Vulnerability based management of water resources systems

V. K. Kanakoudis

ABSTRACT

Must the water networks be fail-proof or must they remain safe during a failure? What must water system managers try to achieve? The present paper introduces a methodology for the hierarchical analysis (in time and space) of the preventive maintenance policy of water supply networks, using water supply system performance indices. This is being accomplished through a technical–economic analysis that takes into account all kinds of costs referring to the repair or replacement of trouble-causing parts of the water supply network. The optimal preventive maintenance schedule suggested by the methodology is compared with the empirically based maintenance policy applied to the Athens water supply system.

Key words | water supply system performance indices, preventive maintenance policy

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INTRODUCTION

One of the most crucial tasks that every water utility has to accomplish is the planning of the optimal preventive maintenance of the water system. To achieve maximum safety, periodic checks on system operation, in order to detect any possible problems, are necessary. Unfortunately, the real conditions of 'running' water supply systems greatly differ from theoretical considerations due to financial shortcuts that make inspections of the entire system an impossible goal to achieve, or due to time restrictions, due to insufficient water tanks which do not allow for temporary interruptions of the water supply. Under these hardly flexible operating conditions, a system manager has to prioritize all the possible system maintenance tasks, also considering the forecast operating conditions for the system for the years to come. The present paper introduces a methodology for the hierarchical planning in place and time of the preventive maintenance policy in water supply networks, using the Significance Index of each system part and the Vulnerability Index of the entire system. The main principle of this methodology is to keep the consequences of any failure in the system within accepted levels (safe-fail), rather than try to achieve a failure-free system (fail-safe) (Kanakoudis & Tolikas 2002). The whole attempt is based on a technical–economic analysis of all kinds of costs related to the repair/replacement of trouble-causing parts of a network. The methodology is implemented in the water supply system of Athens, Greece that has a total length of 510 km and a supplying capacity of 1,420,000 m^3/d, satisfying the needs of 4,500,000 customers.

PREVENTIVE MAINTENANCE PRIORITY CRITERIA DEVELOPMENT ATTEMPTS

One of the main goals of preventive maintenance is to extend the network's life as long as possible. In Athens this goal is justified by the fact that the replacement cost of a water supply main is five hundred times greater than its preventive maintenance cost (Kanakoudis 1998). Preventive maintenance priority criteria can be related to the system's performance level that can be quantified using appropriate indices such as the grade of service, quality of service, percentage of use, speed of response, reliability, risk, mission reliability, incident period, availability, reparability, vulnerability, sustainability and engineering risk (Kanakoudis 2002*a*). Several researchers have developed methodologies for the optimal planning of the preventive maintenance policy for water supply networks based on such indices (Hashimoto *et al*. 1982; O'Day 1982; Marks *et al*. 1985; Andreou *et al*. 1987; Wagner *et al*. 1988; Quimpo & Shamsi 1991; Male *et al*. 1994; Shamir & Howard 1981; Duckstein & Parent 1994). Most of them were based on the system reliability that is distinguished from the mechanical (which refers to the uninterrupted operation of any system device/part) and the hydraulic reliability (which refers to the proper operation of the entire system within a specified time period). In order to estimate the system's hydraulic reliability, the estimation of the mechanical reliabilities of its parts is necessary. Kapur & Lamberson (1977) were the first to calculate the hydraulic reliability of a system, when its several parts are placed in series or in parallel. To calculate the hydraulic reliability of a network, whose parts are not placed in series or parallel, several methodologies have been developed (fault and event trees, cut sets, path sets, conditional probability approach, connection matrix method), based on Network Reduction Methods that try to convert the network into a set of blocks (one or more parts) placed in series or in parallel. Each block also consists of individual parts (called arcs) placed in series or parallel. These arcs can be simple network components. The joining points of blocks and arcs are called nodes. Using such methods, it is easy to calculate each component, arc and block mechanical reliability. Then, it is easy to calculate the system's hydraulic reliability using Kapur and Lamberson equations.

From all the attempts developed, Wagner introduced, and Quimpo & Shamsi developed, the most widely used methodology called 'reach-ability and connectivity' (Wagner *et al*. 1988; Quimpo & Shamsi 1991). This method refers to steady-state conditions, can be applied to both water supply and delivery nets and uses the node-pair reliability, defined as 'to secure a constantly open path among the demand and supply nodes during the specified period'. To apply this method it is necessary to predetermine all these paths. For each demand node these paths are disjoint events and the system's hydraulic reliability equals the probability that at least one of these disjoint events occurs. This probability is the sum of the probabilities that any one of these disjoint events occurs independently. The Quimpo and Shamsi method does not considers the cost to restore the failure and the possible differentiation of the failure impacts during the attempt to satisfy the demands. This can result in errors in the hierarchical analysis of the system parts, when the restoring cost and the failure impacts are not fixed but depend on the system's operating conditions.

THE SUGGESTED METHODOLOGY

When a water utility manager adopts the reliability-based analysis of a water supply system, a great danger lies in wait. In Athens, although the water supply system was highly reliable, at the same time it was extremely vulnerable (in terms of failure-caused cost) during a failure, due to the fact that the system's high reliability derived from a certain operation pattern where, although the probability of any failure occurrence was minimized, the failure impacts were huge. In order to analyze a water supply system considering the magnitude of its failure impacts the present work develops the Quimpo and Shamsi methodology, by using each part's *Significance Index* to determine where and the system's *Vulnerability Index* to determine when the preventive maintenance work will take place. The former is the product of each part's *Probability Index* (probability of a failure occurrence) and *Hazard Index* (a cost index reflecting the magnitude of the failure impacts) related to the system *Percentage of Use Index*. For each operating scenario the system's Vulnerability Index is the sum total of the Significance Indices of its parts. The successive steps are:

Step 1. Hydraulic simulation and cost-based optimization of the system operation for (n) water supplying and (k) water demand scenarios (nk normal operating scenarios).
Step 2. Determination of the system parts (r) where possible failures have different impacts (operating cost).

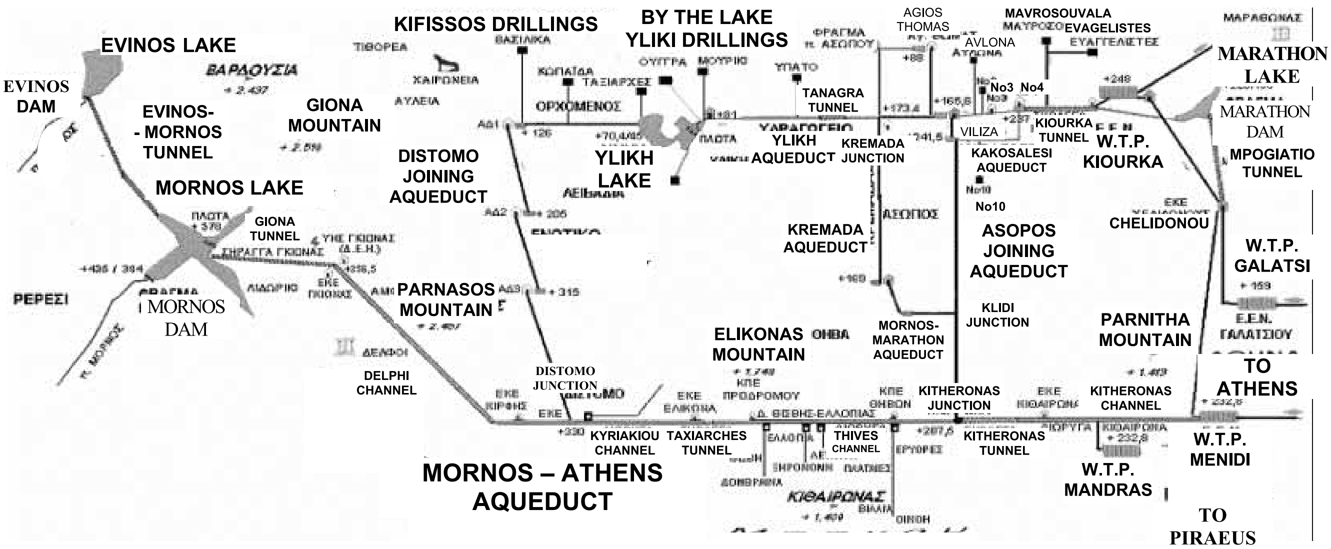

Figure 1 | A sketch of the Athens water supply system.

Step3. Determination of the characteristics of the failure chosen to be the 'typical' failure.

Step 4. Quantification of the failure impacts for each one of the (*nk*) operating scenarios (*Hazard Index*).

Step 5. Calculation of the *Probability Index* for each 'crucial' part of the system (*r* values).

Step 6. Calculation of each part's *Significance Index* related to the system's *Percentage of Use Index* for each operating scenario (*nkr* values).

Step 7. Spatial hierarchical analysis of the preventive maintenance for each part of the network based on the Significance Indices for each operating scenario.

Step 8. Calculation of the network's *Vulnerability Index* for each one of the system's operating scenarios.

Step 9. Determination of the optimal time for beginning the preventive maintenance work for each network part based on the system's Vulnerability Index for each one of its operating scenarios.

APPLICATION OF THE SUGGESTED METHODOLOGY

The suggested methodology was implemented in the Athens water supply system (Figure 1). This system carries water from several water resources through alternative paths to four Water Treatment Plants located just outside the city limits, has a total length of 510 km, a maximum carrying capacity of 1,420,000 m^3/d and satisfies the needs of 4,500,000 customers. The impacts of any failure depend on the specific water supply–demand scenario due to the existence of alternative water resources/paths.

