The modern Athens water resource system and its management

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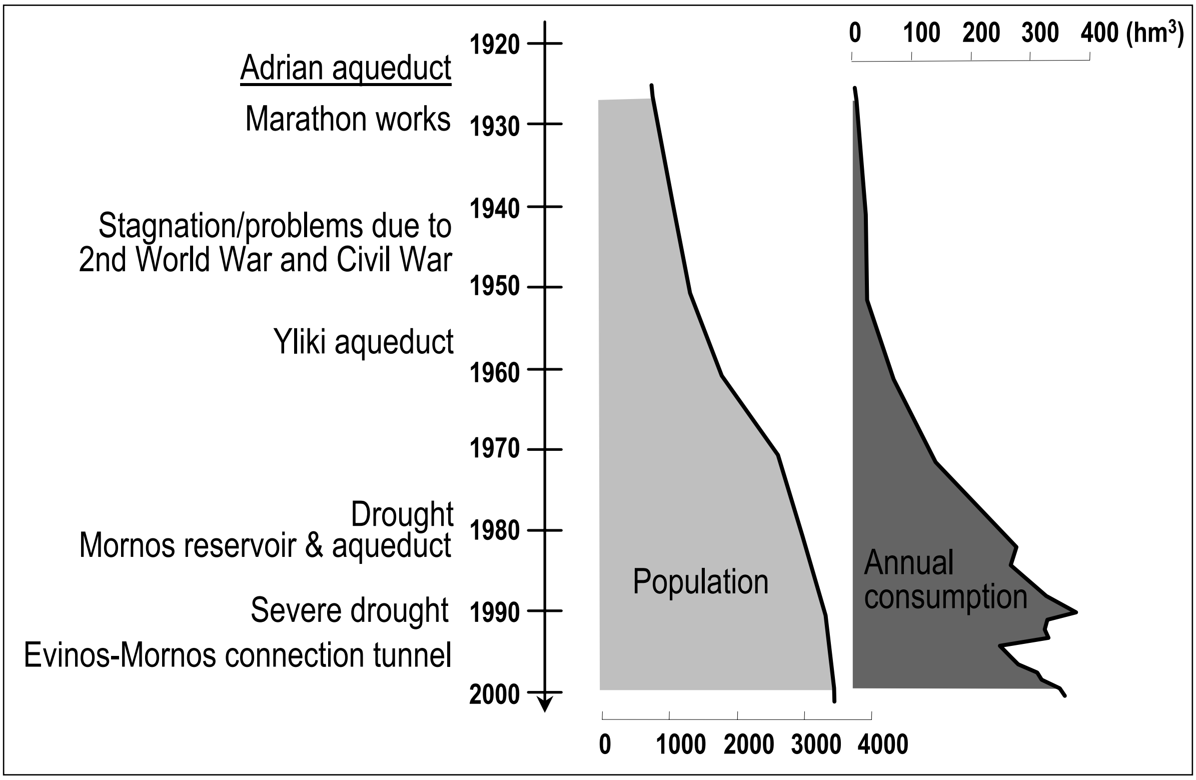
Parts of the presentation

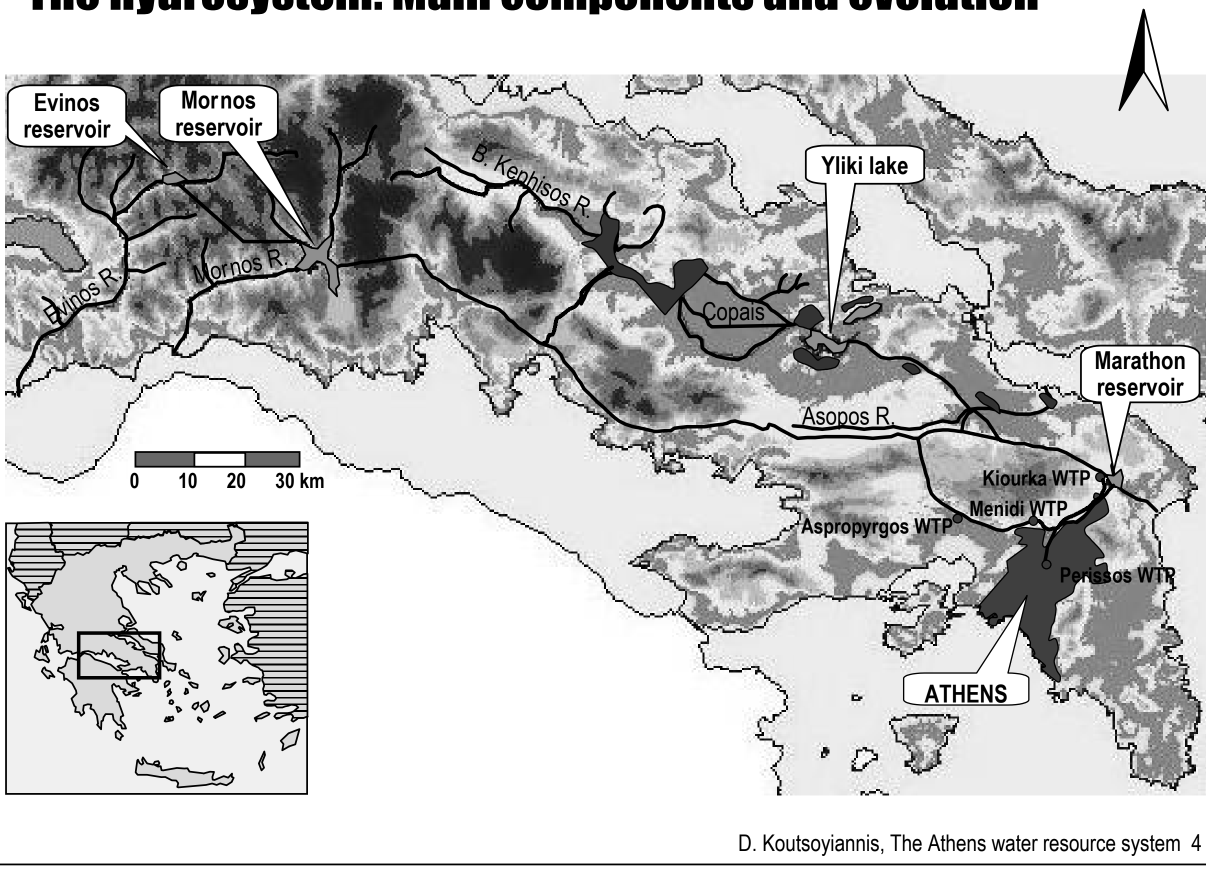
1. The modern Athens water resource system
   - History
   - Components
   - Technical characteristics

2. The methodology
   - The project
   - The decision support system
   - General methodological aspects
   - Stochastic simulation of inflows
   - Optimisation of storage allocation
   - Optimisation of water conveyance

