Minimising water cost in the water resource management of Athens

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Abstract: The minimisation of the water cost is examined in the framework of an integrated water resources planning and management model, implemented within the decision support system for the management of the Athens water supply system. The mathematical framework employs a simulation-optimisation scheme, where simulation is applied to faithfully represent the system operation, whereas optimisation is applied to derive the optimal management policy, which simultaneously minimises the risk and cost of decision-making. Real economic criteria in addition with virtual costs are appropriately assigned to preserve the physical constraints and water use priorities, ensuring also the lowest-cost transportation of water from the sources to the consumption. The proposed model is tested in the hydrosystem of Athens, in order to minimise the expected operational cost for several system configurations.

Keywords: Decision support systems; integrated water resources management; network linear programming; global optimisation; operation rules; virtual costs; water economics.

1. Introduction

The task of water resource managers may be described as the identification or development of possible water resource system designs, management plans and decision-making processes, and the evaluation of their economic, ecological, environmental and social impacts (*Loucks et al.*, 1981). Particularly, the need of incorporating the economic issues in the management of water resources becomes more and more significant.

Traditional economic analysis studies the way in which individuals and societies respond to the scarcity of means available for achieving a multiplicity of needs. Water and the resources required to both exploit and protect it are increasingly scarce; hence, from this point-of-view, it is essential to apply economic criteria to water management decisions (*Young*, 1996). Certainly, water is a natural recourse that differs considerably from most other recourses or commodities. Although renewable, water resources are generally unpredictable in time, space and quality. Moreover, long-term water demand is also unpredictable, depending on factors such as the income and population growth, the development of infrastructure, etc.

From the early 1990's, the important role of economics in water management has been recognised. In 1992, the United Nations Conference on Environment and Development in Rio de Janeiro adopted the integrated water resources management principles (Agenda 21) that have to be taken into account in the implementation of any strategic water policy. These principles have found universal support among the international community as the guides delineating the management of water, to promote equity, efficiency and sustainability (*Rogers et al.*, 2002). Recently, the European Parliament pronounced a Water Framework Directive (2000) that raised the need for economic principles, tools, methods and measures, in order to fulfil a variety of economic, social and environmental targets (*Assimacopoulos*, 2002).

It is broadly recognised that integrated water resources management requires system-wide decision-making (*Grigg*, 1996). The systems approach is necessary to cope with the huge number of variables involved, the nonlinearity of dynamics, the multiple uses that have to be served, and the various uncertainties arising both in water supply and demand. The existence of a large variety of sophisticated mathematical models, in parallel with the development of effective computer tools, enabled the application of systems analysis methodologies into water resources management. Decision support systems (DSS) are widely used in the field of water resource systems planning and analysis, assisting decision makers in their judgment (*Watkins and McKinney*, 1995). These systems provide efficient data gathering, organising, storage, and manipulation capabilities; moreover they communicate the resulting information effectively, through proper visualisation, e.g. by using geographical information systems (GIS). Most decision support systems include economic components, enabling thus the assessment of economic impacts of any management scenario under study.

The scope of this paper is to present an application of integrating the economic issues in a DSS, which is currently used as the main management tool of an extended and particularly complex hydrosystem, the water supply system of Athens. The emphasis is given to the cost of water, whose minimisation is a major task that interests both individuals and organizations, but cannot be viewed separately from other issues like system's reliability in meeting the water demand both at present and into the future. Apart from the introduction (section 1), the paper is organised in five sections. In section 2, a sketch of the hydrosystem is given, in addition with some historical information about its evolution. In section 3, a general description of the DSS and its components is made. Section 4 explains the mathematical framework of the DSS, focusing on the modelling of economic issues within both simulation and optimisation procedures. In section 5, three characteristic applications are presented. Finally, in section 6, some concluding remarks are contained.

2. The Athens water supply system

2.1 Brief description of the hydrosystem

The Athens water supply system, sketched in Figure 1, is an extensive and complex hydrosystem that extends over an area of around 4000 km^2 and includes surface as well as groundwater resources. It incorporates four reservoirs, 350 km of main aqueducts, 15 pumping stations, a hundred of boreholes and four water treatment plants (WTP). The system is run by the Athens Water Supply and Sewerage Company (known as “EYDAP”).

The overall storage capacity of the hydrosystem approaches 1400 hm^3, but only two of the reservoirs, the Mornos reservoir and the natural Lake Yliki, hold 88.5 % of it. Although the capacity of the newly constructed Evinos reservoir (operated since the summer of 2001) is quite small in comparison, inflows to this 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, which is the oldest and the nearest to the city of Athens, is currently used only as a backup for emergency situations and as a complement for the peak water demand during the summer season. The boreholes, lying mainly in the northern part of the hydrosystem, are also used as a backup resource.

Two main aqueducts transfer water from the 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, the Yliki aqueduct carries water merely via pumping with considerable cost. Another characteristic of Lake Yliki is the significant leakage due to its karstic underground. Depending on the water release policy and other factors, even 50% of the overall inflows to the lake end up to the underlying aquifers and finally 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. Hence, while the mean natural inflows are about 840 hm^3 per annum and the groundwater resources can theoretically contribute another 90 hm^3, due to the several losses, the safe yield for the water supply of Athens is less than 500 hm^3 per annum.

The system's main objective is to provide water to the Greater Athens area through the water treatment plants, which lie in the surroundings of Athens. Each plant serves mainly one sub-area of Athens, but there is a limited possibility of water transfer between them, which increases the availability and security of the system in case of a malfunction. In addition, the water resource system provides water for irrigation, water supply of nearby towns and also environmental preservation downstream of the Evinos dam.

The everyday normal operation of the hydrosystem relies upon several decisions, which are concerned with the allocation of withdrawals from 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.

2.2 The challenge of optimising the management policy

Optimising the management of the Athens water supply system is a real challenge, particularly because today's decisions may affect the system's performance in a long-term perspective. To give an example, let us come back to the early 1990s, when Athens was threatened with complete water scarcity. This was, in reality, the consequence of the management policy of the middle 1980s. In 1979, the Mornos reservoir and aqueduct were incorporated to the system (until then, Athens was mainly supplied by the particularly energy-consumptive Yliki aqueduct). The new project, in addition to the high inflows of the first years, created a state of euphoria, which leaded to a dramatic increase of water consumption, by a rate of 54% on a ten-year basis (244 hm^3 in 1979, 376 hm^3 in 1989). At the same time, and in order to save money, EYDAP started to gradually decrease withdrawals from Lake Yliki, preferring to exploit as much as possible the Mornos resources that are virtually at no cost. During years 1985-88, the company almost stopped pumping from Yliki and boreholes, leaving its water leaking to the sea. Then, a persistent drought period, lasting from 1988 to 1994, in addition to the considerable increase of water consumption, almost vanished every surface water resource available. The extremely severe coincidence forced the government to activate new groundwater resources and, simultaneously, take emergent measures in the direction of demand management, which were proved very successful. Indeed, the drastic increase in the water price, some administrative measures and a massive water saving campaign attained to reduce water consumption by a third. Fortunately, and grace also to favourable hydrologic conditions, the difficult situation was surpassed. However, this case set off the subject of imposing rational and well-studied policies, towards both supply and demand management (*Xenos et al.*, 2002).

