value that guarantees flood-control capabilities. Typically, power targets are referred to firm energy production, namely the amount of hydroelectric peak energy that is available on an assured basis (Grigg, 1996). All target values are

given in monthly steps. The program also handles long-term trends, corresponding to predicted demand changes. A maximum allowable failure probability is assigned to each target, usually depending on target type and on an assessment of the impacts in case of failure.

Network structure and individual component attributes can be retrieved or modified via the network management module, which is the interface between the database and the program. After the desired changes have been completed, all database information is loaded via the control module, thus rendering it completely independent. A number of other general options must be specified before setting off the optimization procedure, such as the objective function, input arguments of the optimization algorithm, economic aspects, etc.

The optimization module assigns values to parameters, evaluates the objective function by performing a simulation of the system's operation for the complete simulation period and then modifies parameters appropriately. At any stage, the evolution of a simulation can be viewed via the dynamic visualization module. The process is repeated until the convergence criterion for defining an optimal solution is met. The analytical results, presented in tabular or chart form, include, apart from the optimal operation rules charts, average hydrologic, energy and economic balances, the failure probability for each target or constraint of the system, etc.

As described before, the simulation model requires an internal step-by-step optimization procedure, which is implemented via the network simplex algorithm (e.g., Smith, 1982). For the external (global) optimization process two alternative approaches have been implemented. The first one uses enumeration: a uniform division of the feasible area is implemented and all possible combinations of parameter values (all the grid points of the parameter space) are evaluated (Loucks et al, 1981). The process is applied in the form of successive steps, with grids that are nested into each other and become progressively finer. This method is extremely time-consuming, and the number of calculations required increases exponentially with the number of parameters. On the other hand, it is very likely that the global optimal solution will be tracked down, although there is no absolute guarantee.

The second approach incorporates efficient nonlinear optimization methods, which reduce optimization time, especially for large systems and long simulation periods. Such methods start from a random set of parameters and pursue a search towards the optimum. Moreover, to increase the chance of locating the global optimal solution rather than ending with local optima, multiple searches are conducted starting from different initial values, which are randomly determined. Two well-known algorithms, the multi-start downhill simplex method (Press et al., 1992) and the shuffled complex evolution method (Duan et al., 1992) are incorporated in the current version of the program. An interesting feature of the following version will be the use of high performance computing (parallel processing) technology, in order to take advantage of the power of computer clusters to accelerate the optimization process.

Applications

Hydronomeas was used to analyze two major hydrosystems in Greece: the Acheloos-Thessalia reservoir system (western Greece) and the Greater Athens Water Supply reservoir system (central-eastern Greece). The first system is under study and *Hydronomeas* was used as a planning tool, in order to evaluate the overall impacts and benefits for various project formations. The second hydrosystem is run by the Athens Water Supply and Sewage Company; here *Hydronomeas* is the core of an integrated decision support system (DSS), including also modules that perform data acquisition, manipulation and visualization (the entire DSS is still under development).

Both hydrosystems serve (or are planned to serve) the eastern, almost semiarid areas of Greece, where most people and activities are concentrated, by transporting large amounts of water from the western, rich in aquatic resources, watersheds. However, they have significant differences concerning their general design conception and project characteristics as well as their overall management policy, operational constraints and long-term objectives.

The *Acheloos-Thessalia reservoir system* will, when completed, be the largest hydrosystem in Greece, consisting of 7 reservoirs and 7 hydroelectric power plants [Figure 7]. Acheloos River is one of the most important of the country, having a mean annual discharge of about 130 m^3/s. Three power stations (Kremasta, Kastraki and Stratos) are installed along the river, producing a significant part of the hydroelectric energy of Greece. Two additional hydroelectric dams are currently under construction in the Upper Acheloos watershed (Mesohora and Sykia). Downstream of the dams, the Aitoloakarnania plain is irrigated and also, sensitive estuary and aquatic ecosystems are maintained from the river flow.

Thessalia plain, which is located in central Greece, stands as a key agricultural region for the national economy. However, the impacts of agricultural expansion have resulted in extensive water shortages and ecosystem degradation. To reverse this trend and to maintain the sustainability of the land resources, a water diversion of 600 hm^3/yr has been proposed from the nearby Acheloos river basin. This plan continues to provoke great conflicts among politicians, engineers, farmer leagues, ecologists and the Public Power Corporation.

Some specific features of the reservoirs are given in Table 1. Reservoir leakages are 6 m^3/s in Kremasta and 4 m^3/s in Stratos, while at other reservoirs they are not significant. All reservoirs except Pyli have hydropower generation units, the number and capacities of which are shown in Table 2. The power plants are considered as peak energy facilities. The daily peak period is assumed to last 6 hours. Some studies (e.g., Koutsoyiannis, 1996) examined the installation of pumped storage power plants in Pefkofyto and Mouzaki, in order to increase peak energy generation. In that case, pumping is limited to a maximum of 8 hours per day, so as to function exclusively with night energy. Pumping capabilities are also assumed to operate during the wet season (September to March), when no water transfer towards Thessalia takes place. On the contrary, during the dry season pumps are activated only if normal flow is not adequate to fulfill energy generation targets.

