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Technical Communication:

Modeling the Athens Water Supply System

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Abstract. This paper presents an investigation of a real-world water-resources problem involving both planning and management aspects. The Athens water supply system is studied in order to assist its future operation and the design of alternative system-improving works. The yield of the existing system is first assessed via simulation. Then the risk of system failure to meet the water demand is evaluated for various water demand scenarios and operation policies, with emphasis on the 1989–90 critical situation. Alternative future reservoirs in the Evinos River Basin are studied by testing large number of technical solutions. Uncertainties on hydrology, leakage losses, water demand, and possible damages are taken into account. Finally, a computer programme is developed to assist the water supply policy design for the existing Mornos-Iliki system.

Key words. Athens water supply, reliability, operating rules, safety storage, hydrological simulation, reservoir design, policy analysis.

1. Description of the System

The existing water supply system of Greater Athens which is studied in this paper, is comprised of two basic water resources. The first one is the Mornos River about 200 km west of Athens and the second is Lake Iliki which constitutes the lowest part of the Boeotic Kifissos River Basin (see Figure 1). Lake Iliki suffers from considerable leakage losses reaching up to 50% of its total annual inflow depending on the abstraction policy. This is due to the karstic background of the lake through which the stored water is discharged to various sources and the neighbouring Lake Paralimni. Additional water resources include the Assopos River and some aquifers in Boeotia and Attica Districts.

The two main storage reservoirs are the Mornos Reservoir and Lake Iliki and the smallest Marathon Reservoir near Athens which is mainly used for safety purposes. Water is conveyed to Athens through Mornos Aqueduct and Iliki Aqueduct. Lake Iliki also provides irrigation water to the Kopais Plain. Some technical characteristics of the above works are shown in Table I.

The proposed future water supply system encompasses, besides the existing Mornos-Iliki subsystem, one reservoir in the Evinos River Basin and a connection tunnel carrying water to the Mornos Reservoir. Three alternative dam sites are studied: Perista, Ag. Dimitrios and Dendrochori. The effect of a regulating reservoir

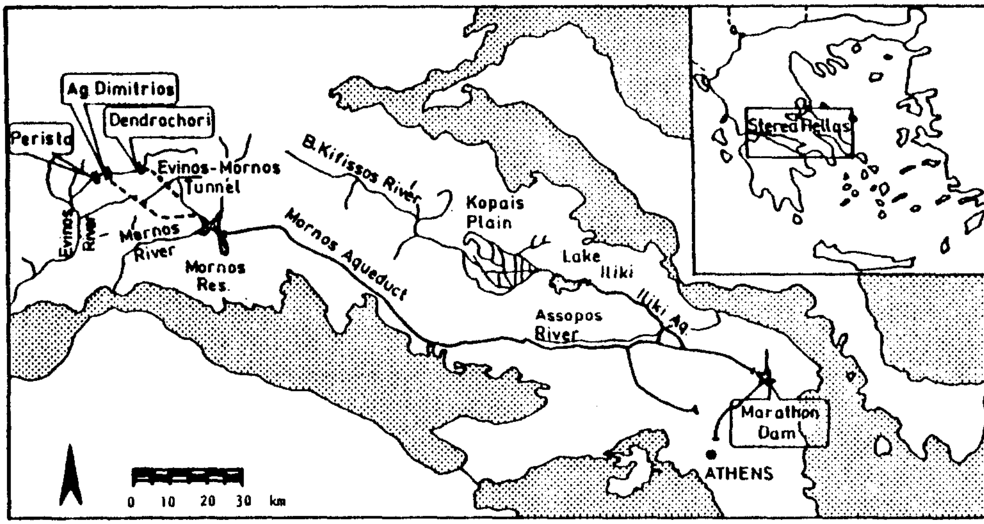

Fig. 1. General layout of the Athens water supply system.