Evolution of water consumption – Milestones



The hydrosystem: Main components and evolution

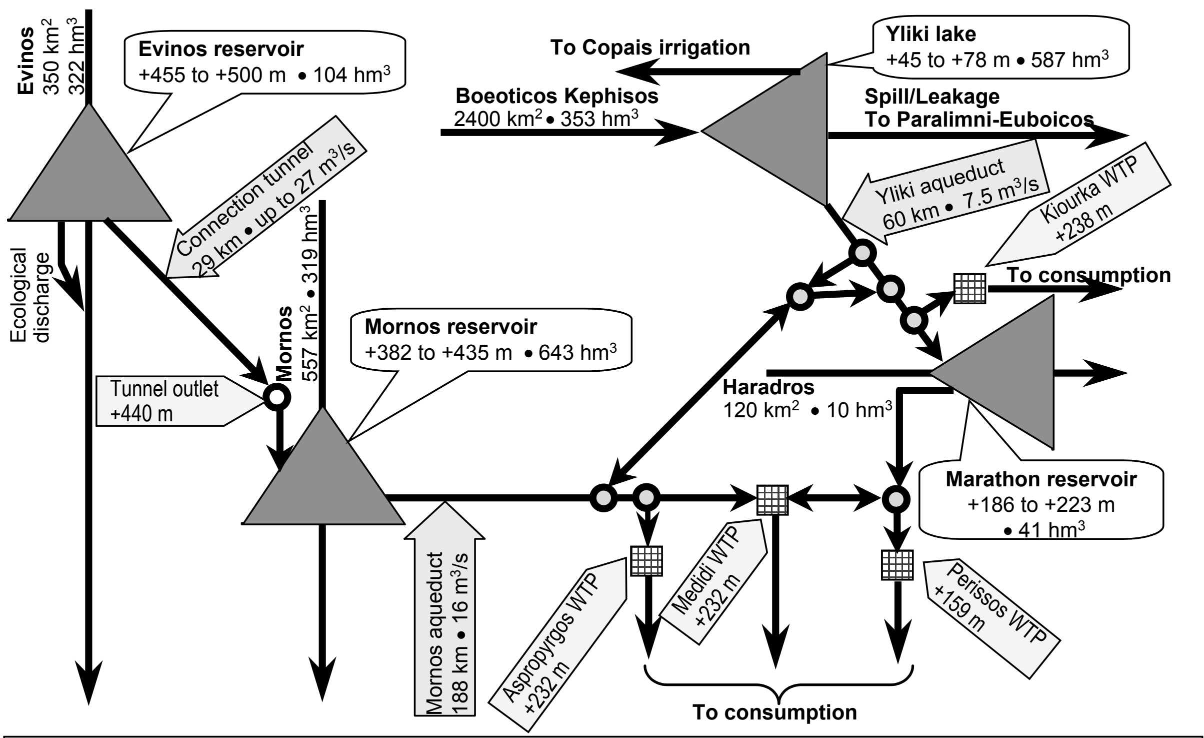


Classification of water resources

	SURFACE WATER		GROUNDWATER
Basin	Primary (Reservoirs)	Secondary (Reservoirs)	Backup (Boreholes)
Evinos 350 km^2	Evinos 322 hm^3/y		
Mornos 557 km^2	Mornos 319 hm^3/y		
Boeoticos Kifisos – Yliki 2400 km^2		Yliki 353 hm^3/y	B. Kifisos, middle course 136 hm^3/y Yliki region 85 hm^3/y
Haradros 120 km^2		Marathon 10 hm^3/y	
North Parnetha			Viliza 26 hm^3/y Mavrosouvala 36 hm^3/y

Area	Inflow	Pumping capacity	High spill	High leakage	Pumping

Hydrosystem: Current structure



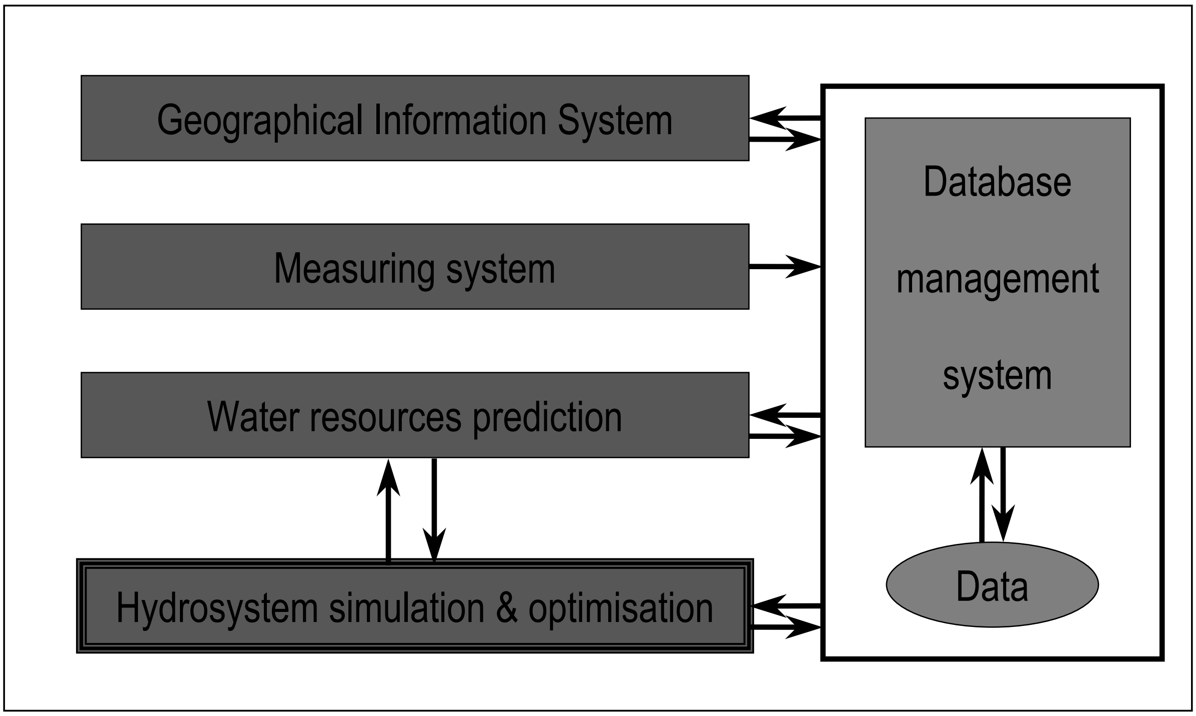
+ Boreholes (with connecting pipes) + Pumping stations + Small hydroelectric power plants

The project: *Modernisation of the supervision and management of the water resource system of Athens*