Except for energy generation and flood control, the reservoir system is expected to provide water for irrigation and maintain sufficient in-stream flows to preserve environmental quality. Water releases for irrigation will take place at the edges of the system, downstream of Stratos and Mouzaki, which constitute the main irrigation dams for the Aitoloakarnania and the Thessalia plain respectively. Irrigation demand in Aitoloakarnania rises to 450 hm^3/yr, whereas in Thessalia the irrigation requirement is set to

600 hm^3/yr. Moreover, minimum flow targets are imposed downstream of each dam, reaching 21 m^3/s at the Acheloos estuaries.

In the framework of an academic research project referring to the Acheloos-Thessalia reservoir system study, an earlier version of *Hydronomeas* was used to assess the economic and energy impacts of different configurations of the planned hydraulic works. The emphasis of the study was not the detection of a specific reservoir management policy, even though the identification of the optimal operation rules was essential in order to maximize the hydrosystem's performance in each studied configuration. Five configuration scenarios were studied, involving either the whole reservoir system or some of its parts (Efstratiadis and Zervos, 1999). Scenario 1 comprised only the existing dams in the Lower Acheloos basin, whereas in Scenario 2 the Upper Acheloos reservoirs were added too. Two sub-cases were examined, in order to assess the impacts of diversion onto the Acheloos basin hydropower potential. In case 2a only irrigation demands downstream of Stratos were considered, whereas in case 2b an additional annual withdrawal of 600 hm^3 from Sykia reservoir was imposed. Scenario 3 dealt with the Upper Acheloos watershed, the diversion tunnel and the related projects in Thessalia. Scenario 4 was a study of the entire hydrosystem.

The objective in all scenarios was the maximization of total firm energy production, allowing a 20% failure probability for all irrigation targets and only 1% for environmental requirements. Firm energy was defined as that available during 99% of the whole simulation period, upon the condition that it can be generated within the daily 6-hour peak period. The additional energy generated was considered as secondary. All simulations were based on a monthly, 34-year-long (Oct. 1960-Sep. 1994) historical record of runoff, rainfall and evaporation. The mean annual values of total energy generation and consumption for each scenario are given in Table 3. Moreover, all irrigation and environmental requirements were satisfied with almost zero probability of failure. The results obtained are in general agreement with those of former studies (Georgakakos et al., 1998).

The *reservoir system for the Greater Athens Water Supply* supplies water mainly for domestic and industrial use to the metropolitan area of Athens and *Hydronomeas* is currently used as the main decision support tool for its management. A schematic layout of the hydrosystem, along with some technical characteristics, is sketched in Figure 8. The system uses surface as well as ground water resources, although the latter are considered only as auxiliary. Two reservoirs, the Mornos reservoir and the natural lake Yliki, are the main storage projects of the system. A small reservoir near Athens, the Marathon reservoir, is also part of the system and it is considered full all the time for emergency situations. The growing water demand and the system's vulnerability during the severe drought of 1988-1993, led public authorities to construct a new dam on the Evinos River, just west of the Mornos watershed, which was completed in the summer of 2001. Inflows to the Evinos reservoir are of a magnitude comparable to that of inflows to the Mornos reservoir, although the reservoir's storage capacity is quite small in comparison. Water from the Evinos reservoir is diverted through a tunnel to the neighboring Mornos reservoir, which stands as the main storage project for the Evinos River flow as well. Specific attributes of reservoirs are shown in Table 4. Major transfer works of the system are the Mornos aqueduct, some 200 km long, which carries water from the homonymous reservoir to Athens via gravity and the Yliki aqueduct, which carries water from Yliki Lake to Marathon reservoir via pumping.

An important feature of the system is that lake Yliki lies on a karstic geologic formation that causes significant leakage. This depends strongly on the water surface elevation of the lake and may equal half of the annual inflow for high elevations. Analysis of historical data established two distinct leakage-elevation relationships, one for the dry period and one for the wet period. Mornos reservoir leakage is concentrated in a limited area of the reservoir and is rather small compared to that of the lake Yliki.

The system's main objective is to provide water to the Greater Athens area which is divided in four sub-areas, allocated downstream of the respective water treatment plants. Secondary objectives are a) the maintenance of a minimum safety storage of about 35 hm^3 in Marathon reservoir, b) an environmental preservation flow of 1.0 m^3/s in the Evinos River, and c) a 35 hm^3/yr withdrawal from Yliki Lake for irrigation of the Kopais plain. Moreover, in order to reduce the spilling probability, upper storage limits are set for all reservoirs except Yliki.

All simulations were based on two synthetic inflow data sets, each one having a length of 2000 years. Both sets have the same statistical characteristics as those of the historical data, but they strongly differ regarding the hydrologic persistence (i.e., the property by which high flows tend to follow high flows and low flows tend to follow low flows), also referred as the "Hurst phenomenon" (e.g., Kottegoda, 1980). The first set, which is more realistic, assumes long-term persistence, whereas the second one assumes short-term persistence and therefore is less severe.

A particular management policy was considered for groundwater 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).