Table I. The Athens water supply system-Main works

	K (10^6 m^3)	C (m^3/s)	L (km)
Mornos Reservoir	643	23.0[a](16.0)[b]	188
Lake Iliki	587	7.5(11.0, 15.0)[c]	60
Marathon Reservoir	40.8		
Evinos Reservoir			
- Perista	199[d]	(.)[e]	30
- Ag. Dimitrios	100[d]	(.)[e]	30
- Dendrochori	252[d]	(.)[e]	14
Regulating reservoir	100[f]	7.5	

K = active storage capacity of reservoir. C = discharge capacity of aqueduct. L = length of aqueduct.
[a] Design value. [b] Maximum value achieved [c] After rehabilitation. [d] Maximum value of storage capacity tested. [e] To be estimated (see Table V). [f] Value selected for tests.

near Athens (possibly in the Assopos River Basin) along with the rehabilitation of the Iliki Aqueduct are also included in the design.

2. Historical Background

Since the construction of the Marathon Reservoir, the first water supply work in modern history of Athens, the water demand did not cease to grow at a fast rate, almost doubling every 10 years except the World War Two period. Insufficiency of the local water resources in the Greater Athens area inevitably led to the development and utilization of remote water resources through the construction of the Iliki Aqueduct in 1958 in the East Sterea Hellas Water District and subsequently

Table II. Water consumption history-Milestones

Hydrological year	Population of Greater Athens	Consumption (10^6 m^3/yr)	Observation
1927–28	802 000	5.5	Andrian Aqueduct (Roman)
1931–32		12.2	Construction of Marathon Dam
1940–41	1 124 109	22.3	
1950–51	1 378 600	22.8	Stagnation due to World War Two
1960–61	1 852 709	69.6	Full operation of Iliki Aqueduct constructed in 1958
1970–71	2 540 241	140.7	
1980–81	3 027 331	275.1	Commencement of operation of Mornos Aqueduct
1988–89	3 370 000[a]	366.8 (438.6)[b]	Combined operation of Mornos Reservoir and Lake Iliki

[a] Estimated value. [b] Including losses from the conveyance works.

the Mornos works in the West Sterea Hellas Water District. The construction of all the above works was always preceded by a period of crisis with a high risk of severe water shortage. The main feature of the existing Mornos-Iliki System management is the need for the pumping of water from Lake Iliki while the Mornos Aqueduct operates by gravity. The ensuing cost difference between the two sources has to be taken into account by the system operator together with the substantially different leakage loss rates from the two reservoirs.

During the 1981–87 period abstractions were mainly made from the Mornos Reservoir. Subsequently, this policy changed and a combined operation of the Mornos and Iliki reservoirs is currently made. This change was supported by the research described in this paper and the results were quite satisfactory especially during the recent 1989–90 extremely dry year with an annual runoff for B. Kifissos Basin less than 20% of the annual mean. This severe drought, together with the prior overexploitation of the Mornos Reservoir during the 1985–87 period, led the system to a particularly critical state that had to be faced only by additional measures both on demand and resources.

Milestones of the Athens water supply history are given in Table II together with the associated population and amount of consumed water.

3. Modeling of Hydrological Variables

The analyses were carried out through simulation (Loucks, 1976, p. 63) which was preferred to optimization for the following reasons: (a) the system, especially in its future configuration, is rather complex, (b) a detailed hydrological modeling is required due to considerable over-year regulation and the high values of system reliability being sought, (c) the main objective was to maximize the system yield and this was relatively an easy task considering the special features of the system, e.g. the leakage losses of Lake Iliki as compared to those of Mornos Reservoir, (d) the

Table III. Historical sample statistics of hydrological variables[a]

	Evinos (Perista)			Mornos			Iliki + B. Kifissos		
	Q	R	E	Q	R	E	Q	R	E
N	20	26	18	19	26	18	23	34	32
m (mm)	920.9	1463.3	1285.7	573.0	1504.3	1309.0	47.4 +165.8	466.4	1363.8
m (10^6 m^3)	361.9			319.4			20.0 +333.3		
s (mm)	318.2	262.3	103.3	139.8	236.2	54.1	57.6	91.3	58.9
r_1	0.17	0.00	0.26	0.03	0.00	−0.06	0.00	0.00	0.01
RC		0.63			0.38			0.10&0.25	
S (km^2)		393.00			557.5			422.0&2010.0	
H (m)		1175			1082			201.4	

Q = runoff. R = rainfall. E = Penman lake evaporation. N = sample size. m = mean. s = standard deviation. r_1 = lag-1 autocorrelation coefficient. RC = runoff coefficient. S = watershed area. H = watershed mean altitude.