Today, the need for integrated management of the water resource system of Athens is more imperative than ever. In fact, providing sufficient quantity and high quality water is a subject of vital importance for about 4 million people who live in the Greater Athens area. Moreover, from year 2000, EYDAP has operated under a new status, and has to make decisions under free-market criteria. Therefore, the management policy has to effectively accomplish the objectives of sustainability, reliability and economy. Sustainability and reliability are directly related, because the exhaustion of water resources evidently leads to water shortage. It is agreed that both objectives can be satisfactory ensured by keeping the long-term risk of shortage (expressed as the probability of failure to satisfy demand on an annual basis) at 1% at most. On the other hand, the requirement for rational use of economic assets is mainly associated with the minimisation of the pumping cost, which may be very high if the auxiliary resources (Lake Yliki and boreholes) are activated. To derive optimal management policies, EYDAP has used since the year 2000 a DSS for the supervision and management of the hydrosystem, which is presented in next section.

3. The DSS for the management of the Athens water supply system

The DSS for the management of the Athens water resources system (*Koutsoyiannis et al.*, 2002) consists of several modules, some of which can operate as stand alone programs. Figure 2 illustrates the architectural structure of the DSS. Three of the basic components of the DSS, namely the database, the GIS, and the telemetric system are the information subsystem of the DSS. Two other components, the stochastic hydrologic simulator *Castalia* and the hydrosystem simulator and optimiser *Hydronomeas*, implement the mathematical models of the DSS. All software has been developed from scratch and its fully operational version is scheduled to go online by the end of 2003.

The interface between the various modules of the DSS is a relational database, where all necessary information concerning the supervision and management of the hydrosystem is stored. Two special software applications have been developed to gather and process data (program *Hydrognomon*), including dynamic data provided by the telemetric system, and to generate synthetic inflow series (program *Castalia*), by applying state-of-the-art stochastic hydrology techniques (*Koutsoyiannis and Manetas*, 1996; *Koutsoyiannis* 1999, 2000, 2001).

The core of the DSS is *Hydronomeas*, the module performing the system simulation and optimisation (*Koutsoyiannis et al.*, 2001a). Although the program was developed for the hydrosystem of Athens, its design is general enough so that it can be applied to any water resources (especially multiple-reservoir) system. Particularly, *Hydronomeas* can handle complex hydrosystems with conflicting water uses, aiming at locating the optimal management policy, which maximises the system yield and the overall operational benefit and minimises the risk of decision-making. More details about the methodology, focusing on the incorporation of economic issues, are given in the following section.

4. Modelling of economic issues within the DSS

The mathematical framework of *Hydronomeas*, which is the decision-making module of the DSS, follows the parameterisation-simulation-optimisation scheme (*Nalbantis and Koutsoyiannis*, 1997; *Koutsoyiannis et al.*, 2001a), where simulation and optimisation are effectively combined to derive the optimal management policy for the scenario under study. To define the scenario, several categories of input data are needed. First is the hydrosystem structure, namely the system components and their attributes (including technical and economic characteristics), and the topology. The hydrosystem components are nodes and aqueducts. Nodes may refer to reservoirs, boreholes, junctions or demand points, whereas aqueducts may refer to physical (e.g., streams) or artificial (e.g., channels, pipes, etc.) conveyance paths. The second input is the inflow data series, either taken from historical records or generated synthetically. Next input arguments are the operational targets and constraints, referring to consumptive (e.g., water supply, irrigation, etc.) as well as non-consumptive (e.g., storage and discharge control) water uses, and given in a specific priority series. A final category of input data includes the overall management objectives, which characterise the system's performance; the latter are concerned with the reliability, average cost or safe yield capacity of the management policy.

The management of the hydrosystem is stated as an optimal control problem. Its operation is systematically employed according to parametric rules, the parameters of which are assumed to be the control variables of a global optimisation problem. However, the operation rules are not sufficient to cope with the large variety of physical and other constraints of the problem. Hence, the latter are handled through a mathematical programming framework, implementing an optimal (in the sense of feasibility and economy) allocation of water from the sources (reservoirs, aquifers) to the consumption. The fundamental issues of this methodology are explained herein.

4.1 The parametric rule for the management of multiple reservoir systems

The model that determines the general management of the hydrosystem follows an operation rule, namely a law that specifies the desirable amount to be released from each one source as a function of the actual system's state (*ReVelle*, 1999, p. 14). Usually, operation rules are empirical or heuristic (and consequently pre-specified) mathematical expressions that are incorporated into simulation models, where the aim is to accurately represent the real-world system's performance rather than locate an optimal policy (*Oliveira and Loucks*, 1997; *Lund and Guzman*, 1999). Simulation models are generally preferred instead of typical optimisation schemes (such as linear, dynamic or stochastic dynamic programming models); the latter suffer both from the high dimensionality and the exaggerated and often unrealistic simplifications that are unavoidably made, concerning the operation of the real-world system.

In order to couple both simulation and optimisation approaches into reservoir control models, *Nalbantis and Koutsoyiannis* (1997) introduced a parametric expression of operation rules. Their concept is to allocate the actual total active storage of the system to its reservoirs, according to a mathematic formula that uses two parameters (control variables) per reservoir. In Figure 7, two graphical examples of these rules are given, for particular management scenarios. Each curve, which refers to a specific reservoir of the Athens water resource system, indicates the corresponding target storage as a function of the total system storage. Therefore, assuming that the values of the operation rules' parameters are known, the desired releases from each reservoir will also be known at each time step.

Apart from some theoretical cases, referring to hydrosystems of very simple topology, the optimal parameters values are unknown; however, the latter can be derived through a systematic searching procedure, such as a nonlinear optimisation algorithm. Indeed, the parsimonious formulation of the parametric rules (only two control variables per reservoir, regardless of the control horizon), makes searching much more effective compared to typical optimisation models. Moreover, this feature enables the use of stochastic simulation for the estimation of future inflows, making thus decisions consistent with the hydrological uncertainty that characterises any water resources management problem.

4.2 The simulation procedure

The knowledge of the target storages (or, equivalently, releases) of the reservoirs may not be sufficient for the specification of the actual values of all system's state variables because of at least one of the reasons below:

- due to the aqueducts' discharge capacity constraints, the desired releases cannot be conveyed downstream;
- there exist multiple ways to convey the reservoir releases through the network, each one having different transportation cost;
- multiple and conflicting water uses have to be satisfied simultaneously;
- the available water is either insufficient to fulfil the total demand or too much to be totally stored.

The complications caused by the above listed cases are handled through the simulation procedure. Specifically, at each time step, after determining the desired releases according to the parametric operation rules, an optimisation problem is solved to specify the appropriate values of all system's state variables (storage, release, spill, withdrawal and discharge rates). The problem is formulated such that the following hierarchy of requirements is fulfilled:

1. strict satisfaction of all physical constraints;
2. satisfaction, if possible, of the operational targets and constraints, according to the user-defined priorities;
3. minimisation of departures between the actual and the desired releases, so as to assure that the management policy imposed by the optimised operation rules is implemented as much as possible;
4. minimisation of system's operation cost.