In the framework of the 2000 Master Plan of the Athens Water Supply and Sewage Company, two basic scenarios were studied (Koutsoyiannis et al., 2000). Scenario 1 aimed at evaluating the theoretical potential of the system's water resources. The optimization objective was to maximize the system's firm yield for an adopted reliability level equal to 99% on an annual basis (only in 1 of 100 years the system cannot meet with success the target), a value that provides a high level of security. The discharge capacity of all aqueducts was set to an infinite value, so as to eliminate any restrictions imposed by conveyance capacity limits of aqueducts. On the other hand, Scenario 2 aimed at evaluating the real potential of the system and finding the suitable policy which, ensuring a 99% reliability level, maximizes the system release also keeping the total pumping energy as low as possible; obviously, this is a multi-objective problem and to tackle it we used a typical weighting factors method.

Using both parameters a_i and b_i, the total number of control variables of the optimization model was $2 \times 4 = 8$. Given that the length of each simulation period was 2000 years (or 24000 monthly steps), the computational effort to obtain the system's performance index was very high (an entire simulation of the system required about 2 minutes, on a Pentium III processor). However, the dramatic restriction of system's variables made feasible the location of optimal management policy after a relatively limited number of function evaluations (about 1000), using the shuffled complex evolution method (Duan et al., 1992).

The results for the two scenarios are summarized in Figure 9, whereas the corresponding operation rules for optimal solutions that correspond to 1% failure probability are shown in Figure 10. The mean annual supply of the natural system, namely the mean annual runoff, is about 840 hm^3, without including groundwater resources. Assuming the long-persistence data set, the safe yield of the system for the water supply of Athens is about 480 hm^3. The difference is mainly due to reservoir losses, namely evaporation, spills and leakages, as well as secondary water releases such as irrigation and environmental conservation. In Scenario 1, the operation rules attempt to restrict those losses, by storing water primarily in Mornos reservoir and maximizing releases from Lake Yliki and Evinos reservoir. This is characteristically depicted on the left panel of Figure 10, where clearly the optimized rules try to keep Yliki and Evinos as empty as possible.

In Scenario 2, the aqueducts, pumping stations and water treatment plants impose further restrictions, reducing the real potential of the system to 410 hm^3 for 99% reliability. As shown in the right panel of Figure 9, when the target demand exceeds 410 hm^3, there is no way to achieve the required reliability level, regardless of the pumping energy. Here, the operation rules are quite different (Figure 10, right panel), because economic criteria were also considered. In that case, there is a conflict between economy, which acting alone would lead to the minimum possible releases from Yliki, and safety, which would result in the rules of Scenario 1. The final result is a balanced rule that leads to a moderate pumping from Yliki.

The current annual water consumption in Athens is about 390 hm^3 but this amount is expected to increase significantly, due to the expansion plans of the Athens Water Supply and Sewage Company as well as the remarkable increase in water consumption, which at present is as high as 6% per year. The study showed that this increase must be reduced; otherwise the system will be unable to satisfy demand for a 10-year horizon.

Summary and conclusions

The proposed framework is a generalized decision support tool for multi-reservoir planning and management. It includes many innovations, both in the hydrosystems theory and the software application. It employs a low-dimensional approach, named parameterization-simulation-optimization, which reduces dramatically the number of degrees of freedom, by introducing parametric operation rules and using their parameters as control variables. The proposed framework handles the system dynamics and constraints through simulation, also coupling it with typically nonlinear optimization for the parameters of the rules. It is able to incorporate various and competitive water uses, on an inter-basin basis. Output of the model is the best operating policy for the hydrosystem, which guarantees a set of targets and constraints, for a given reliability level and a given hydrologic regime.

The modeling framework was tested in two of the most complex hydrosystems of Greece. The Acheloos-Thessalia reservoir system, which is not yet completed, will be the largest of the country and, without doubt, the hardest to manage. Several groups with completely different interests as well as the local community are in continuous conflict about the operation of the projects and their impacts on the natural environment. The application of the model demonstrated that, via a suitable system configuration, various and contradictory objectives could be accomplished, ensuring also the sustainability in the development of the sensitive river and estuary ecosystems. On the other hand, the Greater Athens Water Supply reservoir system is particularly critical, providing water for almost 40% of the population of Greece. The great drought of recent years proved that the system had little resistance to natural hazards. It is certain that due to the construction of new projects, the probability of water shortage is strongly reduced and an optimal management policy could increase further the system reliability and decrease the operating cost.

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List of Figures

Tables

Table 1 Conservation Storage Ranges for Reservoirs of the Acheloos-Thessalia System.

Reservoir	Minimum		Maximum	
	Storage (hm^3)	Level (m)	Storage (hm^3)	Level (m)
Mesohora	132.8	731	358.0	770
Sykia	94.0	485	590.8	550
Kremasta	999.0	227	4500.0	282
Kastraki	750.0	142	800.0	144
Stratos	60.0	67	70.2	69
Pyli	21.7	310	68.7	335
Mouzaki	54.4	250	237.2	290

Table 2 Hydroelectric Plant Characteristics of the Acheloos-Thessalia System.

Power plant	Number of units	Installed capacity (MW)
Mesohora	2	160
Sykia	2	120
Kremasta	4	436
Kastraki	4	320
Stratos	2	156
Pefkofyto	2	260
Mouzaki	2	270

Table 3 Summary of Mean Annual Results for the Acheloos-Thessalia System (in GWh).