[a] Estimations referred to annual series.

need for accurate estimation of the incremental system yield related to various system schemes and measures excluded any technique involving state-space discretization.

The hydrological simulation was carried out in two stages. In the first stage a multisite Markovian stochastic model is used to generate annual time series at all reservoir locations (Matalas and Wallis, 1976). Then, the annual values are disaggregated into monthly values through a Markovian dynamic disaggregation model (Koutsoyiannis and Xanthopoulos, 1990a). A simultaneous generation of rainfall and runoff series is made while Penman lake evaporation series are obtained independently. With the above two-stage modeling scheme a simultaneous preservation of both annual and monthly sample statistics is achieved. This was absolutely indispensable for a system with substantial over-year storage requirements.

Analysis of the historical time series revealed a significant linear decreasing trend in the B. Kifissos hydrological variables since 1920. It is noteworthy that this trend appears in all variables (rainfall, runoff and evaporation). In further analyses this trend was removed with reference to the 1987–88 level which is a rather conservative assumption. The historical sample statistics preserved by the above two models, both on annual and monthly basis, can be grouped as follows: (a) statistical moments up to order 3 (means, variances, coefficients of skewness), (b) lag-one autocorrelation coefficients, (c) lag-zero cross correlation coefficients. A presentation of these statistics on an annual basis is made in Table III. The gamma distribution function was suitable for rainfall and runoff while evaporation was found to be Gaussian. In both cases the distribution functions were preserved. It should be recalled that the preservation of the above statistics implies that no climatic change is anticipated in future system operation.

4. Modeling of System Operation

The system operation model was formed by the following:

- *Water balance equations* for each storage element.
- *One main water use* namely the domestic, municipal and industrial use in Greater Athens.
- *Irrigation of Kopais Plain* with abstractions from Lake Iliki.
- *Physical constraints* like finite reservoir storage capacities and finite aqueduct discharge capacities.
- *Modeling of the leakage losses* of Lake Iliki as a nonlinear function of stage with addition of a random component. For Mornos Reservoir a linear function was found to be adequate.
- *Operational constraints* such as maintenance of safety storage volumes and consideration of leakage losses from the reservoirs. A safety storage volume is always kept in Lake Iliki to cover the Athens future water demand for a period of 3 months in case of damages in the Mornos Aqueduct. Furthermore, additional safety storage volumes are kept in Lake Iliki to cover irrigation water demand from Kopais Plain for the whole irrigation period.
- *System operating rules.* In the absence of a direct optimization technique the construction of the system operating rules was based on some special characteristics of the system such as: (a) the leakage losses of Lake Iliki greatly exceed those of Mornos Reservoir and they increase very rapidly with stage in a nonlinear manner; this implies that the system yield maximization can be attained by maximizing withdrawals from Lake Iliki, (b) the storage of water is preferable as close to Athens as possible, (c) the main storage element of the Mornos-Evinos subsystem is the Mornos Reservoir due to topographical conditions in Evinos River Basin not allowing for the construction of a large reservoir. The alternative rules laid out and tested are the following:

  (A) Abstractions from Lake Iliki have always the highest priority.
  (B) Alternative priority of abstraction from each of the Mornos-Evinos and Iliki subsystems is dynamically dependent on the availability of water indicated by the Mornos reservoir stage. The value of the threshold at Mornos Reservoir which determines the change of priority from Iliki to Mornos when exceeded, was subjected to indirect optimization (Nalbantis, 1990).

- *Calculation of the system reliability* α or probability of failure $\alpha' = 1 - \alpha$ to meet the water demand given by the following alternative indices (Dyck, 1990, p. 425):

  α_1 = (number of years without failure)/(total number of years),

  α_2 = (number of months without failure)/(total number of months),

α_3 = (total amount of water obstracted)/(total amount of water demanded).