The water consumption in Athens

The mean daily water demands in Athens are 900,000 m^3, supplied under the responsibility of the local water utility known as EYDAP. These demands have grown by about fifty times since the beginning of the 20th century, when they were satisfied through small-scale water works at the local resources (springs) and embryonic water supply/delivery networks. The rapid increase of the water needs and the prolonged drought periods forced the construction of large-scale water works that strip the water resources of Central Greece, from Marathon River to Evinos River, 200 km outside the city limits. The mean annual growth rate of the water needs in Athens has been approximately 8% since 1981, when water conservation measures based on aggressive water pricing policies were adopted due to the inadequacy of the water resources

Table 1 | Water resources reserves capacities scenarios (in millions m^3/yr).

Supplying capacity	Poor	Medium	Rich
Evinos & Mornos	380	455	500
Lake Yliki and supporting drillings	140	165	200
Lake Marathon	20	25	30
Drillings along main aqueducts	45	55	65
Drillings along backup aqueducts	55	60	65
Total	**640**	**760**	**860**

reserves. Such kinds of measures, combined with water consumption suppressing measures, were imposed from 1990 to 1993, to face the drought period that Athens had been experiencing since 1988 (Kanakoudis 1998, 2002*b*).

The capacities of the water resources reserves

The Athens water supply system consists of pumping units (water intake, transfer and boosting with 94,830 hp of installed power that could supply 4,835,000 m^3/d, consuming 0.350 kWh/m^3, with mean cos φ of 0.847), supply mains (43% channels, 33% tunnels, 20% pipes), control devices (valves and gates) and water treatment plants (with 1,460, 480 and 1,940 hundreds of m^3 daily normal, extra and total capacity, respectively). The water resources supplying this system can be split into surface resources (Yliki Lake, Evinos, Mornos and Marathon rivers) and groundwater resources (105 drillings in Attica, Biotia and Fthiotida, with 25,205 hp of installed power that can supply 800,500 m^3/d, consuming 0.448 kWh/m^3). The estimation of the supplying capacity of each one of these water resources was the subject of an intensive study, resulting in three separate (poor, mean and rich) scenarios (Table 1) based on the development of hydrological forecasting models (Kanakoudis 1998).

Hydraulic simulation principles in brief

The sketch of the system gives an image of all possible alternative water supply resources and paths. The system's branched configuration is modelled using the EPA net code (Kanakoudis 2002*c*). The Mornos and Yliki aqueducts are the main water supply paths that can 'communicate' through the Mornos–Marathon Joining Aqueduct. The location of the water resources allows their joint operation and management. The system's configuration is simplified by adopting Network Reduction Methods (blocks, arcs, nodes). The simulation is based on the principle of Mass Conservation in each node in conjunction with the estimation of the water losses along each part of the system. Along the water supply mains, water losses occur due to leaks (pipes and tunnels) and evaporation (channels). Since 1990, the water losses in the Mornos aqueduct (110 km of channels) have decreased from 15% to 8% of the supplied water due to an extended programme of leak detection and pipe lining. Also in the Yliki, Kakosalesi and Mornos–Marathon aqueducts, these losses are between 1–2% of the water being supplied (EYDAP 2001). Finally, the water losses of each part are linearly allocated along its supply mains (Kanakoudis 2002*d*).

Estimating the system's operating cost under normal operating conditions

The optimization of the system's operation is based on the minimization of both the energy cost to pump and transfer

Table 2 | Monthly Demand Factors (MDF) (actual daily consumption per month compared to the mean constant daily consumption of the base year *T*).

	MDF		MDF		MDF
January	86%	May	104%	September	110%
February	79%	June	112%	October	105%
March	89%	July	121%	November	93%
April	91%	August	117%	December	93%

the water and the cost of the water losses that occur during the supply process. To calculate the energy cost spent to pump and transfer the water, the characteristics of the pumps, boosters and drilling capacities, the structure and level of the rates used by the Greek Electricity Company to charge for the energy consumed by EYDAP and details concerning the in-field pump station operation and management techniques were considered. Regarding the energy rates, the charge depends on the patterns of the power and energy demand. If these patterns include peaks greater than the mean constant predetermined demand, and as the Greek Electricity Company energy rates 'punish' any load or voltage fluctuations, charging penalties appear. In the present study for each pumping, boosting or drilling station the energy cost is calculated through a unit-cost factor in Ecents per m^3 that equals the mean value of its operating range (the upper limits are the pumping capacity of the station and network carrying capacity). This cost ranges between 0.19 and 8.8 Ecents/m^3 depending on the water resource used and the path chosen to carry the water. The operating cost of a plant includes the cost of energy spent and chemicals used during the process, the payroll of the stuff and the cost of repairs and maintenance. In Athens this cost is 0.94 Ecents/m^3 for the plants of Galatsi, Menidi and Mandra and 3.87 Ecents/m^3 for Kiourka Plant due to its high altitude. Additionally, based on each plant location, the cost to transfer water through all the possible paths among them is: from Menidi to Kiourka or to Mandra 3.52 Ecents/m^3 and from Menidi to Galatsi 2.35 Ecents/m^3. Finally, as the water being lost along each path connecting a water supply (water resource) and a water demand (treatment plant) node is actually being replaced by an equal water volume supplied from the next more expensive alternative water resource, the cost of the water losses in Athens water paths ranges between 1.98–24.5 Ecents/m^3. To distribute the cost of the water losses occurring in a water supply network that carries water from alternative water resources, the *Micro-flow Distribution & Complete Mixing Assumption Method* was applied (Wood & Ormsbee 1989; Jowitt & Chengchao Xu 1993). This method determines the significance factor of each water resource, based on its failure impacts, regarding the operation of the system.

Water demand scenarios

The next task is to determine the water supply and demand scenarios. In Athens the determination of the water demand pattern is based on the following aspect: 'the demand pattern includes the mean daily demands for each one of the twelve months of the year (stated as *T*) whose maximum daily demand equals the maximum water volume that can reach the plants with respect to the carrying capacities of the aqueducts, the pumping capacities of the pumps and the treatment capacities of the plants' (Kanakoudis 1998). The Athens system model revealed that 1,419,300 m^3 of water could be supplied daily to the plants. The next step is to form Table 3 from

Table 3 | Mean water demand for each month of year T (10^3 m^3/d).

	Water demand		Water demand		Water demand
January	1008.8	May	1220.0	September	1290.3
February	926.7	June	1313.8	October	1231.7
March	1044.0	July	1419.3	November	1090.9
April	1067.4	August	1372.4	December	1090.9

Table 4 | Water demands in the four plants for the year T (10^3 m^3/d).

Month	$\Sigma Q_{TOT\ DEMAND}$	Q_{MANDRA}	Q_{MENIDI}	$Q_{GALATSI}$	$Q_{KIOURKA}$
October	1231.7	168.7	514.9	379.4	168.7
November	1090.9	149.45	456.0	336.0	149.45
December	1090.9	149.45	456.0	336.0	149.45
January	1008.8	138.2	421.7	310.7	138.2
February	926.7	126.95	387.35	285.45	126.95
March	1044.0	143.0	436.4	321.6	143.0
April	1067.4	146.25	446.15	328.75	146.25
May	1220.0	167.15	509.95	375.75	167.15
June	1313.8	180.0	549.15	404.65	180.0
July	1419.3	194.45	593.25	437.15	194.45
August	1372.4	188.0	573.7	422.7	188.0
September	1290.3	176.8	539.3	397.4	176.8

EYDAP records, concerning the mean daily demand of each month of the year T. From Table 2, which includes the Monthly Demand Distribution Factors, it shows that July is the month with the maximum mean daily water demand (MDF = 121%). The mean daily water demand of the year T is therefore 1,173,000 m^3 (= 1,419,300/1.21). From the mean daily demand of the whole year T and the demand factors presented in Table 2, the actual mean daily demand for each month of the year T is estimated (Table 3). Assuming that the daily demands are allocated to the plants according to their capacities Table 4 is formed.

Table 5 | Water supplied by the resources, water supplied to the plants and water losses (ΣQ) (10^3 m^3/d).

Month	ΣQ_D	Q_{M+E}	Q_{YLIKI}	ΣQ_{WR}	ΣQ	ΣQ (%)
October	1231.7	1336.3	0	1336.3	104.68	7.8
November	1090.9	1183.3	0	1183.3	92.4	7.8
December	1090.9	1183.3	0	1183.3	92.4	7.8
January	1008.8	1094.3	0	1094.3	85.5	7.8
February	926.7	1005.2	0	1005.2	78.5	7.8
March	1044.0	1132.4	0	1132.4	88.4	7.8
April	1067.4	1157.8	0	1157.8	90.4	7.8
May	1220.0	1323.6	0	1323.6	103.6	7.8
June	1313.8	1378.5	44	1422.5	108.7	7.6
July	1419.3	1378.5	151.5	1530	110.7	7.2
August	1372.4	1378.5	103.8	1482.3	109.9	7.3
September	1290.3	1378.5	20.1	1398.6	108.3	7.8

Results of the hydraulic simulation and operating cost-based optimization of the network

- The cheapest water comes from the joint operation of the Mornos and Evinos reservoirs, followed by Lake Yliki.
- The water demands in the plants can be satisfied directly without any further redistribution.
- Assuming a 'medium' hydrologic scenario, the total water volume annually supplied by the resources is 464.5×10^6 m^3 (97.9% supplied by the Mornos–Evinos reservoirs and 2.1% by Lake Yliki and its drillings).
- The Mornos–Evinos supplying capacity is 1,378,500 m^3/d while Lake Yliki can supply 670,000 m^3/d.
- The maximum water demand in the plants satisfied using only the Mornos–Evinos system is 1,270,600 m^3/d.
- The maximum daily water demand in the plants satisfied using all the water resources is 1,419,300 m^3.