Scenario	1	2a	2b	3	4
Firm energy	1167	1633	1126	1249	2144
Secondary energy	839	1222	1201	465	1197
Pumping energy	–	–	–	769	578
Total energy	2006	2855	2327	945	2763

Table 4 Reservoir Characteristics of the Greater Athens Water Supply system.

Reservoir	Minimum		Maximum	
	Storage (hm^3)	Level (m)	Storage (hm^3)	Level (m)
Evinos	27	455	140	500
Mornos	127	382	770	435
Yliki Lake	10	45	587	78
Marathon	7	186	41	223

Figures

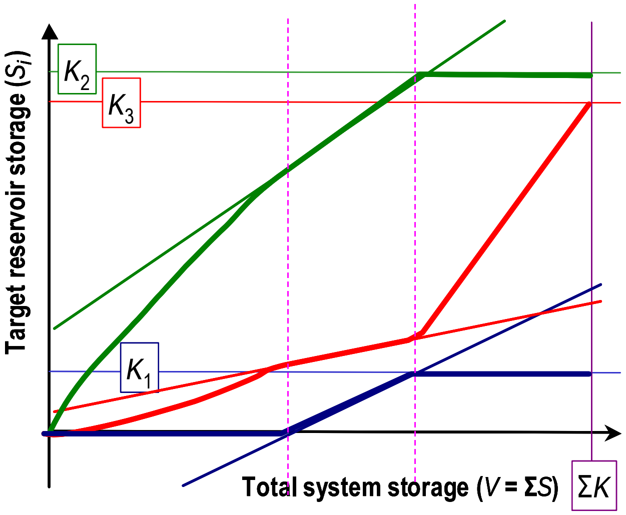


Figure 1 Graphical representation of operating rules for three hypothetical reservoirs; thin lines represent the initial linear rules whereas thick lines represent the adjusted ones.

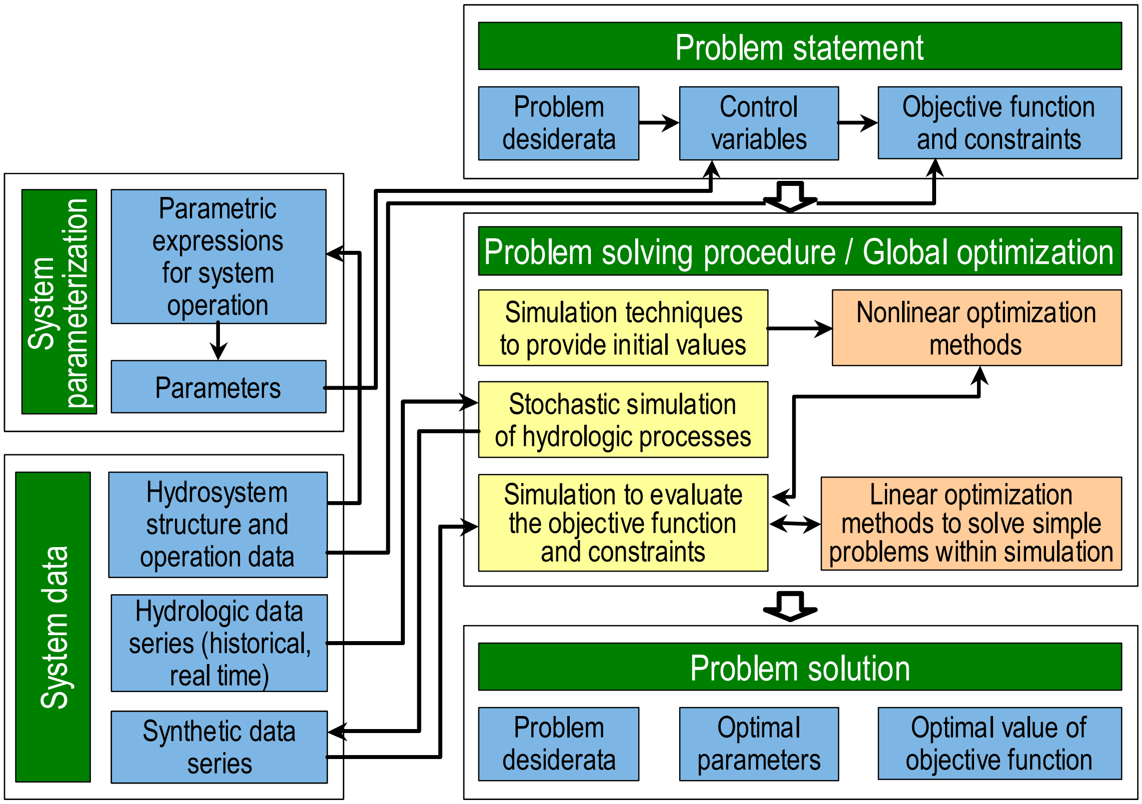


Figure 2 Outline of the parameterization-simulation-optimization methodology.