The last requirement is strongly related to the scope of this paper. As mentioned above, the simultaneous assurance of feasibility and economy in hydrosystem management models is not always straightforward. However, the proposed methodology attains to cope with both feasibility and economy, by transforming the real-world system to a digraph model and setting virtual attributes to its components. The next two sub-sections explain how this is automatically implemented within the simulation model.

4.3 Transformation of the hydrosystem to a digraph model

A digraph is a mathematical entity, defined as a set of nodes and a set of ordered and directed pairs of them (arcs). A network is a digraph in which all the arcs possess some properties in addition to their two end nodes (*Smith*, 1982). The network structure of physical water resources systems enables the development of models based on a particular form of linear programming, the network linear programming (LP). Such models have a particular mathematical formulation, which can provide much faster solutions than general linear programming models do. The objective of the network LP model is the identification of the cheapest way to transfer a total amount of resources from the source to the sink nodes of a network. Assuming a network consisting of λ nodes and μ arcs, the matrix formulation of the network LP model is:

$$\begin{aligned} &\text{minimise } f(\mathbf{x}) = \mathbf{c}^{\mathrm{T}}\,\mathbf{x} \\ &\text{s.t.} \qquad \mathbf{A}\,\mathbf{x} = \mathbf{y} \\ &\qquad\quad\ \mathbf{0} \le \mathbf{x} \le \mathbf{u} \end{aligned} \tag{1}$$

where **c** is the μ-dimensional vector of unit transportation costs, **x** is the μ-dimensional vector of the shipped amounts, **A** is the $\lambda \times \mu$ incidence matrix that describes the topology of the network, **y** is the λ-dimensional vector of supply and demand values (with positive and negative values for supply and demand nodes, respectively, and zero to all other nodes) and **u** is the μ-dimensional vector of conveyance capacities. Matrix **A** is made up of entries + 1, – 1 and 0. If the *k*th arc connects node *i* with node *j*, then the *k*th column of the matrix has + 1 in the *i*th row, – 1 in the *j*th row, and zeroes everywhere else.

Models based on network LP have been used in a variety of water resources planning and management applications. For example, *Kuczera* (1989) introduced a multiperiod optimisation scheme, where the boundary conditions between adjacent periods are taken into account through the use of virtual carryover arcs. However, the variety of network LP schemes (e.g., *Graham et al.*, 1986; *Labadie*, 1995; *Fredericks et al.*, 1998; *Dai and Labadie*, 2001) are essentially simulation models, performing static optimisation for a single time period to find the least cost flow allocation through hydrosystems of network format. The optimisation is based either on real economic criteria or on artificial costs, which are assigned to preserve water rights and water use priorities. *Hydronomeas* follows a similar approach, which is implemented in an integrated manner. The general concept is to distinguish all state and control variables of the problem (i.e., the water fluxes) and optimally allocate them through the hydrosystem, which is represented in a digraph format. To keep the consistency of the real-world system operation, virtual attributes are imposed to the digraph components, namely the conveyance capacity and the unit transportation cost. The latter may be either positive or negative. Particularly, positive unit costs are imposed to penalise non-desirable water fluxes, such as spills, whereas negative unit costs are imposed to force the model to provide water for the satisfaction of the physical and operational constraints.

An example of transforming a hydrosystem to a digraph model is illustrated in Figure 3. This typical system consists of four nodes and four aqueducts. Specifically, node 1 is a reservoir, node 2 is a borehole, node 3 is a demand point and node 4 is a junction. Moreover, downstream of the reservoir, a minimum flow target is imposed. As shown in the figure, the nodes and links comprising the physical system are only a subset of the digraph. In addition to the actual components, the digraph comprises also of artificial nodes and arcs, which are represented by dashed lines. More specifically:

- All the actual *nodes* except of the reservoir (i.e., the borehole, the junction and the demand point) remain as they are, whereas an additional "dummy" node, collecting the sum of water that is stored, spilled or consumed is introduced; this node is added merely for mathematical convenience.
- The *reservoir* splits into three artificial nodes that represent the supply, storage and release locations (nodes "a", "b" and "c", respectively). Particularly, the supply consists of the actual reservoir storage plus the sum of the hydrologic inflows. Six artificial arcs simulate the processes that are related to the reservoir operation. The first arc (a-c) connects the "supply" to the "release" node and carries water up to the target release, R^*, as specified by the corresponding operation rule. In order to withdraw, if possible, exactly the desired amount, a negative unit cost ($-c$) is imposed to this arc. The second arc (a-b), which has zero unit cost and infinite capacity, connects the "supply" to the "storage" node and carries water that should be stored, provided that no storage capacity constraints are imposed. The third arc (b-c) connects the "storage" to the "release" node and carries water beyond the target release, R^*, if necessary. This arc has also infinite capacity but nonzero unit cost, c, in order to penalise the violation of the operation rule. The other three arcs connect the "storage" node with the "dummy" one. The first one carries water up to the dead volume, DV, having a large negative unit cost, $-M$ (where $M >> c$). The other one carries water up to the reservoir active storage capacity, K, with zero unit cost. The last one carries spills, having infinite capacity and a very high positive unit cost, M. Hence, reservoirs are forced to fill at least up to their dead volume, whereas spilling is prohibited, except of exhaustion of the downstream discharge capacity.
- The *borehole* (more precisely, the aquifer) is assumed as a reservoir of infinite capacity. In that case, an artificial arc is introduced to connect the borehole node with the "dummy" one, having capacity equal to the water supply rate (i.e., the actual groundwater potential, G) and zero unit cost.

- The *demand point* is connected with the “dummy” node by introducing an artificial arc, the conveyance capacity of which is set equal to the actual demand rate, D. On the other hand, its virtual unit cost, $-c'$ (where $c' > c$), is negative to enforce the model to satisfy the corresponding water consumption target.
- The *aqueducts* are represented by digraph arcs, which have conveyance capacity equal to the actual discharge capacity. Here, the economic issues of the hydrosystem are directly incorporated, by setting the unit cost equal to the real transportation one. In case of pumping, this can be expressed in terms of consumed energy per discharge unit (e.g., kWh/m^3). On the other hand, in case of power production this is a negative cost, expressed in terms of produced energy per discharge unit. The unit transportation cost may be either constant or variable. The second case is more complicated. Variable cost can be related to variable hydraulic head (e.g. in a pump at a borehole); this can be easily modelled in a simulation framework, given that in each simulation step hydraulic head can be assumed constant. Another case is met when cost depends on the discharge value (e.g. in a pump-force system). Usually, in such a case the cost function is convex (i.e., increasing with discharge). Under this assumption, the use of multiple parallel virtual arcs can provide a piecewise linear approximation to the cost function and simultaneously make possible the use of linear programming.
- The *minimum flow* requirement is modelled by splitting the related aqueduct into two parallel sub-arcs, with common end nodes (c-4). The first one (dotted line in Figure 4) has conveyance capacity equal to the minimum discharge value, $Q_{\min}$, and negative unit cost, $-c''$ (where $c'' > c$), to enforce the model fulfilling the corresponding constraint, whereas the second one (solid line) has the rest of the actual discharge capacity of the aqueduct. In general, for each operational target or constraint, an artificial arc has to be added to the digraph model, the unit cost value of which is set according to the target priority list, which is specified by the user. In case of consumptive or low-bound targets the unit cost is

negative; otherwise it is positive, in order to penalise water uses that violate the upper-bound constraints.