To assist the rational management of the existing water supply system an integrated software package was designed and entirely developed using Pascal programming language. The components of the package are the following:

- A user friendly man-machine interface programme.
- Hydrological simulation programme.
- Operation simulation programme.
- Files containing historical sample statistics and reservoir data.

5. Operation of the Existing Water Supply System

The sole objective was the maintenance of the system's reliability at a very high level to ensure that the system would meet its critical situation. The criterion of reliability for various future water demand scenarios and possible management measures was investigated on a year-by-year basis with the aid of the models described in the preceding paragraphs. The acceptable reliability α_1 is set at 99% for the normal system operation and 99.8% when emergency measures are applied (Koutsoyiannis and Xanthopoulos, 1990b). A detailed data analysis was made on population growth, water supply network expansion, domestic, municipal and industrial consumption and water losses in the distribution network and the main aqueducts (Aftias *et al.*, 1990). As a result, three alternative scenarios of future water demand for the time horizon of 2010–11 were shaped and a linear increase for the period 1989–

Table IV. Computer runs for operation policy evaluation

Computer run	Policy	Water demand		Additional inputs (m^3/day)
		1990–91	2010–11	
A	EP	370[a]	600	215 000[c]
B	EP	370	600	100 000[c]
C	EP	370	600	0
D	EP	370	600	150 000[d]
E	NP	385[a]	500	0
F	NP	385	600	0
G	NP	385	720	0
H	NP	457[b]	600	0

EP = State of Emergency Policy. NP = Normal Operation Policy.
[a] Expected demand after adoption of restrictive measures (difference due to time lag in the analyses).
[b] Expected demand in case of no imposition of measures.
[c] Input entering throughout the year.
[d] Input entering only during the September-to-March period and initial conditions updated with respect to A, B, C.

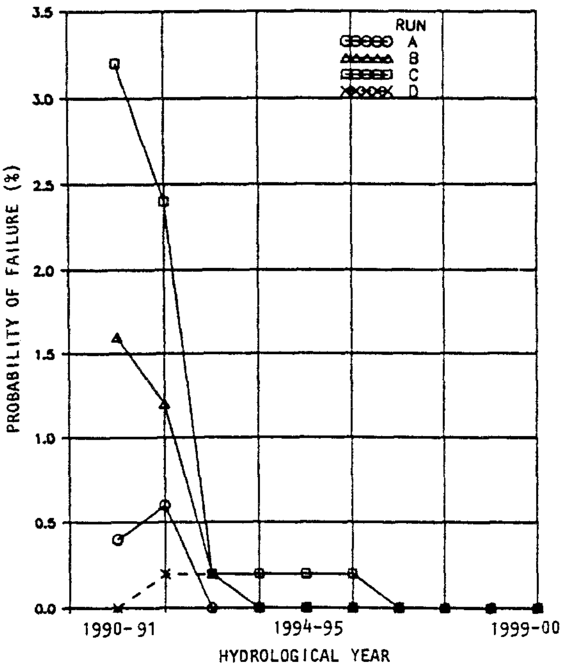

Fig. 2. Probability of failure for the state of emergency policy of the existing system.

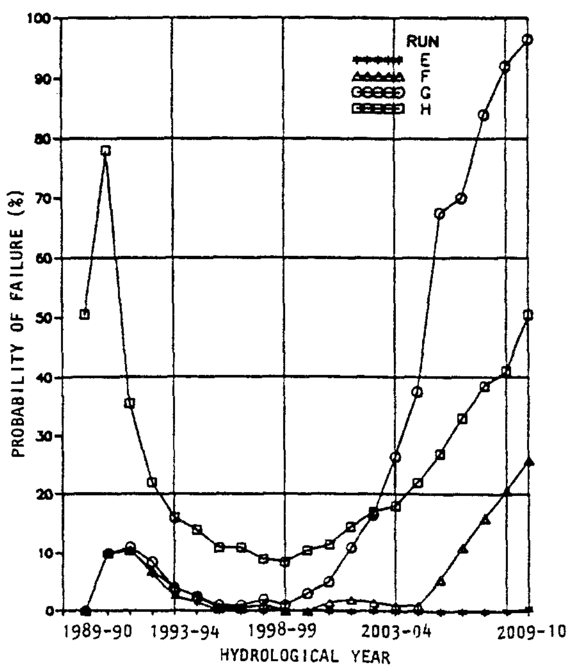

Fig. 3. Probability of failure for the normal operation policy of the existing system.