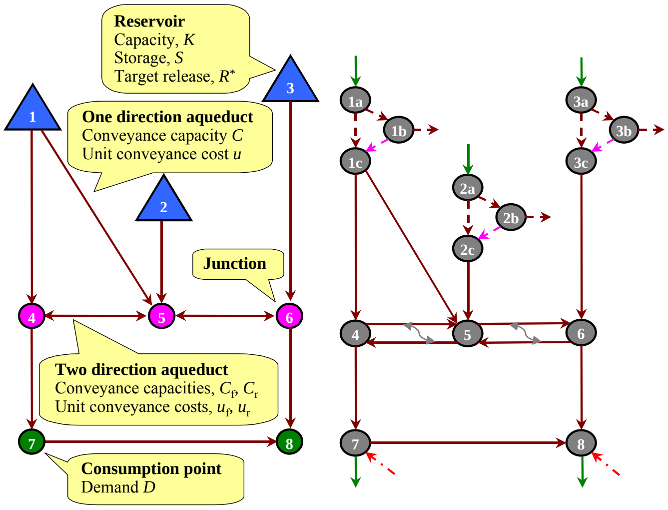
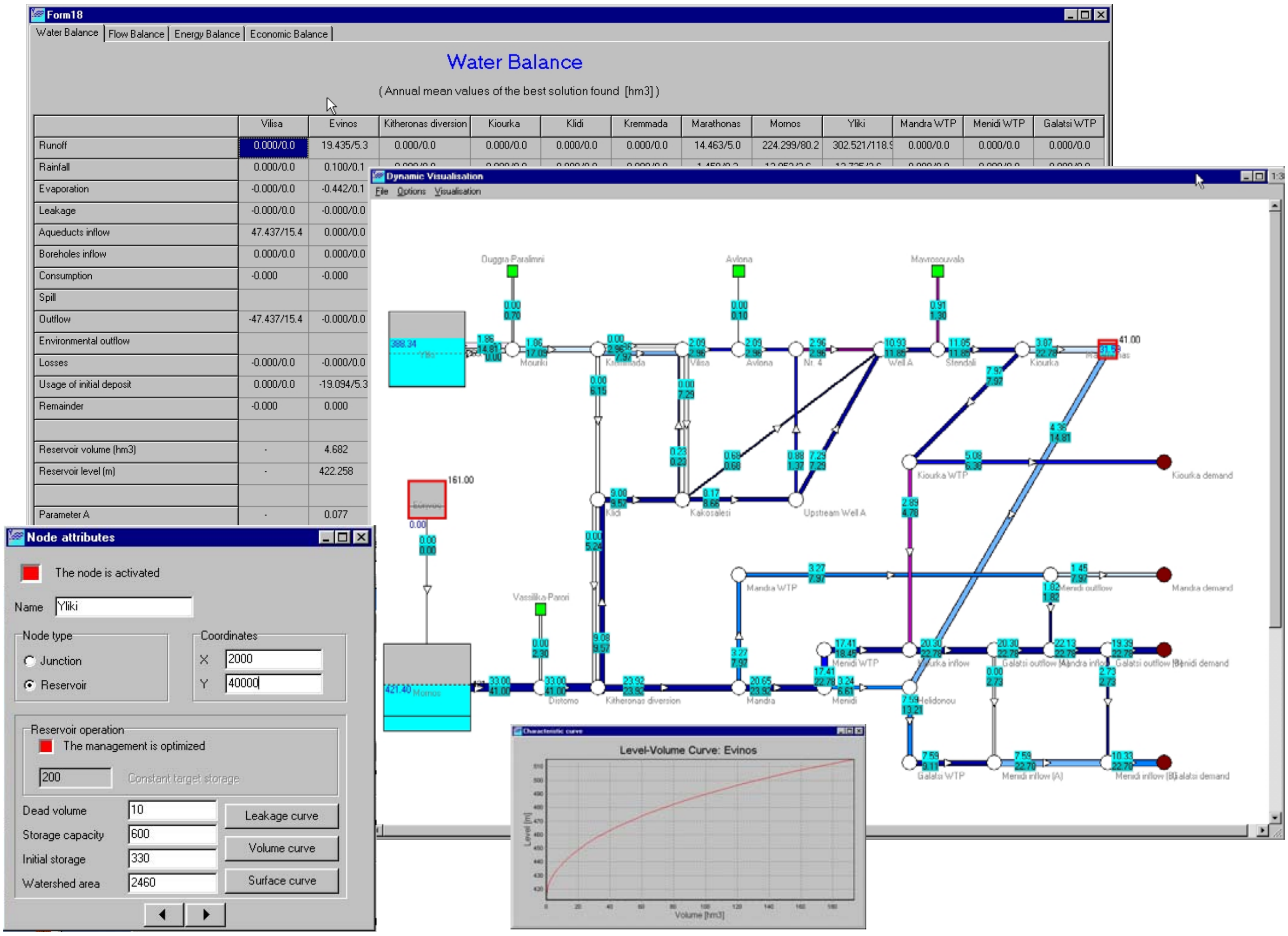


Figure 3 Transformations of hydrosystem components to digraph components.