4.4 Updating the attributes of the digraph

According to the above assumptions, a hydrosystem consisting of n reservoirs, m nodes, p aqueducts and q targets, is transformed to a digraph model of $\lambda = 3n + m + 1$ nodes and $\mu = 6n + p + q$ arcs. The number of control variables of the network LP model is μ, whereas the number of constraints is $\lambda + \mu$ (i.e., λ continuity equations at the nodes and μ capacity constraints at the arcs). Before running the simulation, the $\lambda \times \mu$ incidence matrix is formulated, describing the geometry of the digraph. Then, at each simulated time step, the network LP problem is set by specifying the properties of the digraph components, namely the λ-dimensional supply-demand vector **y** and the μ-dimensional capacity and unit cost vectors, **u** and **c**, respectively.

To define the supply-demand vector **y**, it is necessary to estimate the actual water availability. Provided that there is an estimation of future inflows (e.g., through stochastic forecast), this is easily calculated from the equation:

$$y_i = S_i + I_i \tag{2}$$

where S_i is the actual storage at the beginning of the time step and I_i is the unregulated supply rate from the physical system. For a reservoir, the latter includes inflows due to rainfall and runoff minus various losses due to physical reasons (e.g., evaporation, leakage, etc.), whereas for a borehole this corresponds to the actual groundwater potential. Apparently, simple junctions have $y_i = 0$. On the other hand, given that the total water supply has to be conveyed to the “dummy” node, a virtual demand is imposed to it (with negative sign), which is equal to the sum of water availability.

The arc capacities correspond either to real capacities of system components (reservoirs, aqueducts) or to desired magnitudes, such as target releases, demand rates, upper and lower limits of storage or flow rates, etc. The former attributes are static, in the sense that they are related to real-world properties, whereas the latter are dynamic, because they depend on the actual state of the system. In addition, some capacities are assumed to be infinite, provided that there are no physical restrictions about the related variable of the water balance equation (e.g., spill arcs). In that case, infinity is represented by a large positive number, which has to be some orders of magnitude larger than the maximum of the finite arc capacities. Hence, at least some of the entries of the capacity vector **u** are specified once, while the rest of them are updated at each time step.

The assignment of unit cost values is a key part of the network LP model, because this ensures the preservation of both feasibility and economy. With the exception of arcs that correspond to aqueducts and for which the unit cost equals, by definition, the actual one, the specification of the remaining virtual cost values is not straightforward. For this reason, a recursive algorithm was developed to automatically assign virtual cost values, in order to implement the four requirements analysed in section 4.2. This is implemented by grouping costs into four corresponding priority levels and ensuring that unit costs of any priority level exceed the combined ones of all level with lower priority, namely:

$$c^{[s]} > C^{[s-1]} \tag{3}$$

where $c^{[s]}$ is any unit cost of priority level s and $C^{[s-1]}$ is the sum of unit costs belonging to all lower priority levels (all costs are expressed in absolute values). As a result of (3), the minimisation of costs that correspond to different priority levels is employed independently. Equivalently, the solution of the network LP problem guarantees both feasibility (decisions are taken in accordance to the physical and operational constraints of the hydrosystem) and economy (the transportation of withdrawals is the least expensive).

Specifically, the unit cost values, both positive and negative, are classified in four priority levels, as shown in Table 1; virtual unit costs belonging to a specific level are equal to each other, if the corresponding targets have the same priority, or different, otherwise. According to this classification, the network LP model is first forced to fill reservoirs up to their dead volume; apparently, the corresponding unit cost is negative and belongs to the highest priority level (4). Next, it attempts to fulfil all consumptive water uses as well as the lower-bound constraints that refer to either discharge or storage targets, starting from the ones with the higher priority within level 3. The target releases, as specified by the operation rules, are "carried" through the corresponding artificial arcs, having unit cost that is classified in Level 2. Until this point, the sum of costs so far remains negative, since the model is enforced to transfer water. The rest of unit costs are either zero or positive; in the latter case, the usage of the related digraph arcs is prohibited, if possible. Hence, reservoir spilling (Level 4) is strictly avoided, except if the conveyance capacity of the downstream network is insufficient. If the system's storage capacity is exhausted, instead of spilling, the model attempts to violate the upper-bound constraints (Level 3), starting from the lower-priority ones. Otherwise, the model withdraws water beyond the target releases, paying penalties that belong to the next priority level (2). Finally, the flow allocation through the aqueduct network is done via the most economic manner, restricting pumping as much as possible. The unit cost of the related digraph arcs, which are identical to the real aqueducts, belongs to Level 1. Therefore, the minimisation of the real transportation cost is implemented independently of the virtual one, since the latter is related to the preservation of the physical and operational constraints of the hydrosystem. We note that a minor virtual cost is paid even for the use of aqueducts operating via gravity, in order to avoid useless water conveyance.

4.5 Deriving the optimal management policy

A performance index is introduced to measure the efficiency of a specific management policy. In mathematical terms, this stands as the objective function of a global optimisation problem, whereas the parameters of the operation rules stand as its control variables. *Hydronomeas* provides three types of objectives:

(a) minimisation of the failure probability of the system, for a given set of operational targets;

(b) maximisation of the total annual withdrawal, for a given reliability level;

(c) minimisation of the average annual operation cost, for a given set of targets and a given reliability level.

Specifically, the third type of objective function is concerned with the implementation of incorporating economic targets into the management policy, where the aim is to identify an appropriate management that ensures a low-cost operation of the system in a long-term perspective. At this point we have to discriminate the above objective from the step-by-step minimisation of the water conveyance cost, which is implemented by applying the network optimisation model.

In objective function (c), system's economy has to be ensured simultaneously with an acceptable reliability level. This is achieved by multiplying the average annual cost by a penalty-term constraint of the form:

$$P = \exp\left(\frac{F - F_{\max}}{\xi}\right) \tag{4}$$

where F is the estimated failure probability of the management policy under study, $F_{\max}$ is the maximum allowable failure probability and ξ is a scale factor, specifying the strictness of the reliability constraint.

The objective function is evaluated through the simulation procedure, based on the network optimisation approach. It is emphasised again that the network LP problem is solved separately in each simulation step. In other words, simulation embraces a linear optimisation routine, which is executed as many times as the length of the control horizon (Figure 4). Fortunately, the specific format of the network LP problem enables a very fast execution of simulation. This is of high importance, given that the nonlinear nature of the global optimisation problem requires a vast number of function evaluations to locate an appropriate management policy. To solve this problem with satisfactory accuracy and reasonable computational effort, a specific heuristic algorithm was developed, based on an effective combination of deterministic local search techniques with stochastic optimisation strategies (*Efstratiadis and Koutsoyiannis*, 2002).

5. Applications

The applications are based on extensive research, carried out within the framework of the master plan for the operation of the Athens water resource system for the hydrological year 2001-02 (*Koutsoyiannis et al.*, 2001b). This master plan deals, among others, with a number of scenarios, referring to several hypothetical situations of the hydrosystem. Specifically, these scenarios consider various assumptions about the future water demand, the expected improvements in the water conveyance capability of the network and the hydrological conditions. They also cover different management objectives, including the economical point-of-view. Three of the implemented scenarios are discussed below.