90 to 2010–11 was assumed. These scenarios correspond to a 2010–11 total annual demand of 500 (lower limit), 600 (average estimation) and 720×10^6 m^3 (upper limit).

The various measures studied can be grouped as follows: (i) reduction of water demand due to water pricing and appropriate campaign for water saving, (ii) restrictions imposed on water allocated to Kopais Plain, (iii) abstractions from the reservoirs dead storage volume, (iv) additional sources entering the system such as ground-water or water carried by tankers.

Two distinct system operation policies were considered in the analysis: (a) the Normal Operation Policy and (b) the State of Emergency Policy. In the normal operation the effects of the reduction of the current water demand is tested and the system response to the three water demand scenarios is evaluated while no other measures are assumed. In the State of Emergency Policy conjunctive use of measures (ii), (iii) and (iv) is considered and the resulting reduction of shortage risk is evaluated. The various computer runs are further explained in Table IV and the results are shown in Figures 2 and 3. It can easily be seen that in the absence of measures the system failure was almost certain while demand restriction measures increases reliability to 90% for the 1990–92 period which is also unacceptable. Until the system recovers, as it is possible, additional inputs are needed to reduce probability of failure down to 1:500.

6. Design of Evinos Works

The objective of the planning analyses was to obtain for each alternative scheme the corresponding system yield maximized through appropriate selection of the

Table V. Mornos-Evinos System yield for various alternative Evinos works for a 99% reliability

Dam site	$K(10^6\ m^3)$	C^* (m^3/s)	Mean annual yield (10^6 m^3)		δ(%)
			Total	Evinos Res.[a]	
Dendrochori	50	10	445	165	80.3
	100	8	449	169	81.0
	150	6	453	173	81.7
	252	6	461	181	83.2
Ag. Dimitrios	50	16	497	217	77.6
	100	12	503	223	78.5
Perista	50	16	515	235	75.6
	100	12	529	249	77.6
	150	12	535	255	78.5
	199	10	541	261	79.4

K = active storage capacity of Evinos Reservoir.
C^* = selected final values of the discharge capacity of the Evinos-Mornos connection tunnel.
δ = level of the system development (= mean annual yield / mean annual inflow).
[a] Contribution of the Evinos Reservoir to the system yield.

Table VI. Yield of various alternative water supply schemes for a 99% reliability

Water supply scheme	K (10^6 m^3)	C (m^3/sec)			Mean annual yield (10^6 m^3)		
		Mornos-Athens	Evinos-Mornos	New Iliki Athens	Total	Incremental	
						A	B
Mornos (stand alone)	–	18.5 or 23.0	–	–	280	0	–
Iliki (stand alone)	–	–	–	0 or 3.5 or 7.5	151	–	–
Mornos + Iliki	–	18.5 or 23.0	–	0	461	181	0
	–		–	3.5	475	195	14
	–		–	7.5	476	196	15
Mornos + Dendrochori	50	23.0	10.0	–	445	165	–
	252	18.5 or 23.0	6.0	–	461	181	0
Mornos + Ag. Dimitrios	50	23.0	16.0	–	497	217	36
	100	23.0	12.0	–	503	223	42
Mornos + Perista	50	23.0	16.0	–	515	235	54
	199	23.0	10.0	–	541	261	80
	199	18.5	10.0	–	475	195	14
Mornos + Dendrochori + Regulation	252	18.5 or 23.0	6.0	–	469	189	8
Mornos + Perista + Regulation	199	23.0	10.0	–	557	277	96
	199	18.5	10.0	–	555	275	94
Mornos + Dendrochori + Iliki	252	18.5 or 23.0	6.0	–	631	351	170
Mornos + Perista + Iliki	199	23.0	10.0	–	715	435	254
	199	18.5	10.0	–	668	388	207
Mornos + Dendrochori + Iliki + Regulation	252	23.0	6.0	7.5	667	387	206
	252	18.5	6.0	7.5	658	378	197
Mornos + Perista + Iliki + Regulation	199	23.0	10.0	7.5	750	470	289
	199	18.5	10.0	7.5	687	407	226