Water Balance

(Annual mean values of the best solution found [hm3])

	Vilisa	Evinos	Kitheronas diversion	Kiourka	Klidi	Kremmada	Marathonas	Mornos	Yliki	Mandra WTP	Menidi WTP	Galatsi WTP
Runoff	0.000/0.0	19.435/5.3	0.000/0.0	0.000/0.0	0.000/0.0	0.000/0.0	14.463/5.0	224.299/80.2	302.521/118.9	0.000/0.0	0.000/0.0	0.000/0.0
Rainfall	0.000/0.0	0.100/0.1										
Evaporation	-0.000/0.0	-0.442/0.1										
Leakage	-0.000/0.0	-0.000/0.0										
Aqueducts inflow	47.437/15.4	0.000/0.0										
Boreholes inflow	0.000/0.0	0.000/0.0										
Consumption	-0.000	-0.000										
Spill												
Outflow	-47.437/15.4	-0.000/0.0										
Environmental outflow												
Losses	-0.000/0.0	-0.000/0.0										
Usage of initial deposit	0.000/0.0	-19.094/5.3										
Remainder	-0.000	0.000										
Reservoir volume (hm3)	-	4.682										
Reservoir level (m)	-	422.258										
Parameter A	-	0.077										

Node attributes

🟥 The node is activated

Name: Yliki

Node type
○ Junction
● Reservoir

Coordinates
X: 2000
Y: 40000

Reservoir operation
🟥 The management is optimized
200 Constant target storage

Dead volume: 10
Storage capacity: 600
Initial storage: 330
Watershed area: 2460

Figure 4 Characteristic modules of *Hydronomeas*; in the foreground the dynamic visualization form.

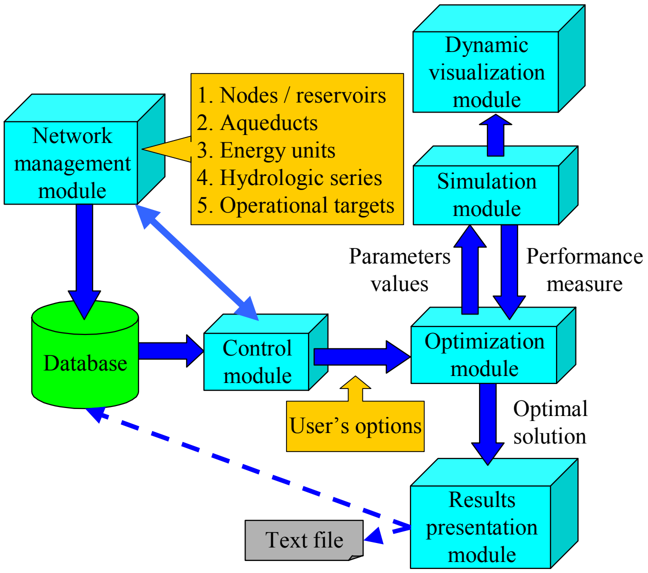


Figure 5 The decision support system modules.

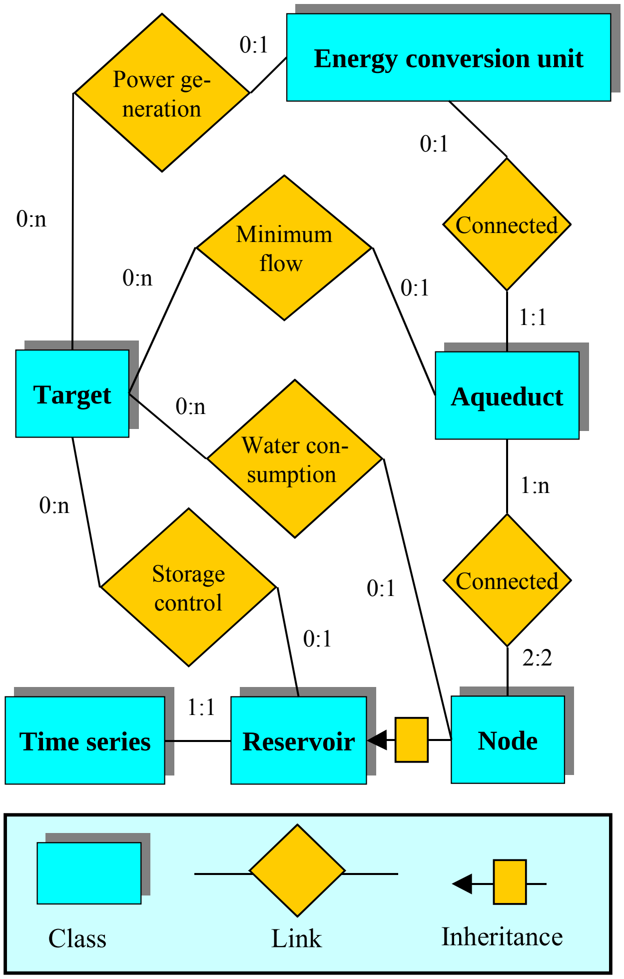


Figure 6 The entity-relationship diagram of *Hydronomeas*.