The mathematical framework

The optimization process resulted in specific operating scenarios of the Mornos–Evinos and Lake Yliki systems (columns 3 and 4 of Table 5, respectively) in order to satisfy the predetermined water demands in the plants (column 2 in Table 5). Additional supplying scenarios were considered assuming that the Mornos–Evinos supplying capacity may range between 65–100% of its maximum capacity (the values of the system's maximum capacity in each water demand scenario are included in column 3 of Table 5). The results revealed that, based on regression analysis, a mathematical model that calculates the water supplies from each water resource as a function of the water demands in the plants can be developed that satisfactorily approaches (>95%) the optimal system operation.

The model in brief

Initially the variables of the mathematical model are determined:

ΣQ_{WTP} = the daily water demands in all four Water Treatment Plants ($\leq$1,419,300 m^3).
Q_{M+E} = the daily water supply from the Mornos–Evinos system ($\leq$1,378,500 m^3),
Q_Y = the daily water supply from Lake Yliki and its supporting drilling system ($\leq$670,000 m^3).

All possible values of ΣQ_{WTP} are then grouped into two distinct ranges:

- $\Sigma Q_{WTP} \leq 1{,}270{,}600$ m^3.

  The water supply from the Mornos–Evinos system necessary to satisfy the needs is derived from ($\times 10^3$ m^3):

$$\Sigma Q_{WTP} = 0.921(1 + Q_{M+E}). \tag{1}$$

  If the Mornos–Evinos system can offer only a part (q_{M+E}) of the water volume calculated using Equation (1), then the water from Lake Yliki necessary to satisfy the needs will be ($\times 10^3$ m^3)

$$Q_Y = 1.397q_{M+E} - 1.425q_{M+E}(q_{M+E}/Q_{M+E}) \Rightarrow (Q_Y/q_{M+E}) = 1.397 - 1.425(q_{M+E}/Q_{M+E}). \tag{2}$$

- 1,270,600 $m^3 \leq \Sigma Q_{WTP} \leq$ 1,419,300 m^3.

  As the Mornos–Evinos system supplies its maximum supplying capacity (1,378,500 m^3), the water supply from Lake Yliki necessary to satisfy the demands is ($\times 10^3$ m^3)

$$\Sigma Q_{WTP} = 1{,}270.6 + 0.981Q_Y. \tag{3}$$

  If the Mornos–Evinos system can offer only a part (q_{M+E}) of the water volume calculated using Equation (1), then the water from Lake Yliki necessary to satisfy the needs will be ($\times 10^3$ m^3)

$$Q_Y = \left[\frac{\sum Q_{WTP} - 1270.6}{0.98145}\right] + q_{M+E}\left[1397 - 1425\left(\frac{q_{M+E}}{1378.5}\right)\right]. \tag{4}$$

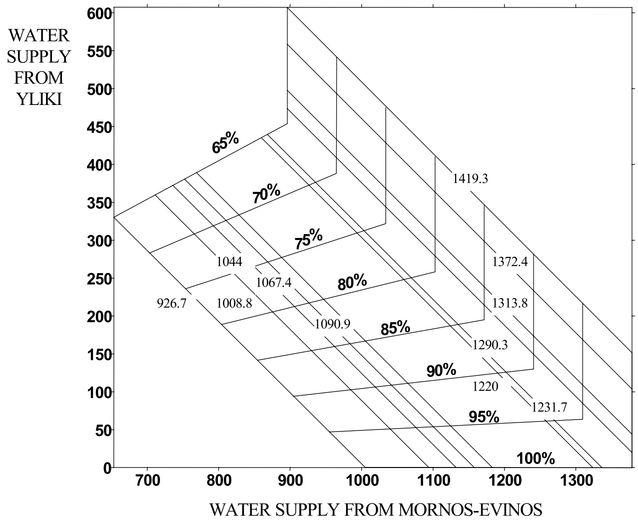

Figure 2 | Optimal operation of the system ($\times 10^3$ m^3/d).

Finally, a graphical approach (Figure 2) of the mathematical model is developed, presenting the contour lines of ΣQ_{WTP} and the Mornos–Evinos supplying capacity (65–100%). In conclusion, the minimum daily operating cost of any water demand–supply scenario depends on the water demands of the plants and the Mornos–Evinos water supplying capacity (Figures 3–5). Figure 3 presents the minimum daily cost (C) of the ‘optimal solution’. The cost of the water being lost along any ‘path’ between the supply and demand nodes is not included in Figure 3 but is presented in Figure 4, in order that these two kinds of costs can be easily compared. Figure 5 combines Figures 3 and 4, where the contour lines represent the daily total operating cost (C_{TOT}) of the optimal solution.

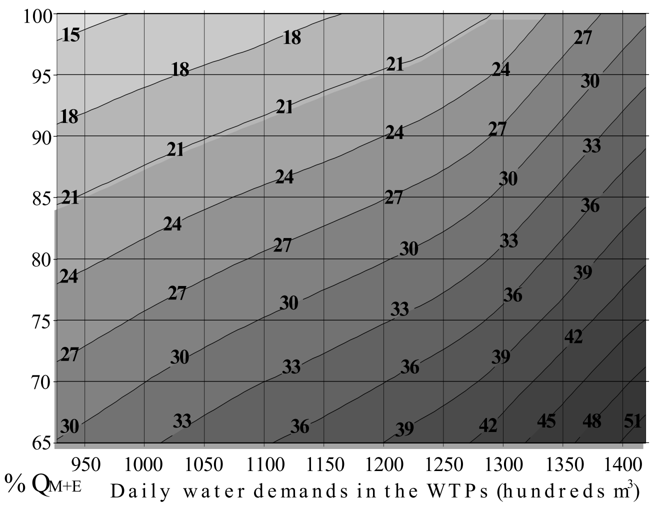

Figure 3 | Daily energy cost (10^3 Euro).

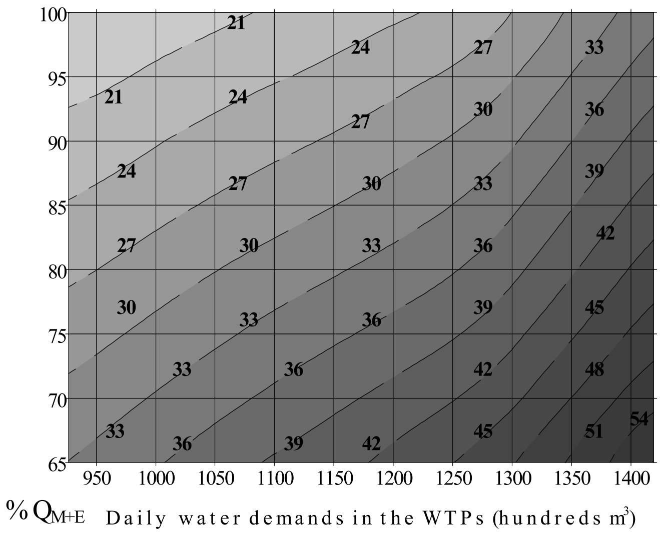

Figure 5 | Daily total operating cost (10^3 Euro).

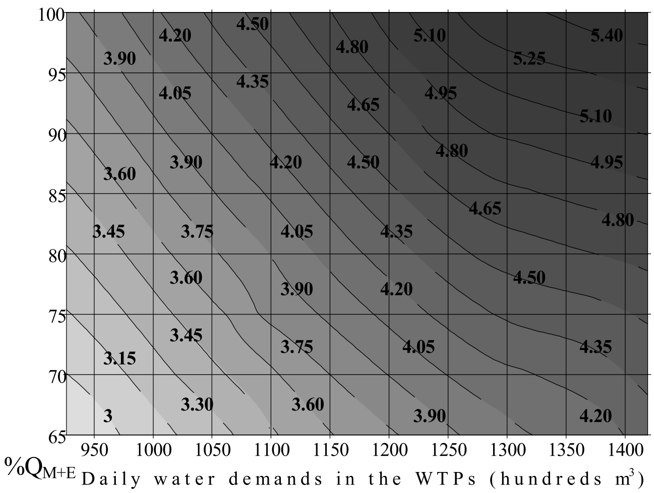

Figure 4 | Cost of daily water losses (10^3 Euro).

OPTIMAL SPATIAL ALLOCATION OF THE MAINTENANCE ACTIONS

Hierarchical analysis of the trouble-causing sections

Initially, all possible trouble-causing parts of the Athens water supply network are grouped into ten individual sections (Table 6, Figure 6) based on their different failure impacts. To quantify these impacts, 880 operating scenarios are simulated considering the 10 failing parts, the 11 daily water demand scenarios in the plants (Table 4) and the 8 water supply scenarios from the Mornos–Evinos system (65–100% of its optimal capacity). This process revealed that the network totally or partially fails to satisfy the water needs whenever a failure occurs in sections 1, 2, 3 or 9. Only the Menidi and Mandra plants face water shortage problems that become greater following the increase in the needs. According to the methodology introduced, we optimally schedule the maintenance actions based on the value of the Significance Index (V_S) of each one of the network's individual trouble-causing sections, which is derived from the values of each part's Hazard Index (V_C) and Probability Index (V_R) related to the specific operating scenario.

Estimating the Hazard (failure caused extra cost) Index (V_C)

Any failure that occurs in a water supply network has various financial impacts on: (a) the water utility, including the cost of restoring the network's normal operation, the cost of the extra energy used to carry water from alternative and more expensive water reserves or/and paths, the cost of water losses and the lost revenues when the water demand is not fully satisfied and (b) the public,

Table 6 | The trouble-causing parts of the network.