- Commissioned by the Athens Water Supply and Sewerage Company (ΕΥΔΑΠ) to the National Technical University of Athens
- Objectives:
  - Supervision
  - Measurement
  - Mathematical modelling and simulation
  - Optimisation

  of the Athens water resource system
- Project units
  1. Development of a Geographical Information System for the hydrosystem visualisation and supervision
  2. Development of the water resources telemetric measurement system
  3. Development of a computational system for the estimation and prediction of water resources
  4. Development of a decision support system for the integrated management of the system
  5. Cooperation and transfer of knowledge between NTUA and EYDAP

Decision Support System: Interconnection of modules



Typical problems to be answered

- Find the **maximum possible annual release** from the system:
  - for a certain (acceptable) **reliability level** (steady state conditions)
  - for a certain **combination of the system components** (e.g. primary resources)

  and determine the corresponding:
  - **optimal operation policy** (storage allocation; conveyance allocation; pumping operation)
  - **cost** (in terms of energy; economy; other impacts)
- Find the **minimum total cost**
  - for a given **water demand** (less than the maximum possible annual release)
  - for a certain (acceptable) **reliability level**

  and determine the corresponding:
  - **combination of the system components** to be enabled
  - **optimal operation policy** (storage allocation; conveyance allocation; pumping operation)
  - **alternative operation policies** (that can satisfy the demand but with higher cost)

Categories of problems

- Steady state problems for the current hydrosystem
  - (e.g., previous slide)
- Problems involving time
  - Availability of water resources in the months to come
  - Impact of a management practice to the future availability of water resources
  - Evolution of the operation policy for a temporally varying demand
- Investigation of scenarios
  - Hydrosystem structure: Impacts of new components (aqueducts, pumping stations etc.)
  - Demand: Feasibility of expansion of domain
  - Hydrological inputs: Climate change/Persisting drought
- Adequacy/safety under exceptional events – Required measures
  - Damages
  - Special demand occasions (e.g. 2004 Olympic Games)

The methodology: General aspects

Question 1: Simulation **or** optimisation?

- Simulation **versus** optimisation (water resources literature)
- Simulation methods **for** optimisation (more mathematical literature)

Answer: Optimisation coupled with simulation

Main advantages

- Determination of optimal policies
- Incorporation of mathematical optimisation techniques

Main advantages

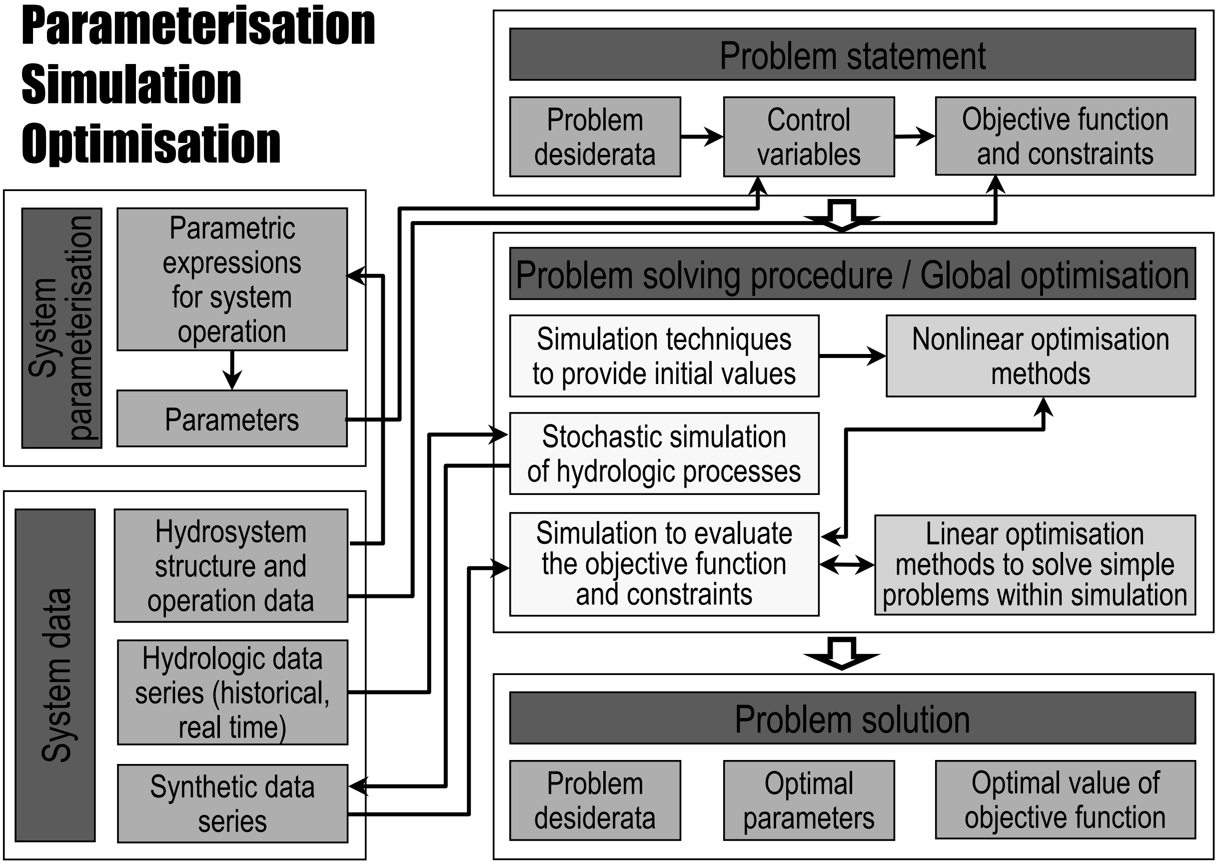
- Detailed and faithful system representation
- Better understanding of the system operation
- Incorporation of stochastic models

Question 2: Which are the control (decision) variables?

- Typically: Releases from system components in each time step

Answer: Introduction of **parametric control rules** with few **parameters** as control variables

Parameterisation Simulation Optimisation

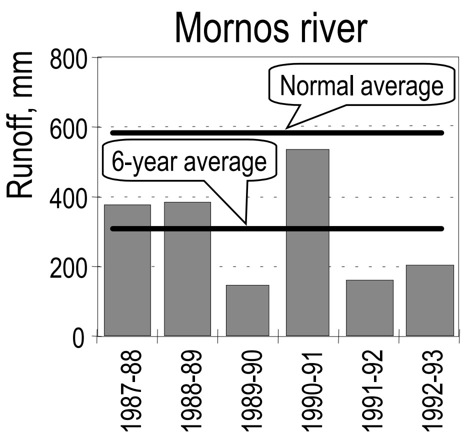


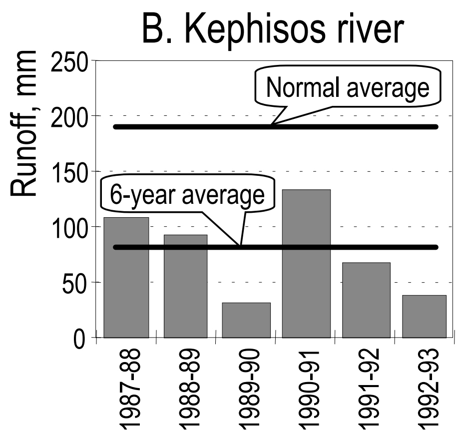
Stochastic simulation/forecasting of hydrologic processes