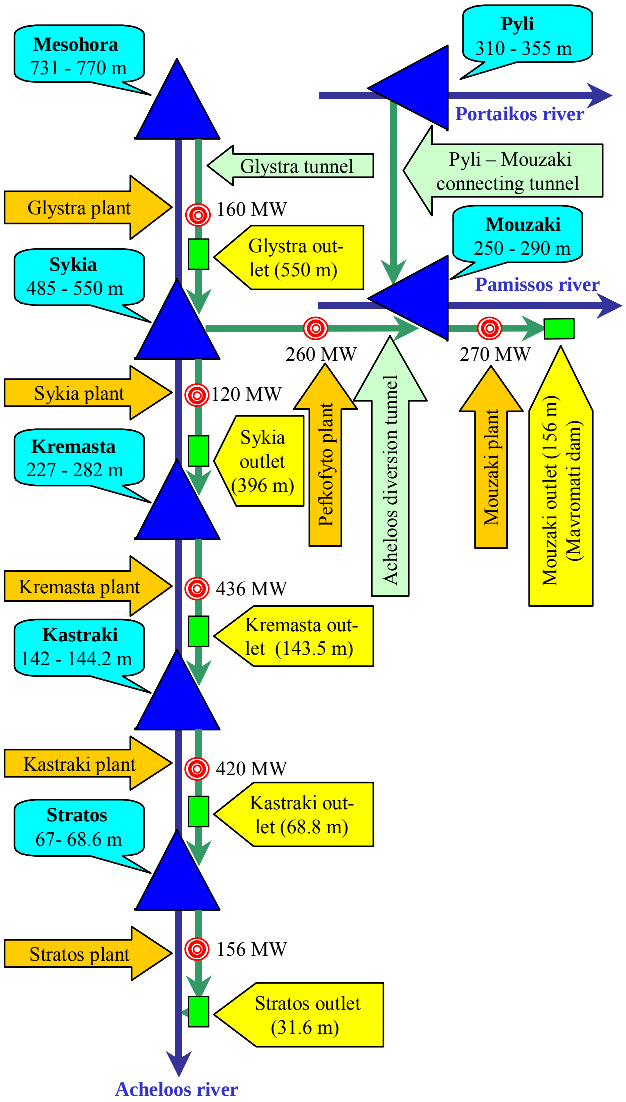


Figure 7 Schematic layout of the Acheloos-Thessalia reservoir system.