	Failing part	Channels (m)	Siphons (m)	Tunnels (m)	Pipes (m)	Length (m)	% total length
1	Mornos Lake to Kitheronas Junction	80,294	5,690	59,880	0	145,864	44.50
2	Kitheronas Junction to Mandra Plant	12,302	812	11,099	0	24,213	7.39
3	Mandra Plant to Menidi Plant	17,249	773	0	0	18,022	5.50
4	Yliki Lake to Viliza water tank	23,385	7,500	3,000	3,800	37,685	11.50
5	Kakosalesi aqueduct	365	1,350	9,325	14,700	25,809	7.87
6	Detour pipe of Kakosalesi aqueduct	0	0	0	15,000	15,000	4.58
7	Water tank no 4 to Marathon lake	0	0	8,400	1,400	9,800	2.99
8	Joining aqueduct Mornos–Marathon	5,720	5,180	0	12,300	23,200	7.08
9	Marathon Lake to Galatsi Plant	0	0	15,786	5,760	21,552	6.58
10	Menidi Plant to Galatsi Plant	0	0	0	6,610	6,610	2.01
Total length (m)		139,315	21,305	107,490	59,600	327,755	100
% of total length		42.5	6.5	32.8	18.2	100	

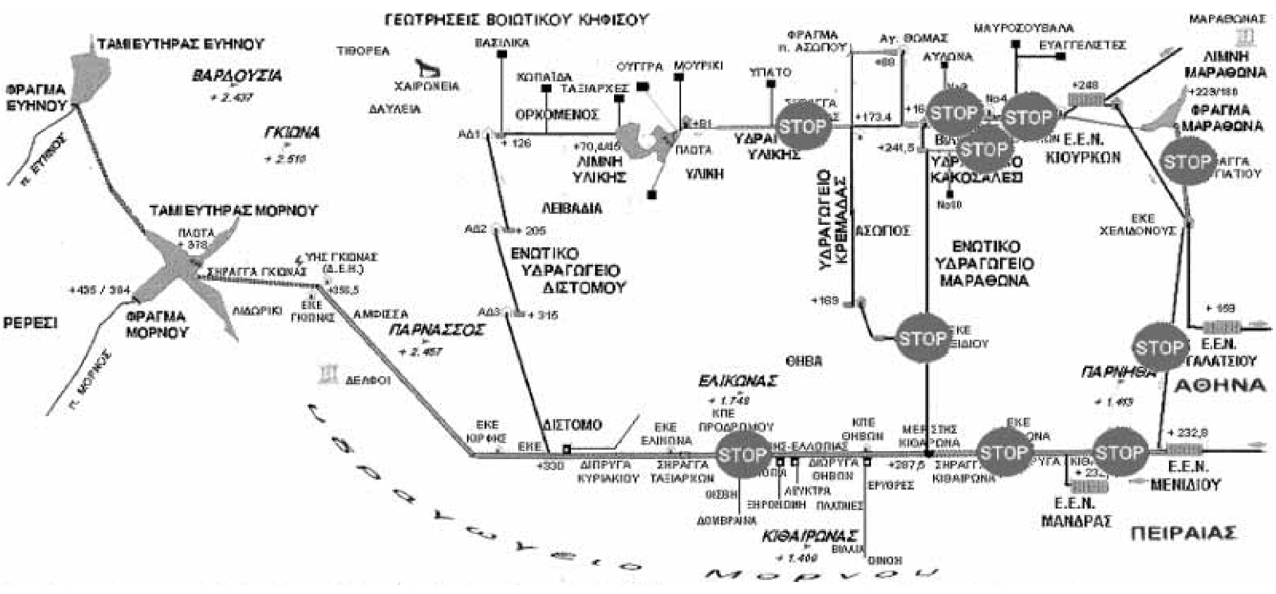

Figure 6 | The trouble-causing parts of the network. *Failure in part 1:* the water deficit in the Menidi WTP reaches 65% as the daily water needs grow from 1,017 to $1{,}419\times10^3$ m^3. *Failure in part 2:* the Mandra WTP shuts down and the water deficit in the Menidi WTP ranges from 10.3 to 78.3% as the daily needs grow from 926.7 to $1{,}419.3\times10^3$ m^3. *Failure in part 3:* the water deficit in the Menidi WTP increases to 60.6% as the daily water needs grow from 1,049 to $1{,}419.3\times10^3$ m^3. *Failure in part 9:* the water deficit in the WTP Menidi increases to 22.8% as the daily water needs grow from 1,273 to $1{,}419.3\times10^3$ m^3.

Table 7 | Repair and replacement costs in Athens.

Type of supply main	Replacement cost (Euro/m)	Repair cost (Euro/m)	Repair rate (m/d)	Repair extent (m)	Repair duration (d)
Channels	1467.35	293.47	10.0	200	20
Siphons	1467.35	293.47	10.0	200	20
Tunnels	2934.70	586.94	5.0	100	20
Pipes	1173.88	234.78	12.5	250	20

appearing as the social cost resulting from the inconvenience and the financial damage when water demand is not fully satisfied.

The *Cost of Repairs and Replacement* is the actual failure cost, depending firstly on the type, extent and duration of the failure incident and secondly on the type, material, size and site of the failing part. In Athens the cost of repairing a failure is 1/5 of the respective replacement cost (EYDAP 2001) (Table 7). The *Cost of Extra Energy* is derived from the main objective of a water supply network, which is to satisfy water demand. Although, in normal operating conditions, this goal must be achieved with minimum cost, during a failure the demand must be met regardless of the unavoidable extra cost. Optimization of the network operation during a failure is possible only when alternative supply–demand paths are available, securing either full or partial satisfaction of these needs. The extra energy cost spent for water intake, transfer and treatment results from the use of alternative, and thus more expensive, paths, the exploitation of alternative, and thus more expensive, water resources reserves and the extra operating costs of the water treatment plants. In Athens the *extra energy cost* is calculated using the unit cost factors of every water path. The *Cost of Water Losses* results from the fact that the water losses of a certain network path or water resource will be replaced using the second cheapest alternative. The financial losses for the water utility due to *Lost Revenues* occur when the water demand is not satisfied by the water supply system. To estimate this financial damage, knowledge of the mean value (Wp in Euro/m^3) of water charge per use and the unaccounted-for water index (UW) are necessary. Wp depends on the level and structure of the water rates, while UW evaluates the total water losses (leaks, breaks, metering errors, theft, legal but not charged uses, etc) during the water supply/delivery process. The cost C from not supplying Q m^3/d is (Kanakoudis 1998)

$$C = QWp(1 - UW). \tag{5}$$

In Athens, considering the level and structure of the Inverted Block Water Rate used (Table 9), the per capita water use, the average charge per water use (Table 8) and the unaccounted-for water (Figure 7), $C = 0.42$ Euro.

Several studies of the public's behaviour towards water (Stacha 1978; Walski & Peliccia 1982; Olsen & Highstreet 1987; Murdock *et al*. 1991; Schneider & Whitlatch 1991) have shown that the *Social Cost* of a failure in the water supply system equals the price the public is willing to pay to ensure that no water supply interruptions will ever occur. This cost expresses the financial damage deriving either from water shortages or the use of alternative, and thus more expensive, water supply solutions and from the public's inconvenience. The study of the failure records of the Athens water delivery system proved that: 'the social cost of a failure is two to four times its actual repairing cost, when the failure occurs in a delivery pipe or a supply main respectively. This results in a unit social cost (UCs) in Euro/m^3 of water not making it from the supply to the demand node' (Kanakoudis & Tolikas 2001). This conclusion presupposes that the system totally fails to satisfy the water

Table 8 | The water rates used in Athens.

Charge of water use (water rates)	Structure (m^3)	Level (Euro/m^3)
Residential (per three months)	0–15	0.343
	16–60	0.522
	61–81	1.508
	82–105	2.113
	>105	2.641
Industrial–commercial (per month)	0–1000	0.675
	>1000	0.792
Public–municipal (monthly)	Overall	0.804
Fire fighting–harbour (monthly)	Overall	0.563
Charity (monthly)	Overall	0.226

Table 9 | Water consumption and charge (*Wp*).

Water use	Per capita use (l/d)	%	Average charge (Euro/m^3)
Residential	200	71.43	0.475*
Industrial–commercial	20	7.14	0.734
Public–municipal	50	17.86	0.804
Rest	10	3.57	0.393
Total	280	100	0.549–0.646†

*The *Wp* for residential use is estimated assuming: (a) 3 persons per bill; (b) billing circle of 3 months.
†*Wp* is further charged with VAT at 18%.

needs during a failure, although usually, partial satisfaction of the water needs is possible. Considering that from the water supplied only water losses due to leaks/breaks are not actually being consumed, the social cost will refer to the rest water volume. For example, if Q is the total water entering the system, then the water volume that will actually be consumed will be $[Q(1-LB)]$, where $LB(\%)$ is the portion of the water supplied that is being lost due to leaks/breaks. In conclusion, the social cost (Cs) deriving from a water deficit of $Q-q$ m^3/d is

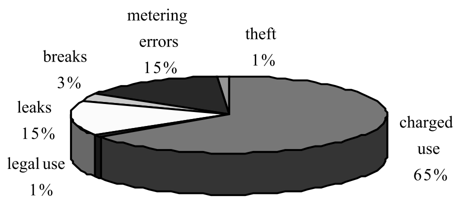

Figure 7 | Water entering the system.

$$Cs = (Q-q)\,\frac{(Q-q)}{Q}\,UCs\,(1-LB). \tag{6}$$

In Athens $Ucs = 2.35$ Euro/m^3 as $LB = 18\%$ (Figure 7) (Kanakoudis 1998).