- Question: Why simulated series?
- Answer
  - Analytical solutions do not exist or would assume extreme oversimplification of the system
  - Detailed inflow and other (rainfall, evaporation) hydrological data are needed at many sites simultaneously and at several time scales for the system simulation
  - Historical hydrological records are too short
  - The acceptable failure probability level for Athens is of the order of 10^{-2}: one failure in 100 years on the average
  - For an reasonable estimation error in the failure probability we need 1000-10 000 years of data

Requirements for stochastic simulation

1. Multivariate model
2. Time scales from annual to monthly or sub-monthly
3. Preservation of essential marginal statistics up to third order (skewness)
4. Preservation of joint second order statistics (auto- and cross-correlations)
5. Capturing/reproduction of “patterns” observed in the last severe drought – Preservation of long-term persistence





Specification of the *Castalia* stochastic simulation software

- Module 1: Annual stochastic model
  - Preserves marginal statistics up to third order (skewness)
  - Preserves autocorrelation structure of any type (not necessarily ARMA)
  - Multivariate model – preserves cross-correlations
  - Preserves long-term persistence (Hurst coefficients of all locations)
  - Can perform in forecast mode, given the current and historical values
- Module 2: Monthly/sub-monthly stochastic model
  - Disaggregates annual series
  - Uses multivariate PAR type (seasonal) schemes as underlying models
  - Uses exact adjusting procedures to produce monthly values consistent with the annual whereas not affecting preservation of statistics
  - Preserves marginal statistics up to third order (skewness)
  - Preserves auto- and cross-correlations
  - Can perform in forecast mode, given the current and historical values
  - On the way: Sub-monthly disaggregation; Treatment of any type of autocorrelation structure

Introduction to the parametric reservoir operation rule – Some analytical solutions

Maximise release from a simple reservoir system with single water use

- Case a: no conveyance restrictions; no leakages
  - Solution: Probability of spill equal at all reservoirs (**New York Rule;** Clark, 1950)
  - Under certain (rather common) conditions about the distribution of inflows: → **Space rule** (Bower et al., 1962)

$$\frac{K_i - S_i}{E[CQ_i]} = \frac{\sum K - V}{\sum E[CQ]}$$

- Case b: no conveyance restrictions; significant leakages; insignificant spills
  - Solution: → **Leakage rule** (Nalbantis & Koutsoyiannis, 1996)

$$S_i = \begin{cases} V & \text{for one reservoir} \\ 0 & \text{for all others} \end{cases}$$

- Case c: restricted conveyance capacity; insignificant spills; no leakages
  - Solution: → **Conveyance rule** (Nalbantis & Koutsoyiannis, 1996)

$$\frac{S_i}{C_i} = \frac{V}{\sum C}$$

Notation: i = Reservoir index, K = Storage capacity, S = Storage, $V = \Sigma S$, CQ = Cumulative inflow, $E[\,]$ = expectation, C = Conveyance capacity

Formulation of the parametric reservoir operation rule

Initial linear parametric form

$S_i^* = K_i - a_i \Sigma K + b_i V$

parameters a_i, b_i such that

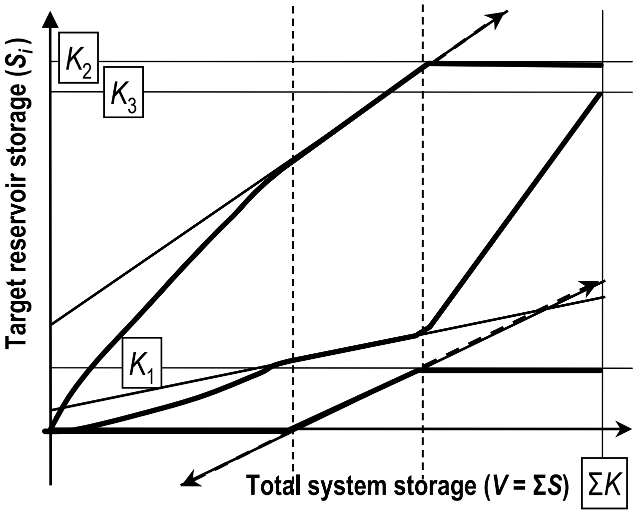
$0 \le a_i \le 1$, $0 \le b_i \le 1$

Corrected for physical constraints

$$S_i'^* = \begin{cases} 0 & K_i - a_i \Sigma K + b_i V < 0 \\ K_i & K_i - a_i \Sigma K + b_i V > K_i \\ K_i - a_i \Sigma K + b_i V & \text{otherwise} \end{cases}$$