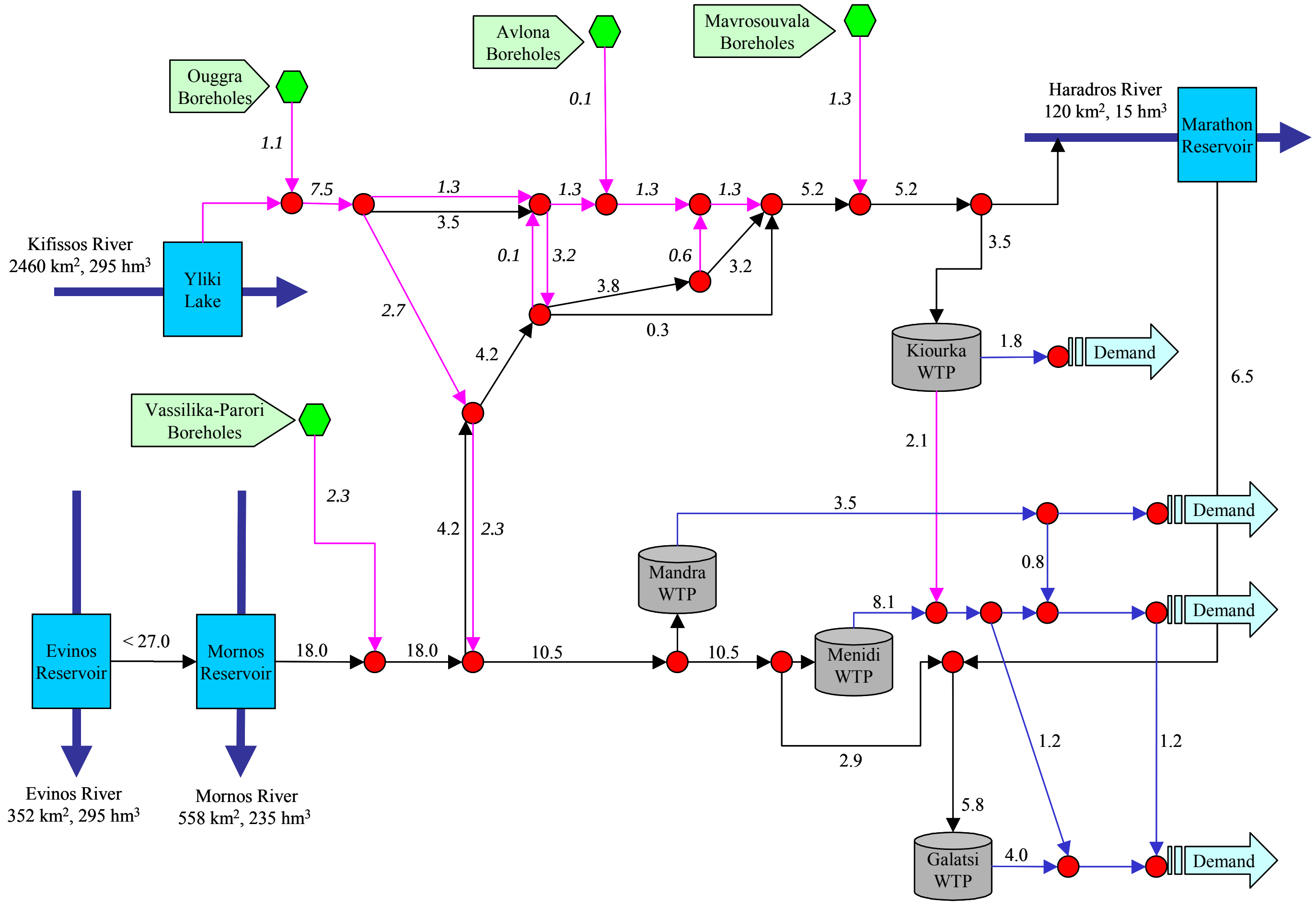


Figure 8 Schematic layout of the Greater Athens Water Supply reservoir system. Characteristic data of the system are annotated; for reservoirs the watershed area and the mean annual runoff; for aqueducts, the monthly conveyance capacity (in m^3/s), with regular letters for gravity flow and with italic letters for pumped flow.

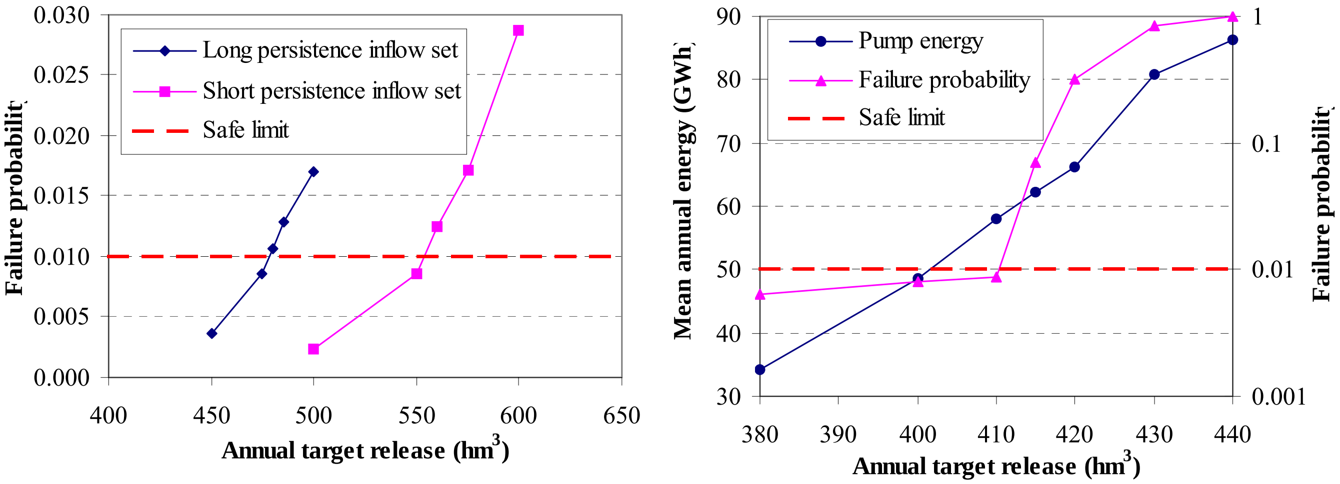


Figure 9 Mean annual release for the Athens water supply versus failure probability, according to the scenarios examined: (left panel) theoretical release, assuming infinite discharge capacity of aqueducts; (right panel) actual release, assuming existing capacities of hydrosystem.

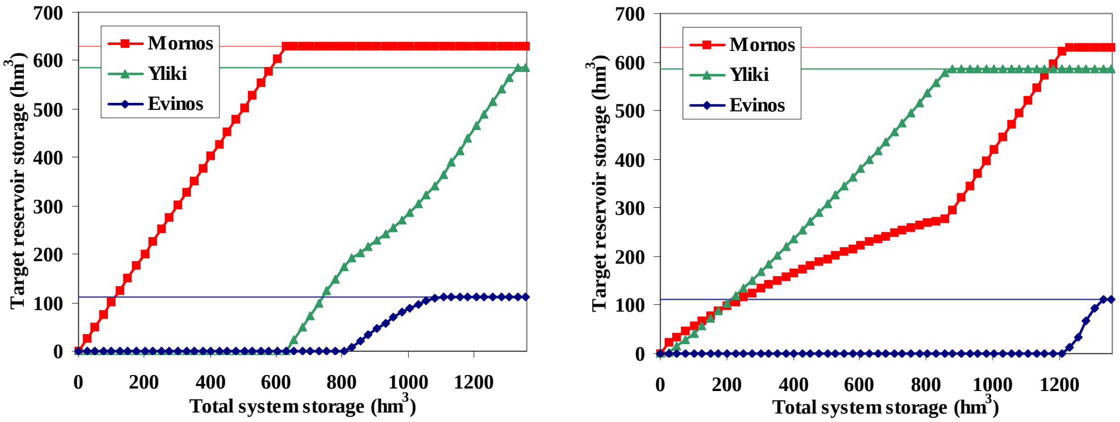


Figure 10 Optimal operating rules for the tree major reservoirs of the Athens Water Supply system, according to the two scenarios examined; on the left for Scenario 1 and on the right for Scenario 2.