K = active storage capacity of alternative Evinos reservoirs.
C = discharge capacity of aqueducts.
A = with respect to Mornos Reservoir.
B = with respect to the Mornos-Iliki subsystem.

system operating rule. The design parameters studied through simulation are for each alternative dam site (Perista, Ag. Dimitrios, Dendrochori), the active capacity of the Evinos Reservoir and the discharge capacity of the Evinos-Mornos connection tunnel. As mentioned before, the Evinos River Basin relief precludes the construction of large reservoirs. In fact, the largest value for the Evinos reservoir active capacity was 250×10^6 m^3 which is small if paralleled to Mornos reservoir (643×10^6 m^3). The problem is solved by using the Mornos reservoir as the main storage element of the Evinos-Mornos system thus imposing the use of the whole Evinos-Mornos system in the design. Seventy combinations of works were tested and the most promising of them are presented in Table V. In this table for each combination of storage capacity and tunnel discharge capacity the system yield that corresponds to 99% reliability is given. It should be noted that the final values of Evinos-Mornos tunnel discharge capacity were selected in such a way that they do not cause a reduction of the system yield, as compared to the infinite discharge capacity case, greater than 2% of the mean annual inflow.

Besides the design of the Evinos works, the entire Evinos-Mornos-Iliki system was analyzed and the contribution of a regulating reservoir near Athens (possibly in the Assopos River Basin) with an active storage capacity of 100×10^6 m^3 was assessed. Finally, a sensitivity analysis as to the Mornos Aqueduct discharge capacity was carried out to check the assumptions on this parameter whose value is actually unknown. The results of the analyses are shown in Table VI.

7. Conclusions

The Athens water supply system was studied using a simulation technique involving two-step hydrological simulation and a detailed representation of the system operation. Multivariate stochastic models were applied to generate synthetic time series with a length up to 5000 years. In the operation modeling several important features and uncertainties of the system were addressed such as reservoir operating rules, safety issues, modeling of reservoir leakage losses especially for the karstic Lake Iliki. The main objective was to optimize the system reliability-yield relationship without involvement of economic or other objectives. Hence, no economic analysis was undertaken.

It was estimated that the existing Mornos-Iliki system yields 461×10^6 m^3/yr for an $\alpha_1 = 99\%$ reliability level. Measures for economizing water were necessary to cope with the 1989–90 severe drought and the enrichment of the system's resources appeared useful. The system's critical state in 1990–91 is expected to improve, provided that the water demand restrictive measures are not abandoned and no climatic change occurs.

The Evinos works increase the system annual yield by 165×10^6 m^3/yr to 261×10^6 m^3/yr and among the alternatives studied the highest dam at Perista was found to maximize the system's performance. The Mornos-Evinos (Perista)-Iliki system yields 715×10^6 m^3/yr thus satisfying the expected maximum water demand in 2010–

11 for the most severe scenario.

The analyses also indicated that Lake Iliki must be permanently introduced to the water supply system for two reasons: safety and maximization of the system's performance. Furthermore, the rehabilitation of Iliki Aqueduct is necessary mainly for safety reasons. As to the possible regulating reservoir near Athens its construction will be beneficial in many aspects: it will minimize leakage losses from Lake Iliki thus increasing the system yield up to 750×10^6 m^3/yr and it will permit a greater flexibility in the system operation. Finally the sensitivity analysis on the discharge capacity of Mornos Aqueduct showed that this is a critical parameter playing an important role in the future system and must therefore be accurately estimated.

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