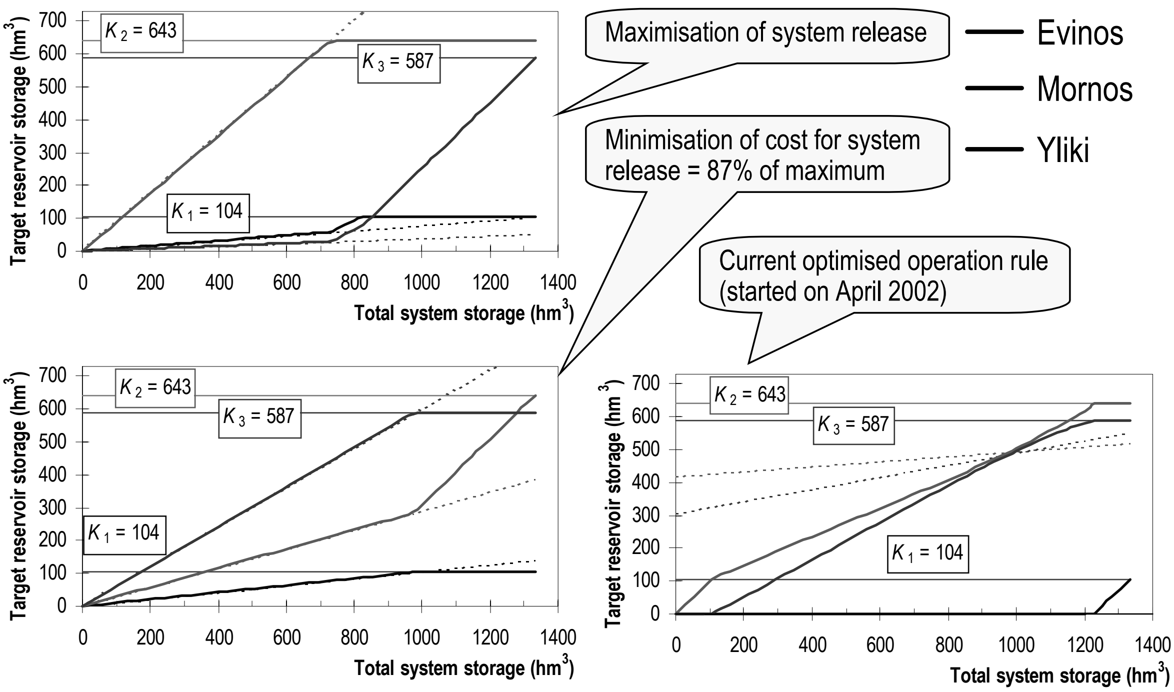
Adjusted, nonlinear form

$$S_i''^* = S_i'^* + \frac{S_i'^*(1 - S_i'^*/K_i)}{\Sigma S_i'^*(1 - S_i'^*/K_i)} (V - \Sigma S_i'^*)$$



Two parameters per reservoir (a_i, b_i) = **Control variables**
Parameter values **determined by optimisation** – depending on the objective function
Parameters may depend also on season (e.g., refilling-emptying period, or months)
2 × (reservoirs – 1) × seasons total parameters for the reservoir system

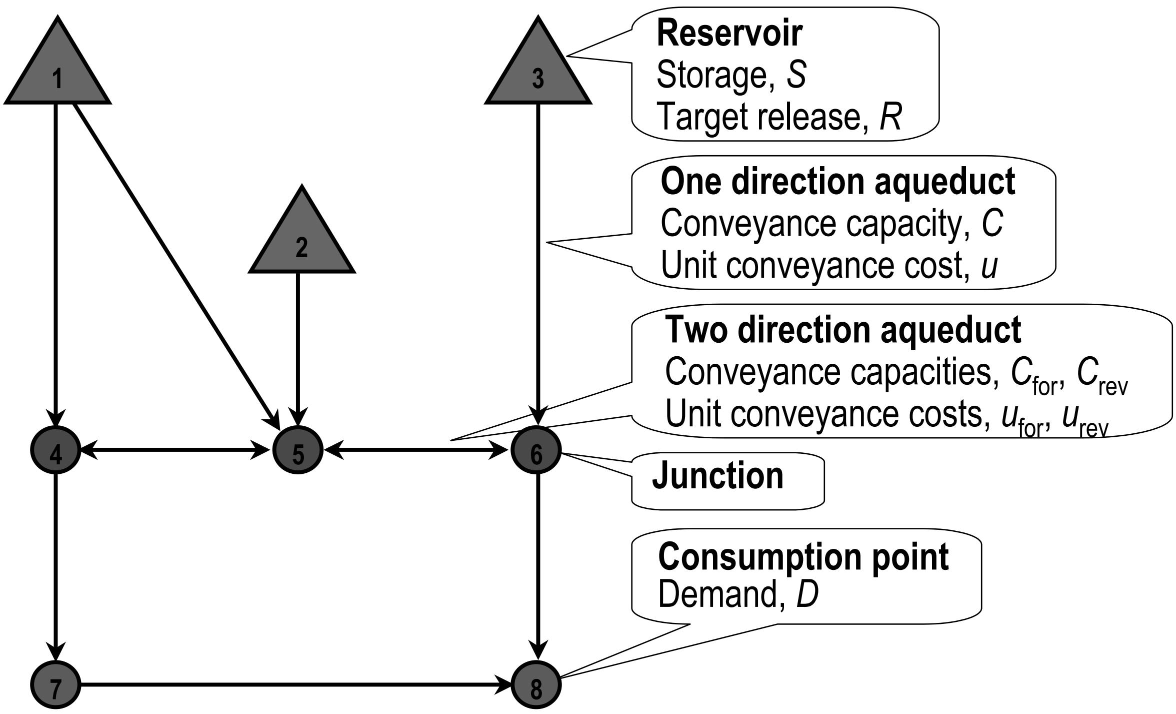
Application of the parametric rule – Optimal results



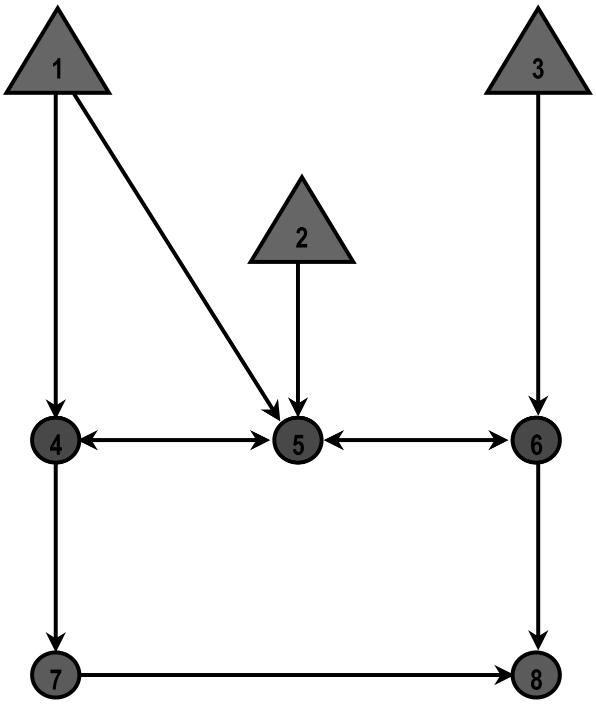
Considering the complete hydrosystem – Simulation

- Assuming that parameters a_i and b_i are known, the **target releases** from each reservoir will be also known in the beginning of each simulation time step
- The **actual releases** depend on several attributes of the hydrosystem (physical constraints)
- Their estimation is done using **simulation**
- Within simulation, an **internal optimisation** procedure may be necessary (typically linear, nonparametric)
- Because parameters a_i and b_i are not known, but rather are to be optimised, simulation is driven by an **external optimisation** procedure (nonlinear)