5.1 Description of the examined scenarios

The scope of the three examined scenarios is to investigate the long-term operation of the hydrosystem, under steady-state conditions. The first one (scenario A) refers to the present configuration of the system, whereas the second one (scenario B) refers to a future configuration, after the implementation of a number of projected works, on a 10-year horizon. The most important of them refer to the Mornos aqueduct, and concern the improvement of its conveyance capacity as well as its imperviousness. The third scenario (scenario C) refers to the present actual system, for which a long-standing malfunction is assumed, revoking the interconnection between the Mornos and Yliki aqueducts.

For the simulation of the hydrological inflows, 2000 years of synthetic series, taking into account phenomena of persistent droughts, were generated, through the stochastic simulator

Castalia. The annual demand rate for the water supply of Athens was assumed constant and equal to 400 hm^3. For all scenarios, the objectives were the minimisation of the average operation cost and keeping the reliability level at least 99%. The latter was empirically determined as the ratio of periods (years) in which the water demand was impossible to meet, to the total number of simulated periods (i.e., 2000).

The operation cost was estimated in terms of mean energy consumption, on an annual basis. The latter is calculated at the end of each simulation, by multiplying the flow rate through each aqueduct with the corresponding unit conveyance cost. The estimation of unit costs was the subject of extended analysis; more details are given below.

5.2 Estimation of unit conveyance costs

As explained in section 4, the mathematical model of the DSS incorporates economic issues in a water resources management scenario, by setting a unit conveyance cost for each branch of the network. This cost can be expressed both in monetary as well as in non-monetary terms. For the examined scenarios, all unit costs were expressed in terms of specific energy, namely the amount of energy consumption per discharge unit.

The estimation of specific energy rates was based on the collection and analysis of the available historical data, concerning both discharge and energy consumption data at the 15 pumping stations of the hydrosystem. For each one station, the specific energy was estimated as the slope of a linear regression graph between the average monthly discharge and the corresponding energy consumption. For convenience, no fixed energy values were taken into account (the homogenous form of linear regression was adopted). The latter are of high importance only in case of relatively low discharge values, since the activation of any pumping facility requires a large amount of electrical power. Therefore, in the statistical analysis, a lower threshold was assumed for at least some of the pumping stations, below which the discharge and energy data were omitted. In Figure 5, a typical example is given, referring to the Assopos pumping station.

5.3 Results and discussion

The results concerning the average annual energy consumption for the three examined scenarios are summarised in Figure 6. In scenario B, the increase of discharge capacity, in addition to the elimination of water losses due to leakage along the Mornos aqueduct, allows a cheaper operation of the hydrosystem. More precisely, assuming a constant demand of 400 hm^3/year, in scenario A, the expected annual energy consumption of the actual system reaches about 60 GWh, whereas in Scenario B it will be reduced to about 25 GWh after the implementation of the projected works, because more water would be transferred via gravity. Moreover, the exploitation of groundwater resources will also be decreased, leading thus to a more sustainable policy. On the other hand, an enduring malfunction of the crucial branch that connects the two main aqueducts would require much more withdrawals from Yliki, increasing drastically the total pumping, which would exceed an annual rate of 130 GWh. Furthermore, it would hinder the alternative water conveyance paths through the network, making thus the system significantly vulnerable to emergent conditions.

The optimised operation rules for scenarios A and B are illustrated in Figure 7. The rules, indicating the target storage for the three main reservoirs (Mornos, Yliki and Evinos) as a function of the total system storage, are only slightly different. In the first case (scenario A), due to the limited capacity of the Mornos aqueduct, the water demand is partially satisfied through pumping from Yliki, whereas the surplus water is stored into the Evinos reservoir. On the other hand, in scenario B, pumping is reduced to ensure a cheaper operation of the system, and the Evinos reservoir is used as a supply rather than a storage facility; this is clearly illustrated by the fact that the Evinos reservoir is kept empty for the whole range of total system storage.

6. Concluding remarks

As natural resources problems become more and more complex and comprehensive, new strategies for sustainable water resources development efforts are needed. Specifically, the competition between sustainability, reliability and economy, which is evident in most decisions related to water management, requires an integrated, system-wide approach. This is offered by decision support systems, which are effective software tools, designed to assist water companies that are obliged to make decisions under a particularly competitive economic environment.

The DSS for the supervision and management of the water resource system of Athens, and especially its modelling core *Hydronomeas*, provides a variety of tools towards integrated water resources management, including the economic aspects of the management of this particularly complex hydrosystem. By applying state-of-the-art methodologies, the DSS enables the determination of appropriate management policies, which ensure the minimisation of both cost and risk of decision-making. The general concept is based on a novel scheme, where simulation and global (nonlinear) optimisation are effectively combined to derive optimal management policies, simultaneously with an accurate representation of system's operation. The latter is implemented transforming the real-world system to a digraph model and applying a network linear programming model to optimally allocate the state variables through the hydrosystem. Virtual properties are automatically imposed, to ensure both feasibility and economy in the allocation of water fluxes.

So far, operation costs are incorporated into the model in the form of specific energy values (consumed energy at each pumping station per discharge unit). Although this is the most important economic issue of the water resource system of Athens, several other issues could also be introduced, providing a better approach of the total operation cost. The latter may include, among others, costs of maintenance or extra payments in case of activation of backup resources (e.g., boreholes). The estimation of such issues is not an easy task.

Moreover, the specific mathematical structure of the network LP model implies the exclusive use of linear or piece-wise linear but convex discharge-cost functions. Therefore, incorporating these additional costs into a mathematical programming model is not straightforward. However, these could be taken into account through the global optimisation phase, as components of the performance measure. This is regarded as one of the main objectives of future developments of the DSS.

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References

Assimacopoulos, D. (2002). The recovery of water cost in Directive 2000/60. *Proceedings of the Water Framework Directive - Harmonization with the Greek reality*, 22 May 2002, 33-41. National Technical University of Athens, Department of Water Resources, Hydraulic and Maritime Engineering, Athens.

Dai, T., and J. W. Labadie (2001), River basin network model for integrated water quantity/quality management. *Journal of Water Resources Planning and Management*, ASCE, 127(5), 295-305.

Efstratiadis, A., and D. Koutsoyiannis (2002). An evolutionary annealing-simplex algorithm for global optimisation of water resource systems. *Proceedings of the Fifth International Conference on Hydroinformatics*, Cardiff, UK, July 2002, 1423-1428, International Association of Hydraulic Research, International Water Association, International Association of Hydrological Sciences.

European Parliament and Council of the European Union, Directive 200/60/EC establishing a framework for Community action in the filed of water policy (2000). *Official Journal of the European Communities*, L 327.

Fredericks, J., J. Labadie, and J. Altenhofen (1998). Decision support system for conjunctive stream-aquifer management. *Journal of Water Resources Planning and Management*, ASCE, 124(2), 69-78.

Graham, L. P., J. W. Labadie, I. P. G. Hutchison, and K. A. Ferguson (1986). Allocation of augmented water supply under a priority water rights system. *Water Resources Research*, 22(7), 1083-1094.