In conclusion, Figure 8 presents the daily extra operating cost of the system for each one of the 880 alternative scenarios. The results verify that the most distressing failures occur in sections 1, 2, 3 and 9.

Estimating the Probability Index (V_R)

The method of Dynamic Analysis

During the last twenty years, two different approaches, the Dynamic and the Time-to-Failure analysis, have been developed to calculate the probabilities of any failure occurrence in water networks. The former is used in water supply networks where failures are either thought to be irreparable or appear randomly so that no break-rate function can be developed (Germanopoulos *et al.* 1986; Kanakoudis 1998). The latter is used in distribution nets where the exactly opposite conditions are usually met (Kanakoudis & Tolikas 2001). The present study uses the dynamic analysis, as it copes better with water supply systems. Failures in water supply mains (open channels, tunnels and large pipes) usually result from random events like pollution accidents or walls collapsing in open channels, pipe breaks due to hydraulic surges and large-scale leaks in tunnels. Dynamic analysis assumes that failures related to a specified network's length (L) occur randomly in time and their probability of occurrence can be described by a homogeneous (Andreou *et al*. 1987*a*, *b*; Jowitt & Xu 1993; Male *et al*. 1994) or non-homogeneous Poisson distribution (Ross 1989; Goulter *et al*. 1993), based on the reliability and extent of the available failure data records. According to the homogeneous distribution the probability that, in a time period (T) a random event—a failure of any duration—related to the specified length (L) will occur (r) times, depends only on the expected value (B) of the event's occurrences (mean number of occurrences in the specified time period) and can be calculated as

$$P(r) = \frac{B^r \exp(-B)}{r!} = \frac{\left(\frac{T}{M}\right)^r \exp\left[-\left(\frac{T}{M}\right)\right]}{r!} \quad (7)$$

where M is the expected time between failures related to the length (L), $B = (T/M)$ is the expected number of failures related to this length (L) in time period (T). In contrast to the homogeneous Poisson distribution, the non-homogeneous distribution (Goulter & Kazemi 1989) accepts that (B) is not constant, but can vary with time (t) or place (s):

$$B = \int_0^S \int_0^T r(s,t)\,\mathrm{d}t\mathrm{d}s. \quad (8)$$

The duration of a failure is also considered as a random variable exponentially distributed:

$$f(t) = \frac{1}{m^*} \exp\left[-\left(\frac{t-c}{m^*}\right)\right] (t \geq c) \quad (9)$$

where (t) is the failure's duration, (m^*) the expected duration of the repairs and (c) the time between the failure's occurrence and the beginning of the repair. The probability that the duration of a failure will be less than or equal to a specified time (t^*) is given by the cumulative density function $P(\alpha) = \mathrm{P}(t \leq t^*) = F(t^*)$. According to dynamic analysis (Germanopoulos *et al*, 1986; Kanakoudis 1998), if the available failure data records refer only to one kind of a failure regarding its duration, the probability analysis of all kinds of failures is possible. This conclusion was used to statistically process the failure data records available in the Athens water supply network.

Probability analysis in Athens

To estimate the value of the Probability Index for each trouble-causing section of the Athens network, the expected values of the mean number of failures in each of these sections must be estimated according to the Poisson distribution (Equation (7)). Additionally, applying dynamic analysis, the probability of any kind of failure regarding its duration can be also estimated (Equation (9)). The analysis of the Athens failure data records showed that the rate of failures in the Yliki aqueduct channels is 0.00105 events/km/yr while for the channels of the rest of the network this value is 0.00154 events/km/yr. The tunnels and pipes of the network proved to be in better shape, as their annual rates of failures are 0.0002 and 0.0007 events/km, respectively. According to these numbers and assuming a time period of 15 years, the probability (p) of occurrence of any kind of failure in each one of the supply mains can be calculated. This probability accepts that at least one failure (with predetermined characteristics) will occur in the specified kind of supply mains within the time period T and is given by

$$p = p(x \geq 1) = 1 - p(x < 1) = 1 - [p(0)] = 1 - \exp\left(\frac{T}{m}\right).$$

So, for Yliki's aqueduct channels $p = 0.3127$, for the channels of the rest of the network $p = 0.8647$ (p_1), for the tunnels of the entire network $p = 0.2834$ (p_2), for the pipes of the entire network $p = 0.4512$ (p_3) and finally for the entire network (siphons not included) $p = 0.9634$ (p_0). The probability of the occurrence of a failure in any kind of supply mains of each trouble-causing section (Table 10) results from the probabilities p_1, p_2, p_3 and p_4. In fact, this is the joint probability of the two statistically independent

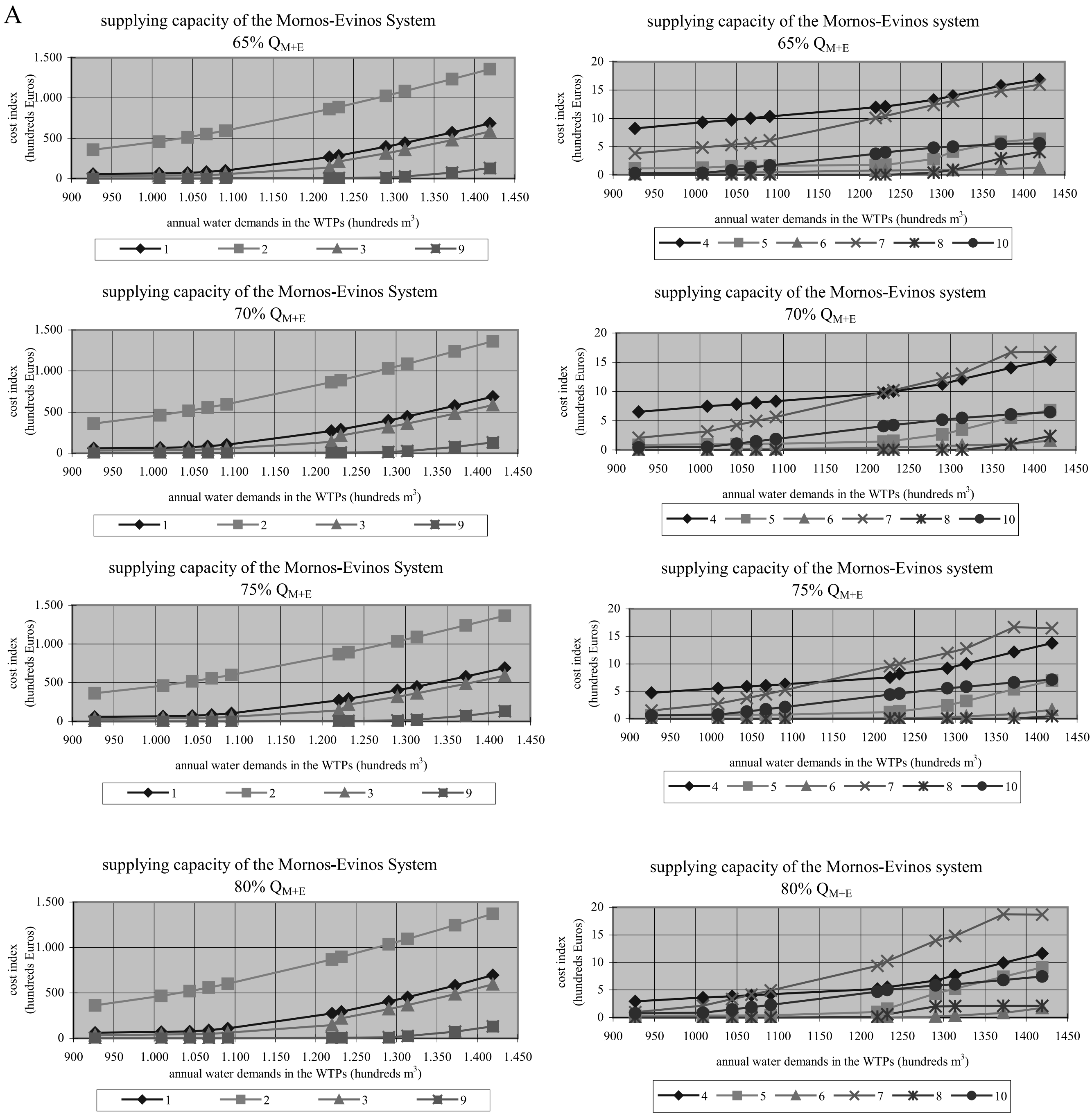

Figure 8 | A. Hazard-failure-caused extra cost index V_C (hierarchical analysis of the trouble-causing parts).

facts ($p(A \cap B) = P(A)^* p(B)$); a failure occurs in the specified kind of supply main (fact A) and this main belongs to the specific section (fact B). The value of each part's Probability Index equals the probability that one of the following facts will occur: the failure occurs in a channel (fact A), in a tunnel (fact B) or in a pipe (fact C) of the part:

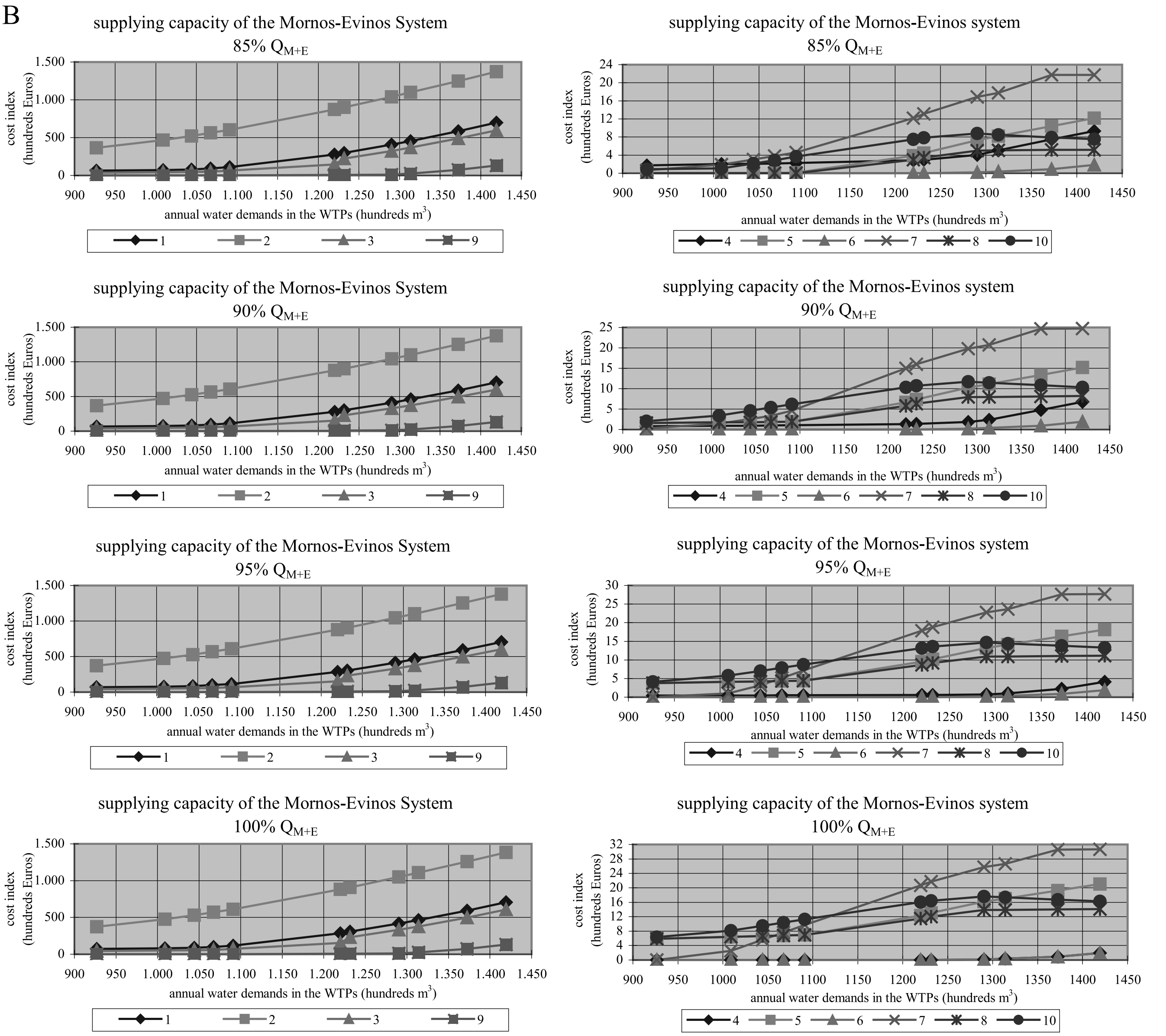

Figure 8 | B. (continued).

$$p(A \cup B \cup C) = p(A) + p(B) + p(C) - p(A)^{*}p(B) - p(A)^{*}p(C) - p(B)^{*}p(C) + p(A)^{*}p(B)^{*}p(C).$$

Comparing the failure probability-based and the cost-based 'top ten', part 2, which was the most costly failing part, is in the sixth most 'risky' place, while part 1, which was the second most costly failing part, is the most 'risky' part of the network. Part 3, from the third most costly, drops to the fifth most risky place and finally part 9, that was in the fourth place, proves to be one of the most reliable parts of the network as it is found in eighth place.

Table 10 | Probability Index (V_R).

Part	Channels Length (m)	Channels (p)	Tunnels Length (m)	Tunnels (p)	Pipes Length (m)	Pipes (p)	V_R
1	80,294	0.600	59,880	0.157	0	0	0.6638
2	12,302	0.092	11,099	0.029	0	0	0.1186
3	17,249	0.129	0	0	0	0	0.1291
4	23,385	0.307	3,000	0.007	3,800	0.028	0.3331
5	365	0.004	9,325	0.024	14,769	0.111	0.1377
6	0	0	0	0	15,000	0.113	0.1135
7	0	0	8,400	0.022	1,400	0.010	0.0326
8	5,720	0.042	0	0	12,300	0.093	0.1318
9	0	0	15,786	0.041	5,766	0.043	0.0834
10	0	0	0	0	6,610	0.050	0.0500

Estimating the Significance Index (V_S)

The Significance Index (Figure 9) of each system part results from $V_S = V_C V_{R'}$, where V_C is the cost index of the specific failure and $V_{R'}$ is the joint probability of the following statistically independent facts:

- fact A: the failure occurs in the specific part (the initial Probability Index=>$p(A) = V_R$),
- fact B: the failure occurs during the specified month of the base year (referring to the needs in the plants),
- fact C: the failure occurs when the Mornos–Evinos system has a specific supplying capacity (65–100%).

Criticizing the results

Table 11 presents the hierarchical spatial analysis of the network sections using the Performance Indices (V_C, V_R, V_S) developed above, revealing that, if the analysis is based only on each part's *Cost Index* or *Probability Index*, it will result in errors when the restoring cost and the failure impacts are not fixed but depend on the system operating conditions. Usually this is the case in a supply network, where the alternative paths among the supply and demand nodes are limited compared to those met in delivery networks. In supply networks any failure's consequences can vary, depending on the supplying capacity of the water resources reserves, the water intake capacity of the exploitation system, the pumping capacity of the pumps/boosters and the carrying capacity of the water mains. Using each part's *Significance Index* the preventive maintenance policy considers both the magnitude of each failure along with the probability of its occurrence.

OPTIMAL TIME SCHEDULE OF THE MAINTENANCE ACTIONS

The final task is to determine the right time for starting the preventive maintenance work. According to the suggested

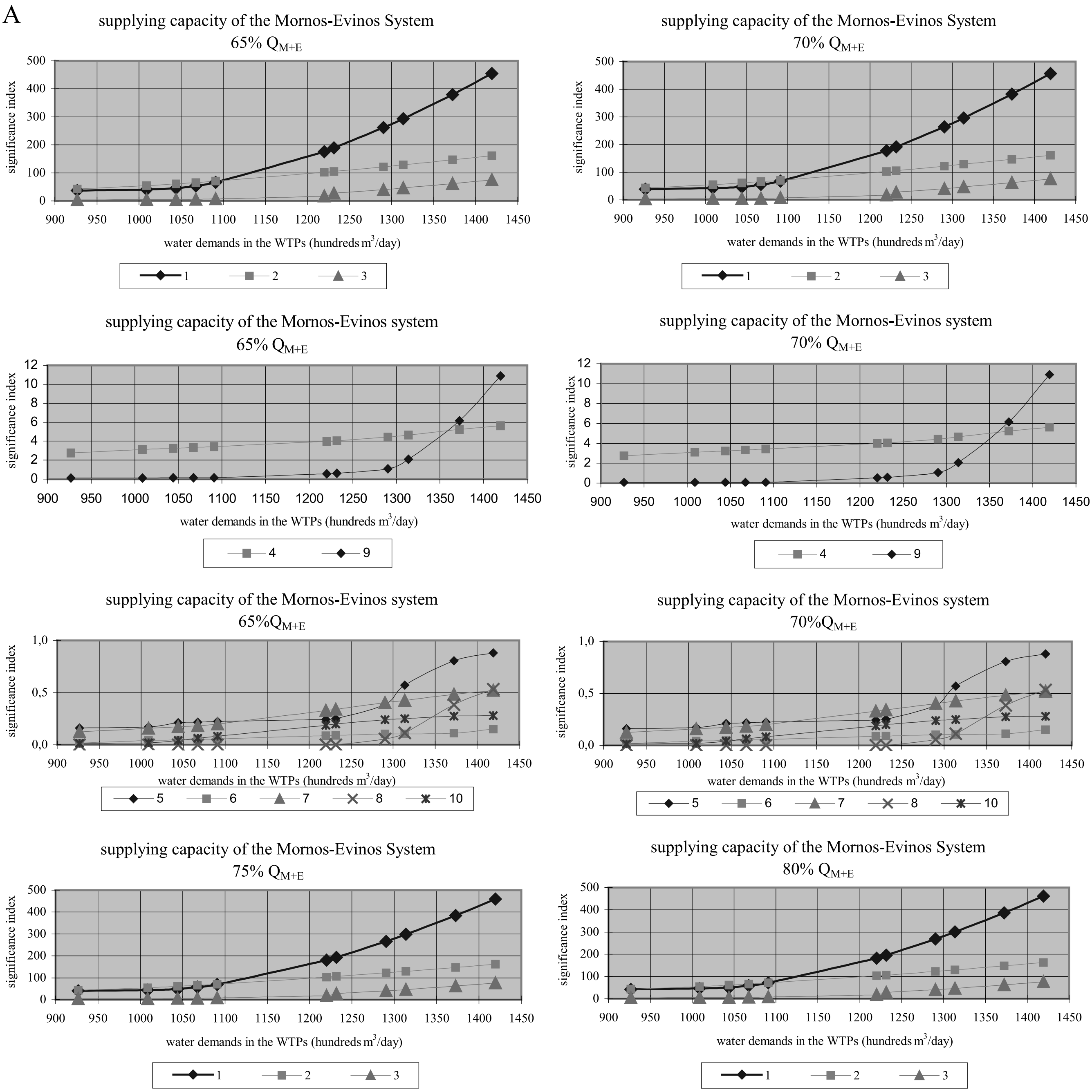

Figure 9 | A. Significance Index (hierarchical analysis of the failing parts).

