The Athens water resource system: A modern management perspective

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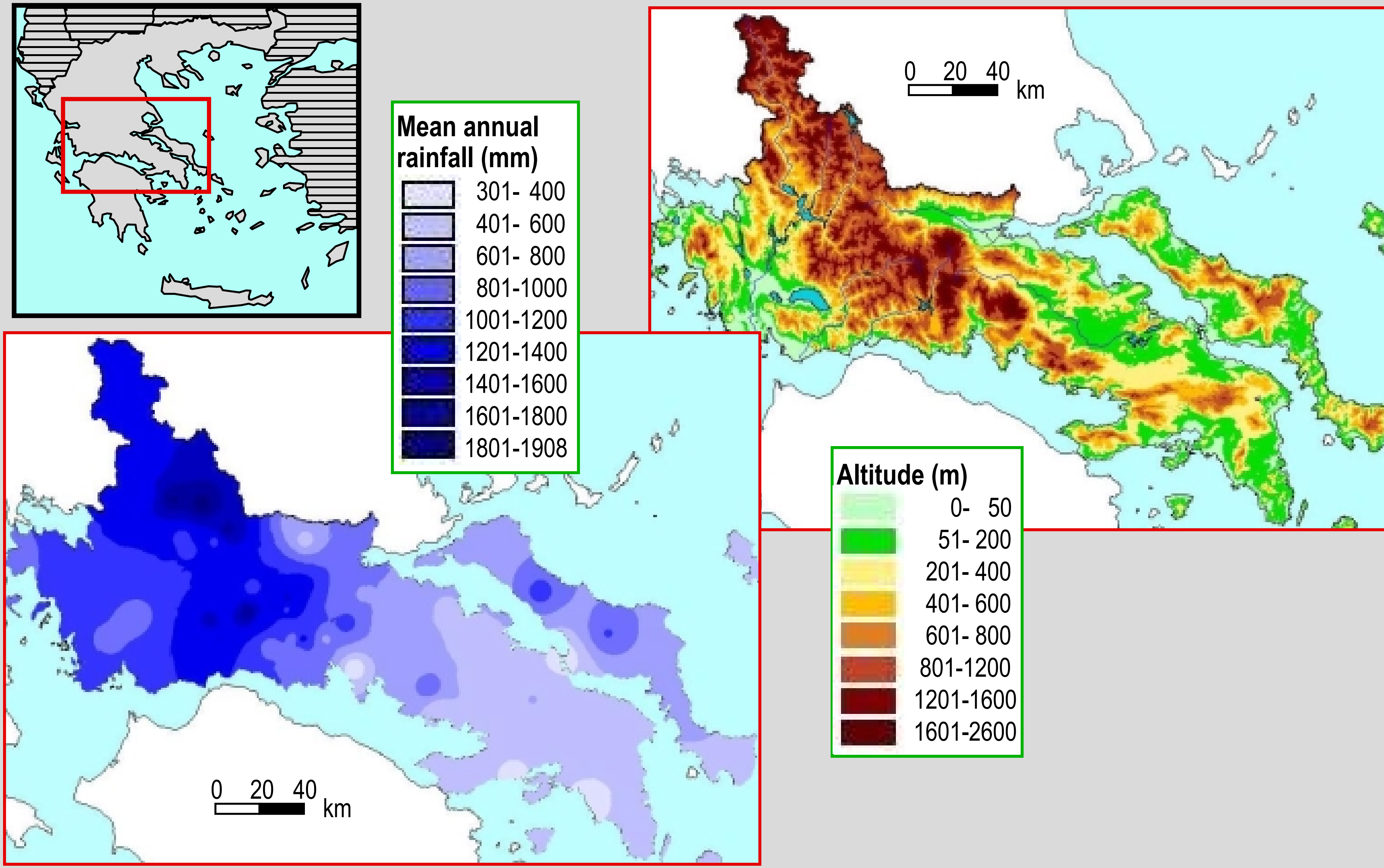
Ὕσον, ὕσον Ζεῦ κατὰ τῆς ἀρούρης τῶν Ἀθηναίων