Grigg, N.S. (1996). *Water Resources Management*. New York: McGraw-Hill.

Koutsoyiannis D., G. Karavokiros, A. Efstratiadis, N. Mamassis, A. Koukouvinos and A. Christofides (2002). A decision support system for the management of the water resource system of Athens. *Physics and Chemistry of the Earth, Section B - Hydrology, Oceans and Atmosphere* (in publice).

Koutsoyiannis, D. (1999). Optimal decomposition of covariance matrices for multivariate stochastic models in hydrology. *Water Resources Research*, 35(4), 1219-1229.

Koutsoyiannis, D. (2000). A generalised mathematical framework for stochastic simulation and forecast of hydrologic time series. *Water Resources Research*, 36(6), 1519-1534.

Koutsoyiannis, D. (2001). Coupling stochastic models of different time scales. *Water Resources Research*, 37(2), 379-392.

Koutsoyiannis, D., A. Efstratiadis, and G. Karavokiros (2001a). A decision support tool for the management of multi-reservoir systems. *Proceedings of the Integrated Decision-Making for Watershed Management Symposium*. Chevy Chase, Maryland, January 2001, U.S. Environmental Protection Agency, Duke Power, Virginia Tech.

Koutsoyiannis, D., A. Efstratiadis, G. Karavokiros, A. Koukouvinos, N. Mamassis, I. Nalbantis, D. Grintzia, Damianoglou, Ch. Karopoulos, S. Nalpantidou, A. Nassikas, A. Nikolopoulos, A. Xanthakis, and K. Ripis, Master plan of the Athens water resource system – Year 2001-02 (2001b). *Modernisation of the supervision and management of the water resource system of Athens*. Department of Water Resources, Hydraulic and Maritime Engineering - National Technical University of Athens, Athens, (in Greek).

Koutsoyiannis, D., and A. Manetas (1996). Simple disaggregation by accurate adjusting procedures. *Water Resources Research*, 32(7), 2105-2117.

Kuczera, G., (1989). Fast multireservoir multiperiod linear programming models. *Water Resources Research*, 25(2), 169-176.

Labadie, J. (1995). *MODSIM: Technical manual river basin network model for water rights planning*. Colorado State University, Fort Collins, Colorado.

Loucks, D. P., J. R. Stedinger, and D. A. Haith (1981). *Water Resource Systems Planning and Analysis*. New Jersey: Prentice-Hall.

Lund, J. R., and J. Guzman, (1999). Derived operating rules for reservoirs in series or in parallel. *Journal of Water Resources Planning and Management*, 125(3), 143-153.

Nalbantis, I., and D. Koutsoyiannis (1997). A parametric rule for planning and management of multiple reservoir systems. *Water Resources Research*, 33(9), 2165-2177.

Oliveira, R., and D. P. Loucks (1997). Operating rules for multi-reservoir systems. *Water Resources Research*, 33(4), 839-852.

Rogers, P., R. de Silva, and R. Bhatia (2002). Water is an economic good: How to use prices to promote equity, efficiency, and sustainability. *Water Policy*, 4(1), 1-17.

Smith, D. K. (1982). *Network Optimisation Practice: A Computational Guide*. New York: John Wiley & Sons.

UNCED (1992). *A guide to Agenda 21: A global partnership*. Geneva.

Watkins, D. W., and D. C. McKinney (1995). Recent developments associated with decision support systems in water resources. U.S. National Report to International Union of Geodesy and Geophysics 1991-1994. *Reviews of Geophysics*, Vol. 33 Supplement 1995, American Geophysical Union.

Xenos, D., I. Passios, S. Georgiades, E. Parlis, and D. Koutsoyiannis (2002). Water demand management and the Athens water supply. *Proceedings of the 7th BNAWQ Scientific and Practical Conference "Water Quality Technologies and Management in Bulgaria"*. Sofia.

Young, A. R. (1996). Water economics. *Water Resources Handbook*, Chapter 3, L. W. Mays (editor). New York: McGraw-Hill.

Tables

Table 1: List of cost priority levels and related procedures, used within the unit cost assignment algorithm.

Level	Procedures with positive cost	Procedures with negative cost
1	Water conveyance via pumping	
2	Reservoir withdrawal, beyond the target release	Reservoir withdrawal, up to the target release
3	Preservation of upper-bound constraints	Withdrawal for water supply and irrigation, and preservation of lower-bound constraints
4	Reservoir spill	Filling of reservoirs, up to their dead volume

Figure captions

Figure 1: The Athens Water Supply System.

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

Figure 3: An example of transforming a real hydrosystem to a digraph model. Node 0 corresponds to the dummy one. Solid lines represent real arcs (i.e., aqueducts), whereas dashed lines represent artificial ones. In parenthesis, the conveyance capacity and the unit transportation cost for each arc are given.

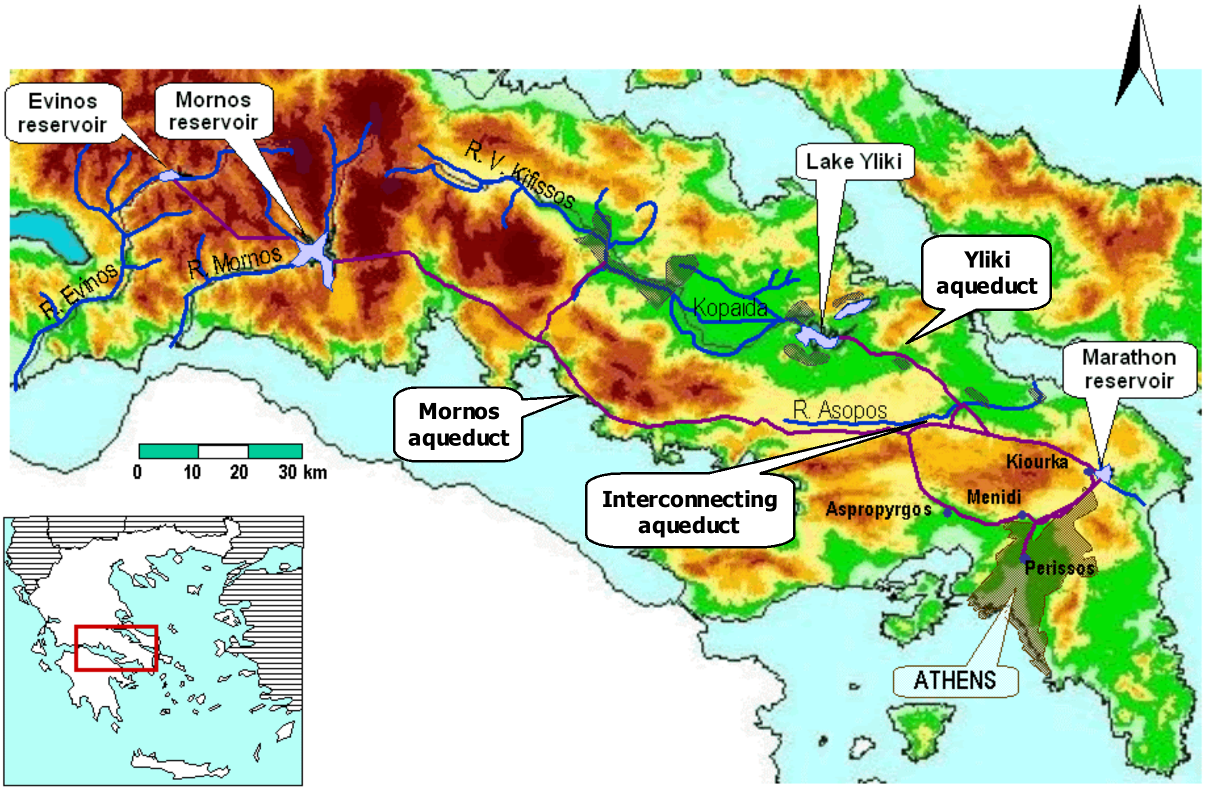
Figure 4: Outline of the simulation-optimisation model.