Hydrosystem components and attributes



Conveyance problem formulation

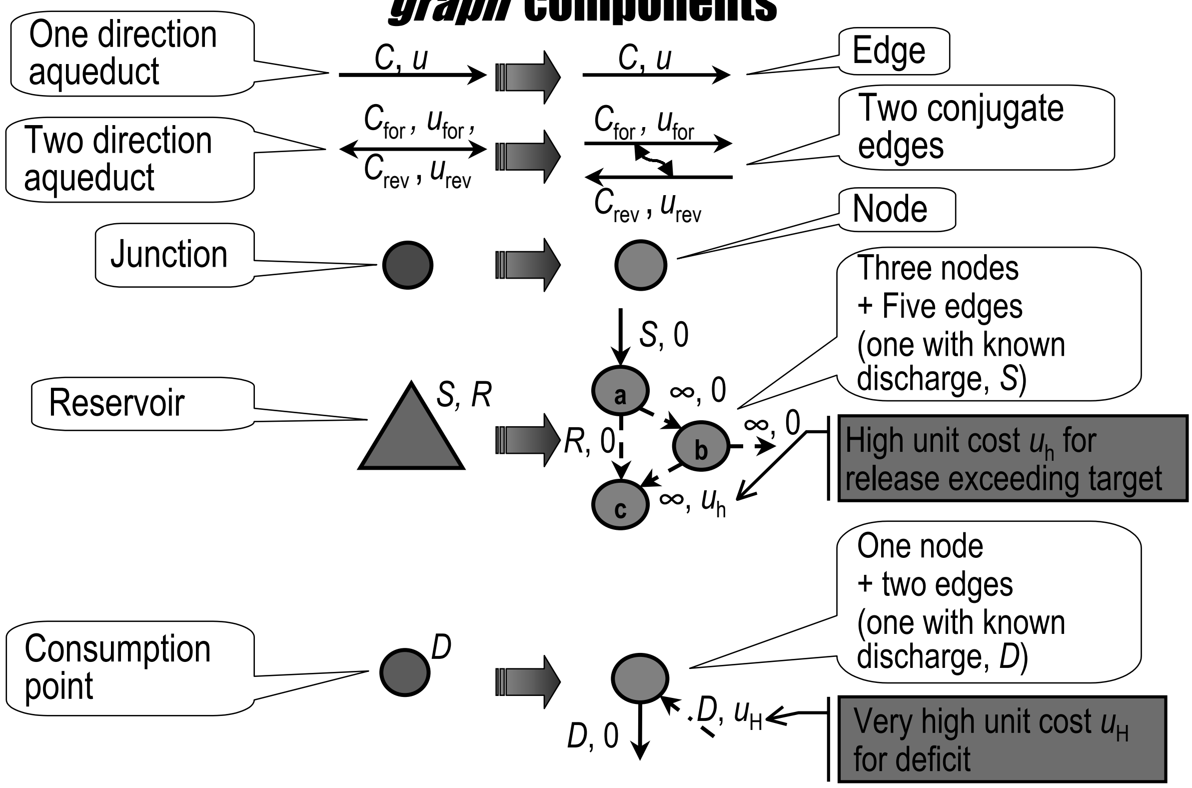


Given:
- Demands (D)
- Reservoir storages (S),
- Reservoir target releases ($R \leq S$; $\Sigma R = \Sigma D$; from parametric rule)

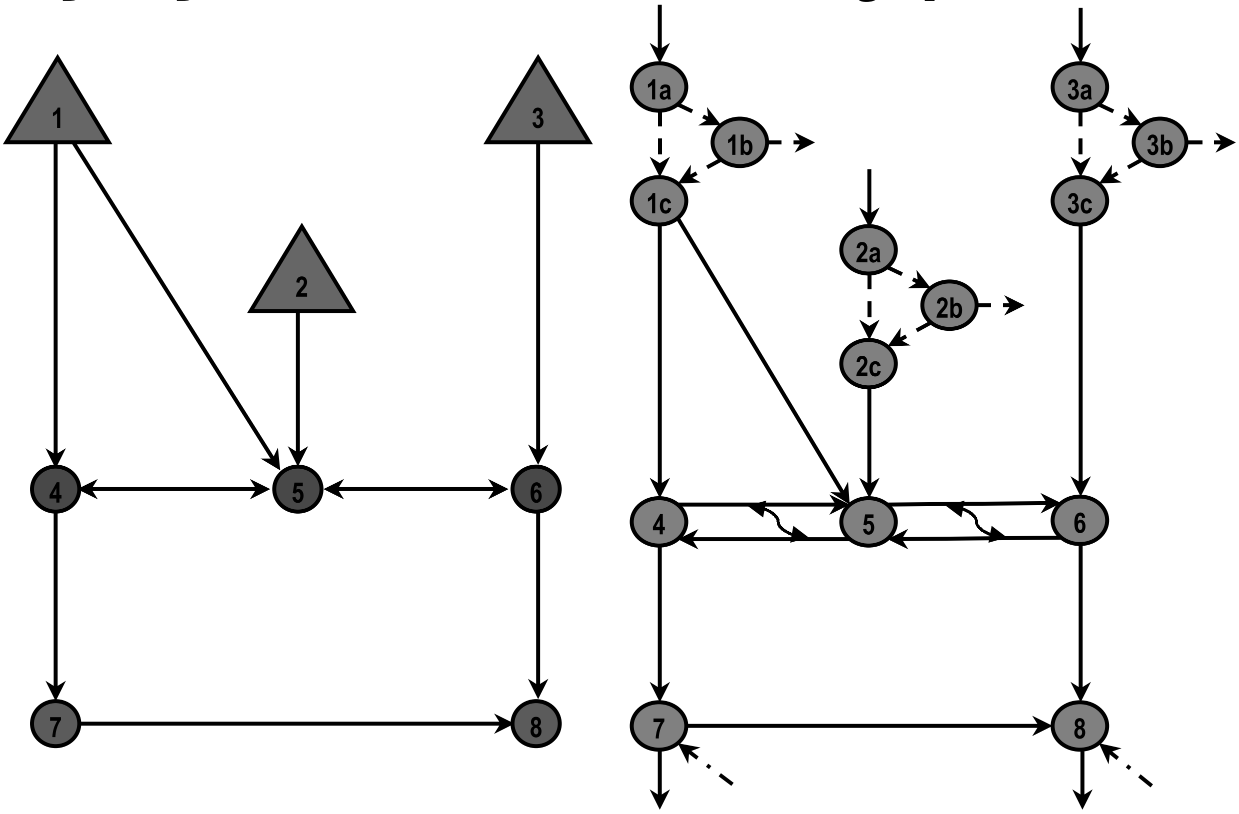
Required:
- Actual (feasible) consumptions (at consumption points)
- Actual (feasible) releases (from reservoirs)
- Aqueduct discharges
- Conveyance cost

Conditions:
- If possible, no deficits at consumption points
- If possible, releases from reservoirs equal to target releases
- Minimum conveyance cost