methodology, the preventive maintenance work must begin when the system's Vulnerability Index (V_I) takes its minimum value. As this index expresses the significance level of the failures occurring in the system parts during any of its operating scenarios, it is calculated from

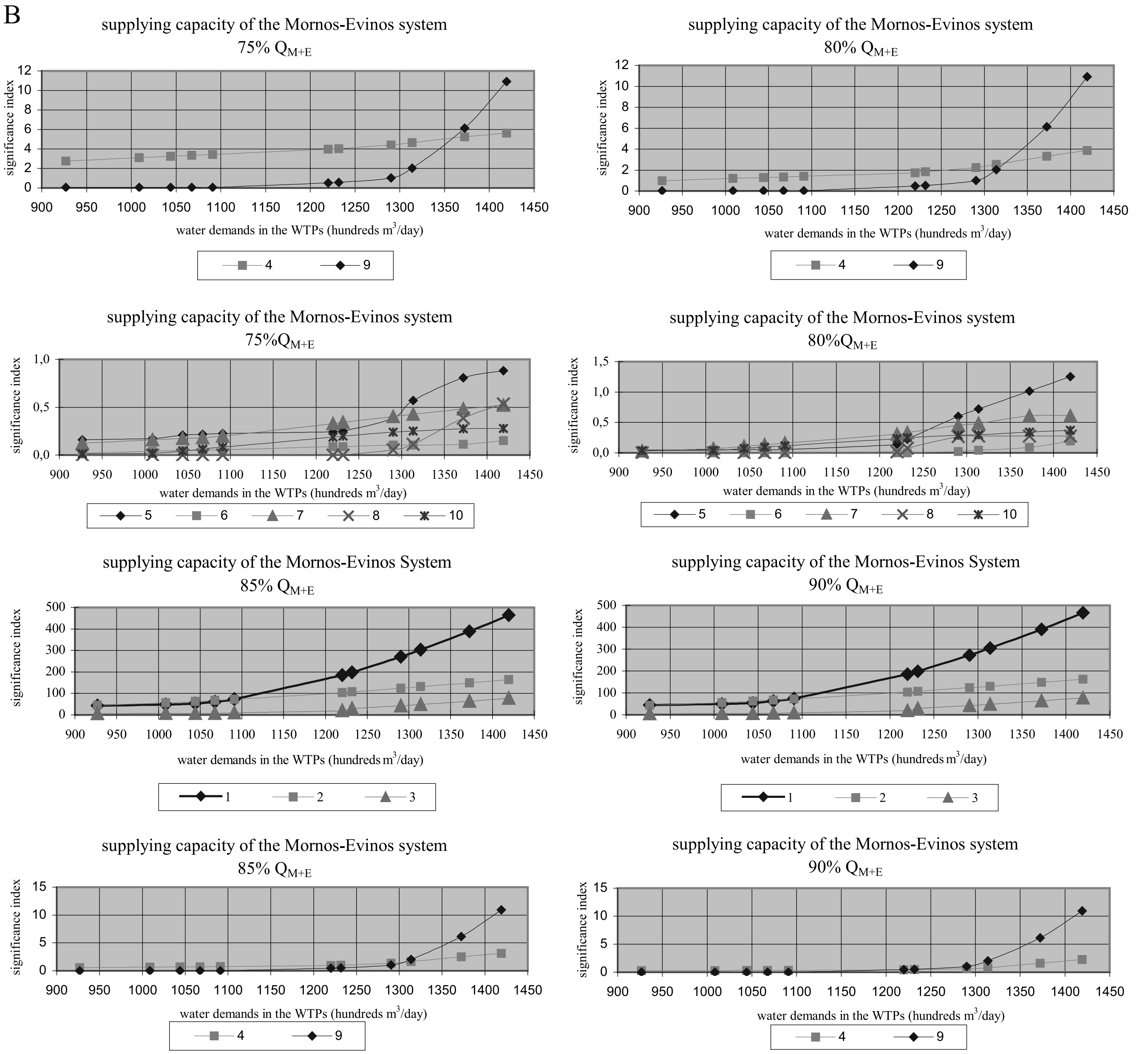

Figure 9 | B. (continued).

$$V_1 = \sum_{i=1}^{k} V_{Si}$$

where k is the number of the system parts and V_{Si} is the Significance Index of part (i) for the specific operating scenario. Figure 10 reveals that the vulnerability of the Athens network increases as the water demands grow in the plants and mostly depends on the Mornos–Evinos water supplying capacity, due to the fact that 99% of the V_{I} value expresses the effect of the Significance Indices of parts 1, 2, 3 and 9 (responsible for 64, 23, 10.5 and 1.5% of the V_{I} value, respectively), whose values follow the same trend.

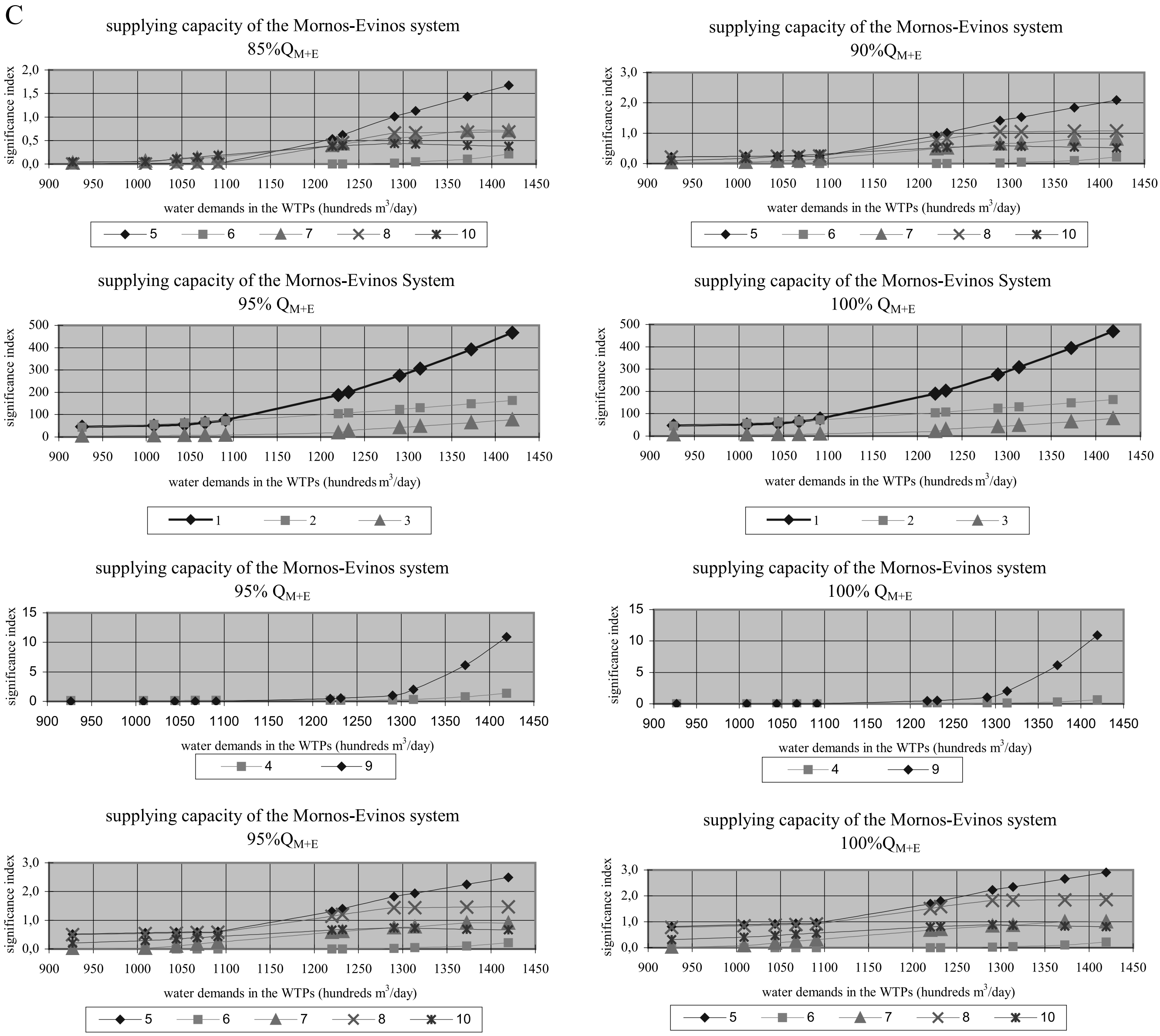

Figure 9 | C. (continued).

PREVENTIVE MAINTENANCE: EMPIRICAL VS SIGNIFICANCE BASED POLICY

Review of the preventive maintenance work empirically performed in the Athens water supply system

In order to get a full view of the preventive maintenance works in the Athens system, a brief presentation of the policy applied and the costs involved is necessary. Since 1981, EYDAP has kept detailed data records regarding the preventive maintenance work performed. Table 12 presents the characteristics of the preventive maintenance work that took place in the various kinds of Athens water supply mains, based on the valuable experience of the workgroups. Analytically, Table 12 presents the values of

Table 11 | Hierarchical analysis (ranking) of the trouble-causing sections of the Athens network.