Figure 5: Estimation of the specific energy (in GWh/hm^3) for the Assopos pumping station (southern of Lake Yliki), through statistical analysis of the historical monthly discharge and energy consumption data.

Figure 6: Average annual energy consumption for the three examined scenarios.

Figure 7: Graphical representation of the optimal operation rules, for scenarios A (left diagram) and B (right diagram). Solid lines with rhombi, squares and triangles correspond to Evinos, Mornos and Yliki reservoirs, respectively, and represent the adjusted operation rules, whereas thin lines represent their active storage capacity.

Figures



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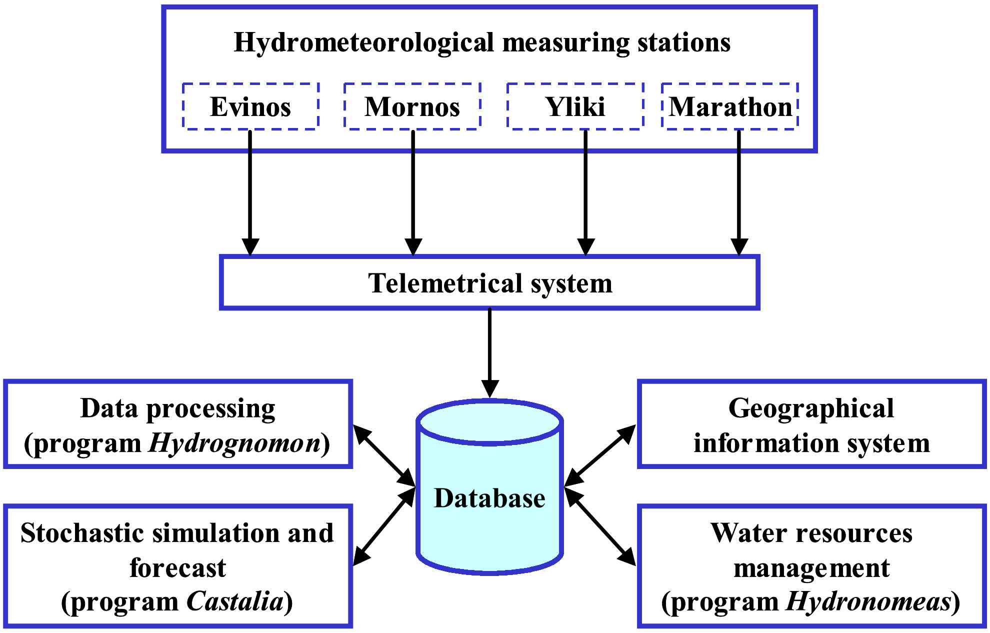

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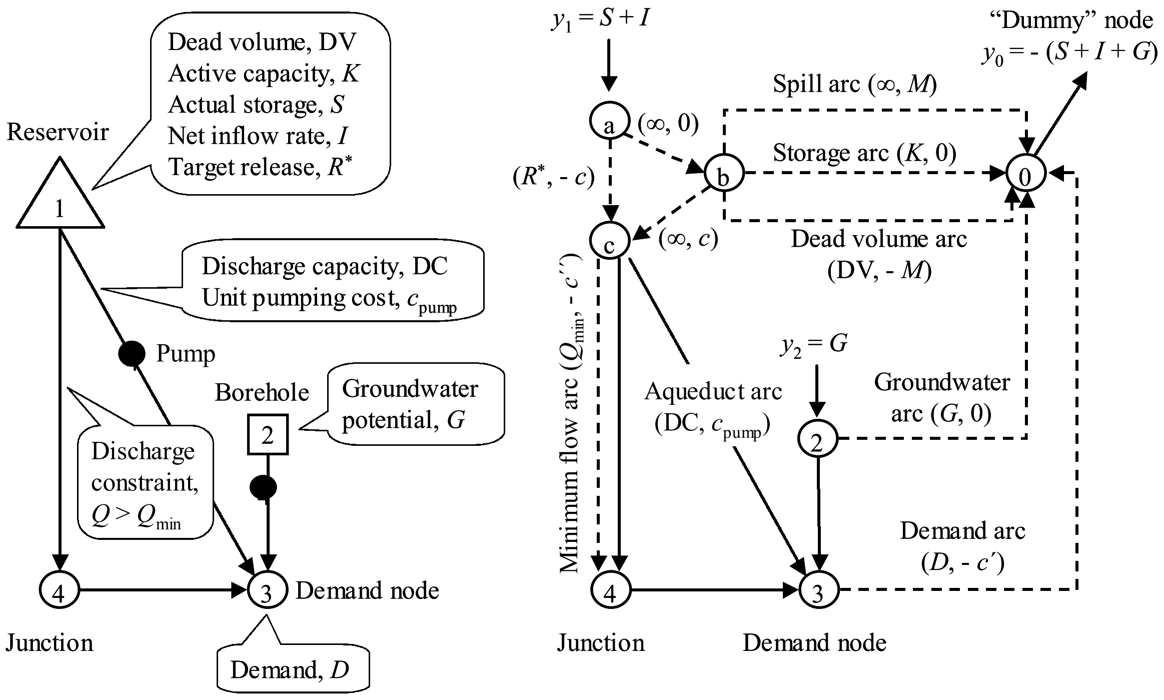