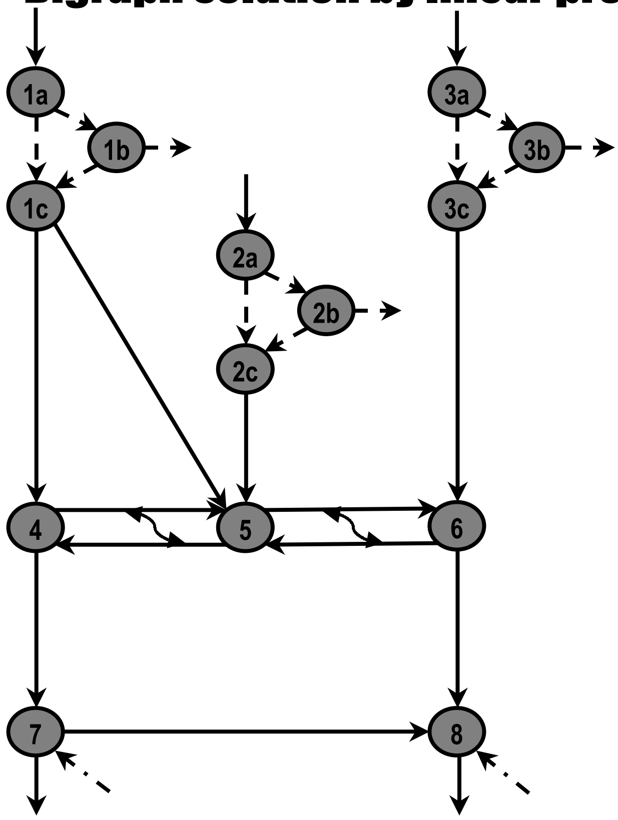
Transformations of hydrosystem components to *graph* components



Hydrosystem and its transformation to *digraph*



Digraph solution by linear programming



Determine all unknown discharges Q_{ij} at edges *ij*, by **minimising total cost**

$$TC = \boldsymbol{\Sigma}_{ij}\, u_{ij}\, Q_{ij}$$

subject to equality constraints for each node *i*

$$\boldsymbol{\Sigma}_j\, Q_{ij} - \boldsymbol{\Sigma}_j\, Q_{ji} = 0$$

and to **inequality constraints** for each edge *ij*

$$1 - Q_{ij} / C_{ij} \geq 0$$

or, for conjugate edges,

$$1 - Q_{ij} / C_{ij} - Q_{ji} / C_{ji} \geq 0$$

and, simultaneously, for each edge *ij*

$$Q_{ij} \geq 0$$

Concluding remarks

1. The project for modernisation of the management of the water resource system of Athens
   - develops new methodologies in the field of water resources management
   - provides better insights of the hydrosystem and its components' interactions,
   - improves its operation and management, and
   - assists the handling of crisis situations.
2. The Athens water resource system seems to be sufficient for the visible future unless major changes occur in
   - the climate,
   - the demographic conditions,
   - the life style standards.
3. The bottleneck of the hydrosystem today appears to be the conveyance capacity of aqueducts, which must be increased by constructing new hydraulic works.
4. The most worrying problem regarding the Athens water resource system appears to be the significant increase of the annual water demand. To remedy this, the management of the hydrosystem must be combined with water demand management.

References and further reading

- Bower, B. T., M. M. Hufschmidt, and W. H. Reedy, Operating procedures: Their role in the design and implementation of water resource systems by simulation analysis. in *Design of Water Resource Systems*, chap. 11, edited by Maass et al., pp. 443-458, Harvard University Press, Cambridge, Mass, 1962.
- Clark, E. J., New York control curves, *J. Am. Water Works Assoc., 42*(9), 823-857, 1950.
- Karavokiros, G., A. Efstratiadis, and D. Koutsoyiannis, A decision support system for the management of the water resource system of Athens, *26th General Assembly of the European Geophysical Society, Geophysical Research Abstracts, Vol. 3,* Nice, 2001, European Geophysical Society, 2001.
- Koutsoyiannis, D., and A. Efstratiadis, A stochastic hydrology framework for the management of multiple reservoir systems, *26th General Assembly of the European Geophysical Society, Geophysical Research Abstracts, Vol. 3,* Nice, March 2001, Euro-pean Geophysical Society, 2001.
- Koutsoyiannis, D., A. Efstratiadis, and G. Karavokiros, 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, 2001.
- Nalbantis, I., and D. Koutsoyiannis, A parametric rule for planning and management of multiple reservoir systems, *Water Resources Research*, 33(9), 2165-2177, 1997.

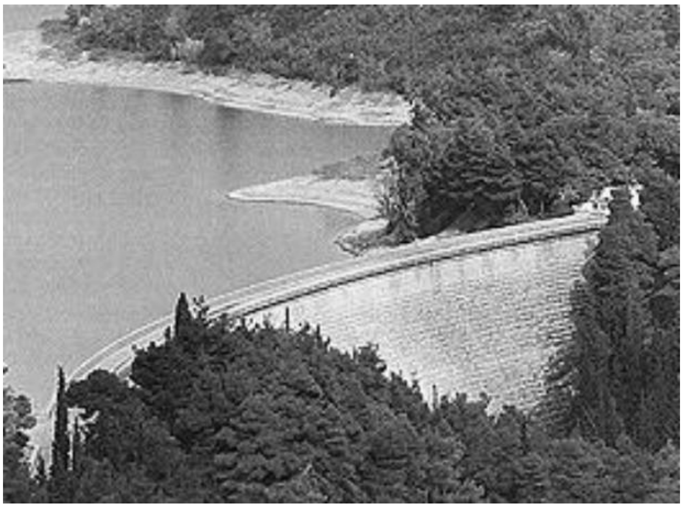
Pictures

Early stage

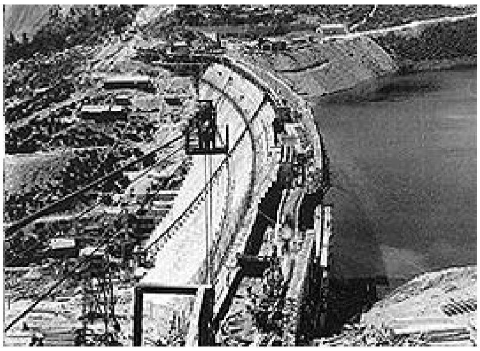
The Adrian aqueduct

Supplementary water collection and distribution in Athens (early 20th century until 1930s)