Part	Hazard Index	Probability Index	Significance Index
1	2	1	1
2	1	6	2
3	3	5	3
4	10	2	5
5	6	3	6
6	9	7	10
7	5	10	8
8	8	4	7
9	4	8	4
10	7	9	9

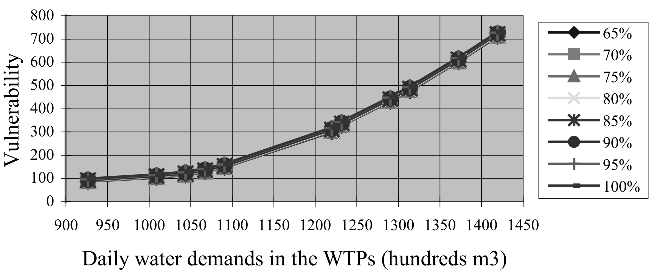

Figure 10 | The vulnerability of the Athens network.

the basic parameters of the preventive maintenance work, which are the rate (in km/d) and the present value of the cost (in Euro/km) of the maintenance work for each kind of water supply main that can be inspected and repaired by the workgroups available and finally the frequency of the maintenance works (how often these works must take place).

From 1981 to 1990 the preventive maintenance work strictly followed the 'rules' presented in Table 12. The details of the annual preventive maintenance of each trouble-causing part of the network (as identified in the

Table 12 | Characteristics of the preventive maintenance policy applied in Athens.

	Maintenance cost (Euro/km)	Maintenance rate (km/d)	Frequency of maintenance work
Channels	2,934.70	3	Every year
Siphons	2,934.70	3	Every year
Tunnels	8,804.11	1	Every five years
Pipes	5,869.41	1.5	Every year

present study: see Table 6) are presented in Table 13. Table 13 also presents the annual depreciation cost of each part. This cost is based on the replacement cost (Table 2) and the optimal replacement time of each water supply main (channels, 70 years; siphons, 70 years; tunnels, 100 years; pipes, 70 years) (Walski & Peliccia 1982). Unfortunately, since 1991, time and budget restrictions forced EYDAP to prioritize the maintenance work. As the priority criteria used were completely empirical, the timing and location of each maintenance work were not determined by a sophisticated hierarchical analysis of the trouble-causing parts of the network. The records provided revealed that preventive maintenance was focused on section 1, which developed the most trouble-causing behaviour due to structural instability and leakage problems (EYDAP 2001). The duration of the maintenance work for section 1 followed a declining rate due to the increase of the annual water needs and the decrease of the natural inflows to the water resources.

Comparing the empirical to the significance based management of the preventive maintenance work

Table 14 presents what should have (column 2) and what indeed took place (column 3) regarding the empirical based planning of the preventive maintenance work in the Athens network from 1991 to 2000. The ranking of the maintenance empirical priorities (column 5) derives from the efficiency of the work (column 4). This ranking can be compared with the respective one based on the value of

Table 13 | Characteristics of the preventive maintenance works in Athens (1981–1990).

Part of the network ⇒		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
Length of the channels	m	80,294	12,302	17,249	23,385	0,365	0	0	5,720	0	0	**139,385**
Days of maintenance per year		26.8	4.1	5.7	7.8	0.1	0	0	1.9	0	0	**46.4**
Annual maintenance cost	Euro	235,639	36,103	50,621	68,628	1,071	0	0	5,720	0	0	**397,782**
Annual depreciation cost	Euro	1,683,137	257,875	361,576	490,201	7,651	0	0	40,857	0	0	**2,841,297**
Length of the siphons	m	5,690	812	773	7,500	1,350	0	0	5,180	.0	.0	**21,305**
Days of maintenance per year		1.9	0.3	0.3	2.5	0.5	0	0	1.7	0	0	**7.2**
Annual maintenance cost	Euro	16,698	2,383	2,269	22,010	1.350	0	0	5,180	0	0	**49,480**
Annual depreciation cost	Euro	119,393	17,021	16,202	157,215	3,962	0	0	37,000	0	0	**350,743**
Length of the tunnels	m	59,880	11,099	0	3,000	9,325	0	8,400	0	15,786	0	**107,490**
Days of maintenance per year		12.0	2.2	0	0.6	1.9	0	1.7	0	3.2	0	**21.8**
Annual maintenance cost	Euro	105,438	19,542	0	5,282	16,420	0	14,791	0	27,796	0	**189,269**
Annual depreciation cost	Euro	1,757,300	325,723	0	88,041	273,661	0	246,515	0	463,272	0	**3,154,512**
Length of the pipes	m	0	0	0	3,800	14,769	15,000	1,400	12,300	5,766	6,610	**59,645**
Days of maintenance per year		0	0	0	2.5	9.8	10	0.9	8.2	3.8	4.4	**39.6**
Annual maintenance cost	Euro	0	0	0	22,304	86,685	88,041	8,217	72,194	33,843	38,797	**350,081**
Annual depreciation cost	Euro	0	0	0	63,725	247,672	251,546	23,478	206,268	96,694	110,848	**1,000,231**
Total length	m	**145,864**	**24,213**	**18,022**	**37,685**	**25,809**	**15,000**	**9,800**	**23,200**	**21,552**	**6,610**	**327,755**
Total days of maintenance per year		**40.7**	**6.6**	**6.0**	**13.4**	**12.3**	**10**	**2.8**	**11.8**	**7.0**	**4.4**	**115**
Total annual maintenance cost	Euro	**357,775**	**58,026**	**52,890**	**118,224**	**105,526**	**88,041**	**23,008**	**83,094**	**61,639**	**38,797**	**987,020**
Total annual depreciation cost	Euro	**3,559,830**	**600,619**	**377,777**	**799,182**	**532,946**	**251,546**	**269,993**	**284,125**	**559,966**	**110,848**	**7,346,832**

Table 14 | Preventive maintenance policy (1991–2000: empirical vs significance based).

Section	Empirically based necessary days of preventive maintenance work (Table 13)	Days of preventive maintenance work actually performed (EYDAP records)	Efficiency of maintenance (%)	Empirical hierarchical analysis ranking	Significance based hierarchical analysis ranking (Q_{M+E}=75%, ΣQ_{WTP}=1,000,000 m^3/d)
(1)	(2)	(3)	(4) = (3)/(2)	(5)	(6)
1	407	346	85.0	1	2
2	66	53	80.3	2	1
3	60	40	66.7	3	3
4	134	60	44.8	4	4
5	123	28	22.8	7	6
6	100	20	20.0	10	8
7	28	7	25.0	6	7
8	118	25	21.2	9	10
9	70	28	40.0	5	5
10	44	10	22.7	8	9

each part's significance index (column 6), considering that for the period 1991–2000: (a) the mean annual water supplying capacity of Mornos–Evinos was 75% of optimal and (b) the mean annual water demands were 365 million m^3.

Comparing the basic conclusions of both management approaches:

- The Mornos Aqueduct is the most significant part of the network as its three sections (1, 2 and 3) take the first three places in both rankings. Actually, according to the significance based ranking, sections 1 and 2 share the first place (Figure 9).
- Experience showed that the maintenance work used to take place from November to April each year. This is the period of lowest water demand (Table 4). This is also the period when the system's vulnerability index takes its smallest value.

Both management approaches (empirical and significance based) resulted in the same conclusions regarding the time and location of the maintenance work. This convergence can be used to certify their adequacy, as it is well known that the experience of the workgroups usually provides the best-justified criteria.

THE BENEFITS FROM IMPLEMENTING THE SUGGESTED METHODOLOGY

The methodology suggested was applied in the Athens water supply system and successfully:

- determined the system's minimum operating cost regarding the cost of water intake, water supply and water losses, both under normal and abnormal operating conditions,

- determined the significance of a failure incident, occurring in each one of the system's individual parts, based on its impact on the system's daily operating cost,
- hierarchicallu spatially analyzed the system's parts based on the value of their Significance Index,
- determined the most appropriate time for the preventive maintenance work to begin.

In conclusion, the methodology can be used to assist a water utility plan its preventive maintenance policy for a specified time period (e.g. for the *N* years to come), applying the following steps:

Step 1. Estimation of the mean annual water demands in the plants for the specified time period of the *N* following years, based on their annual growth rate derived from appropriate forecasting models.
Step 2. Calculation of the monthly water demands based on the mean annual value, using the factors of the monthly demand distribution (monthly demand factor—MDF).
Step 3. Estimation of the annual water supplying capacity of each water resource for the *N* years to come, using appropriate hydrologic models.
Step 4. Cost-based optimization of the system's monthly operation, considering the water demands in the plants and the water resources supplying capacities, using the system's simulation model.
Step 5. Determination of the system's mean daily operating cost for each month using the system's model.
Step 6. Cost-based optimization of the system's monthly operation under abnormal operating conditions (failure incidence in each one of the system's parts), using the system's simulation model.
Step 7. Determination and quantification of the impacts on the system's daily operating cost of each one of the above-mentioned failures (Hazard Index V_C).
Step 8. Probability analysis of the above mentioned failures for the specified time period of the *N* following years based on the Dynamic Analysis Method (Probability Index V_R).
Step 9. Calculation of the Significance Index (V_S) of each one of the system's parts for each month.
Step 10. Calculation of the annual Significance Index of each one of the system's parts (the sum of the respective monthly values calculated in the previous step).
Step 11. Hierarchical spatial analysis of the system's parts based on their Annual Significance Index values.
Step 12. Determination of the value of the system's Vulnerability Index (V_I) for each month of the case study year. The annual value of the index determines the optimal time for the maintenance works to begin.

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