Actual system configuration

Digraph transformation

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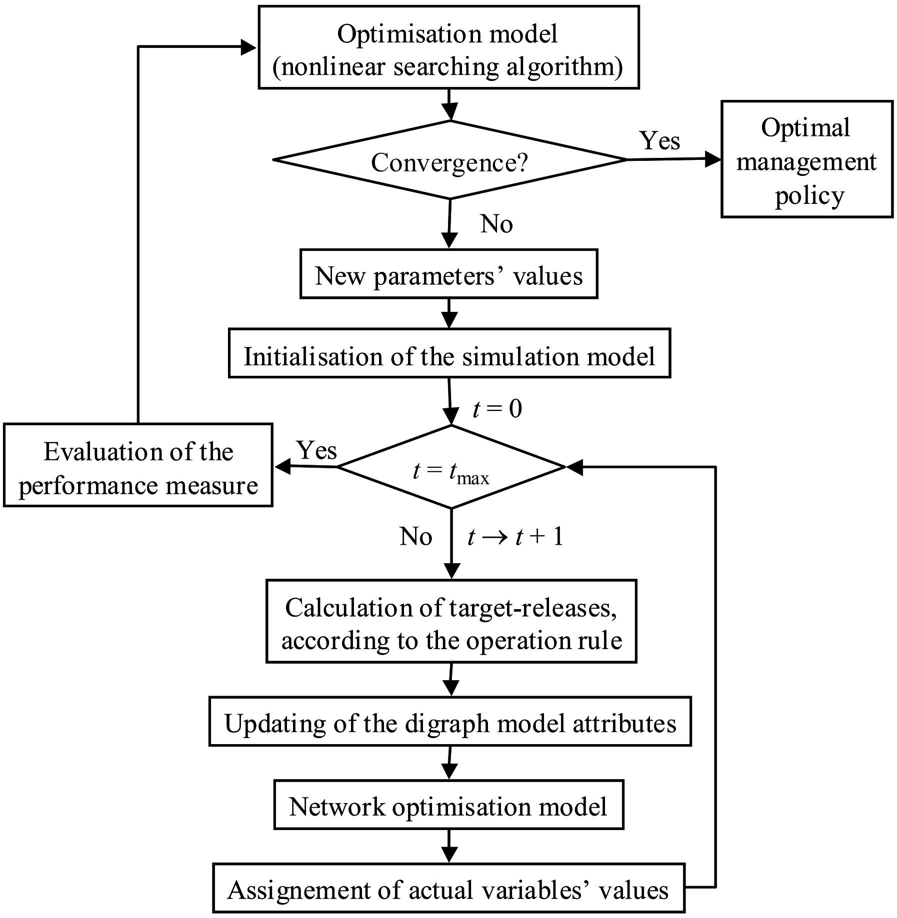

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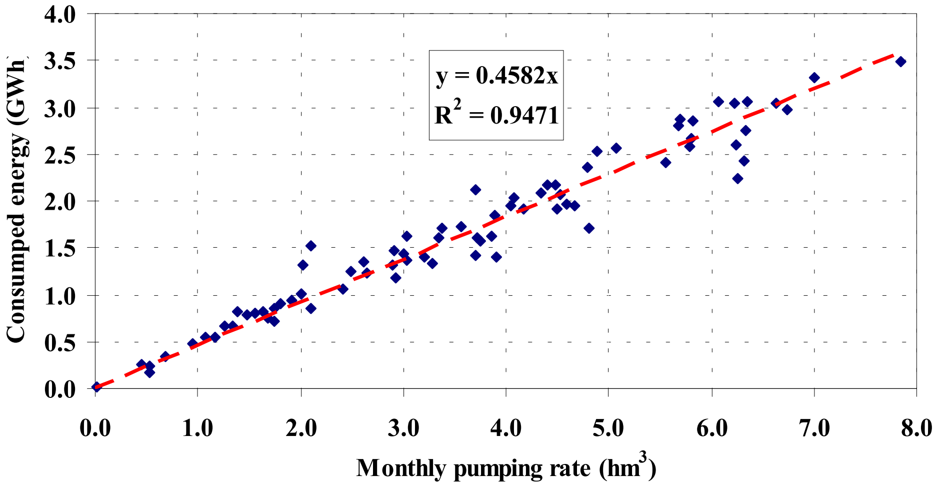

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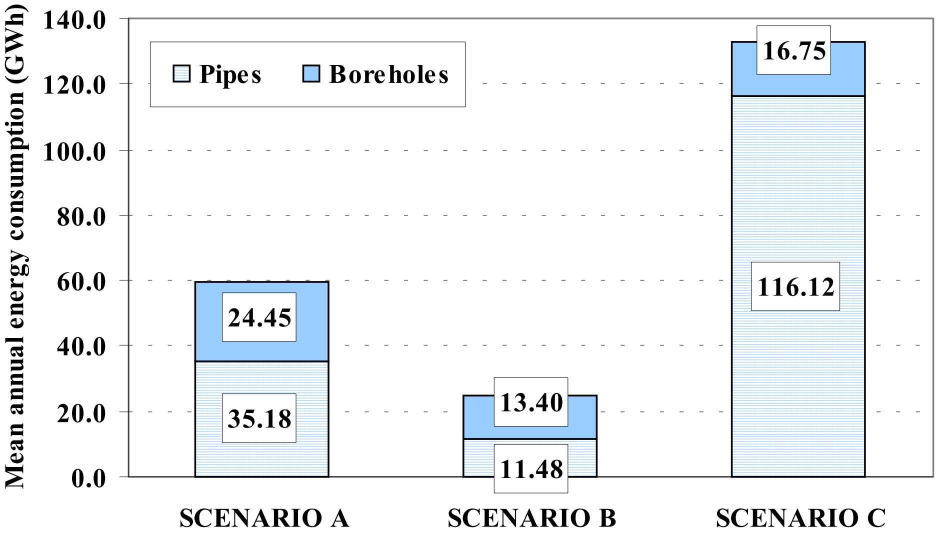
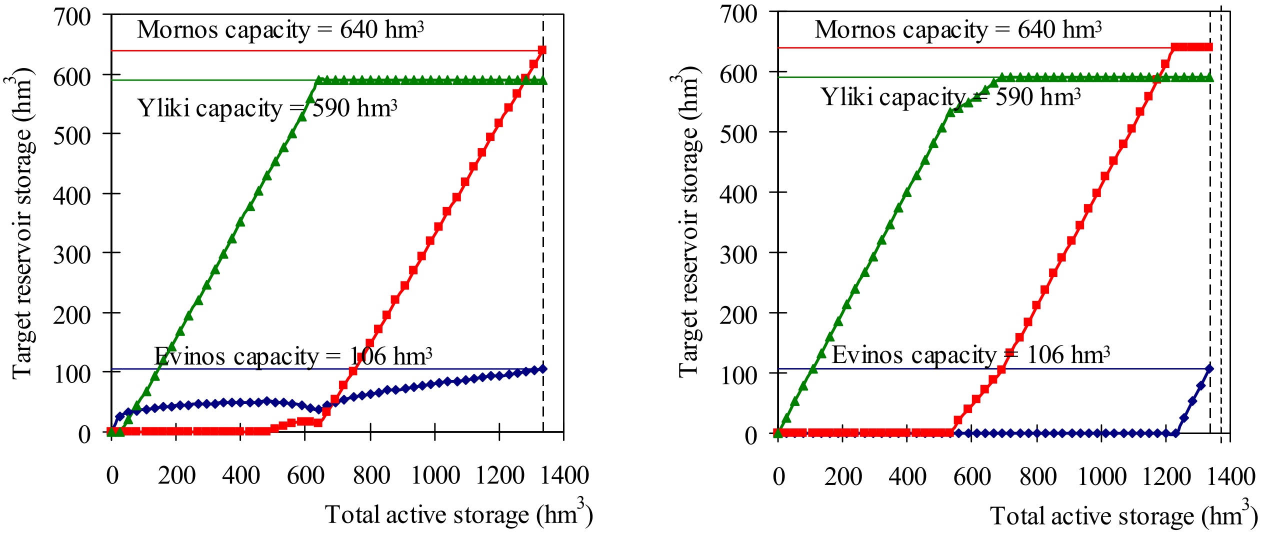


Figure 6: Average annual energy consumption for the three examined scenarios.



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