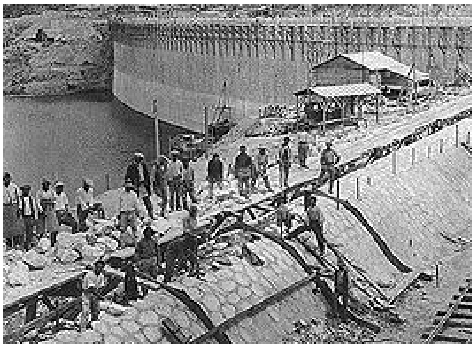
Marathon dam



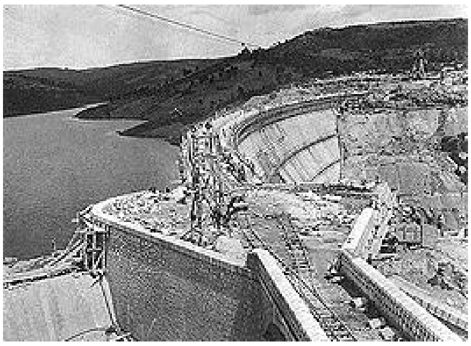
Today



Construction of dam, 1928

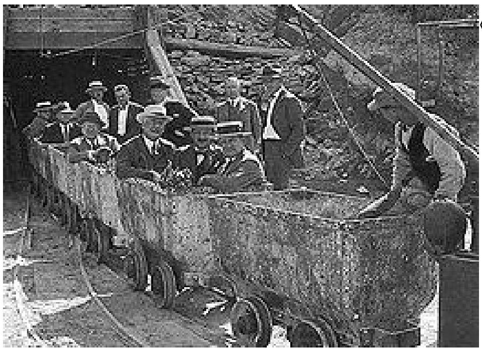


Construction of spillway, 1928



Marathon dam (2)

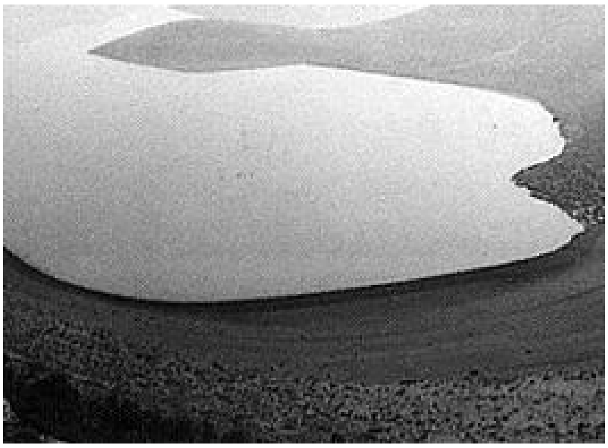
Devastating flood, 1926



Inauguration of Boyati tunnel, 1928

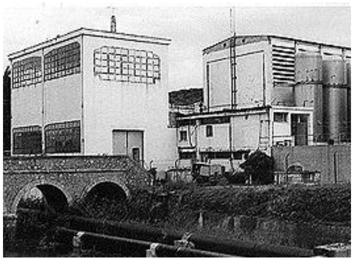
Marathon spillway in action, 1941

Yliki lake and pumping stations

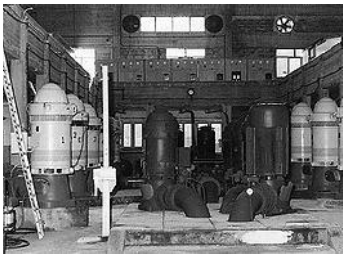


Yliki lake

Yliki, floating pumping stations



Yliki, main pumping station



Kiourka pumping station

Mornos reservoir and aqueduct

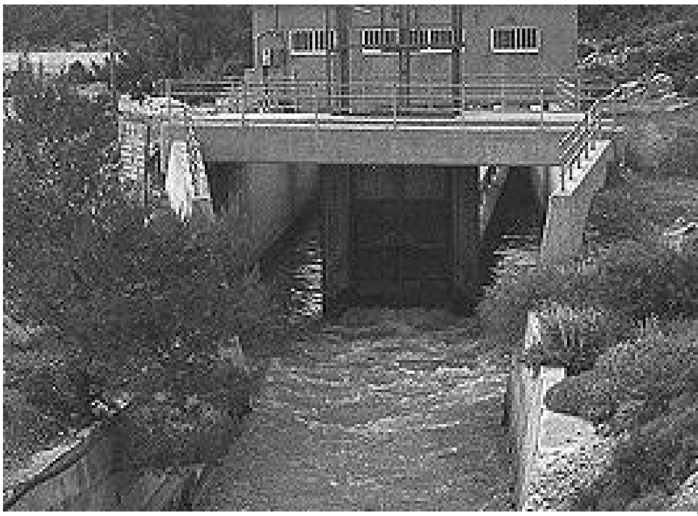
Mornos reservoir

Mornos canal at Delphi

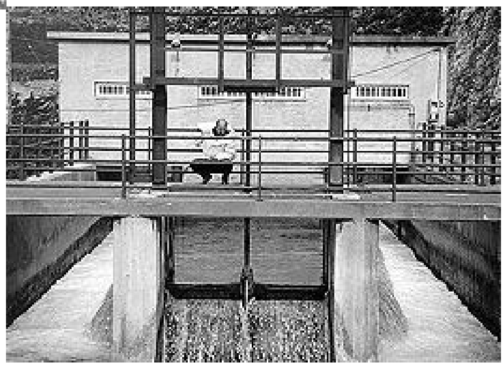
Siphon at Distomo

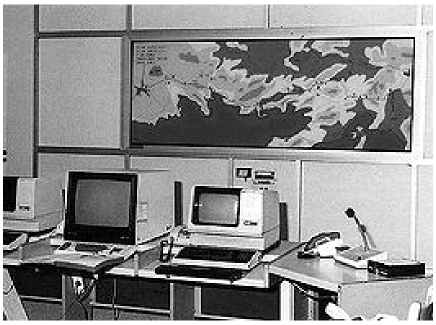
Mornos canal at Thebes plain

Control of Mornos aqueduct



Canal flow control construction

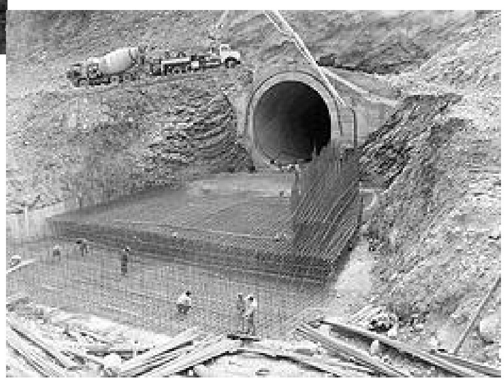




Aqueduct supervising & control centre

Evinos dam and tunnel

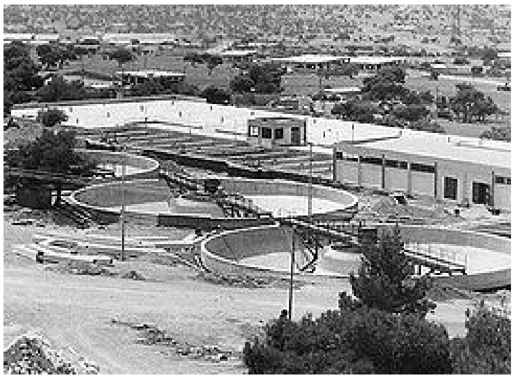
Evinos dam during construction



Construction of the Evinos-Mornos connection tunnel

Treatment plants

Perissos water treatment plant



Aspropyrgos water treatment plant