Do rain, do rain Zeus against the earth of Athenians (Ancient Greek prayer)



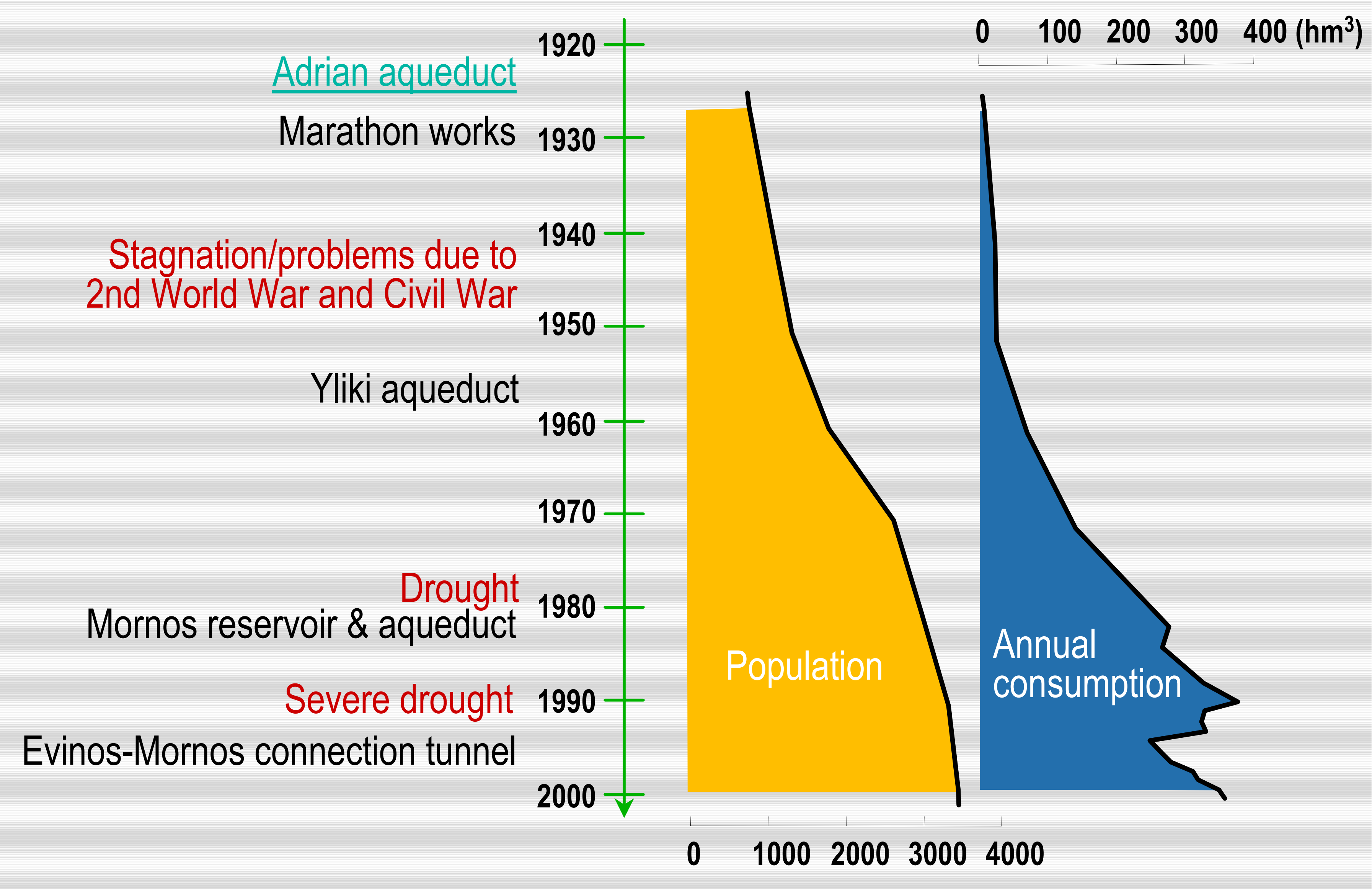
Parts of the presentation

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

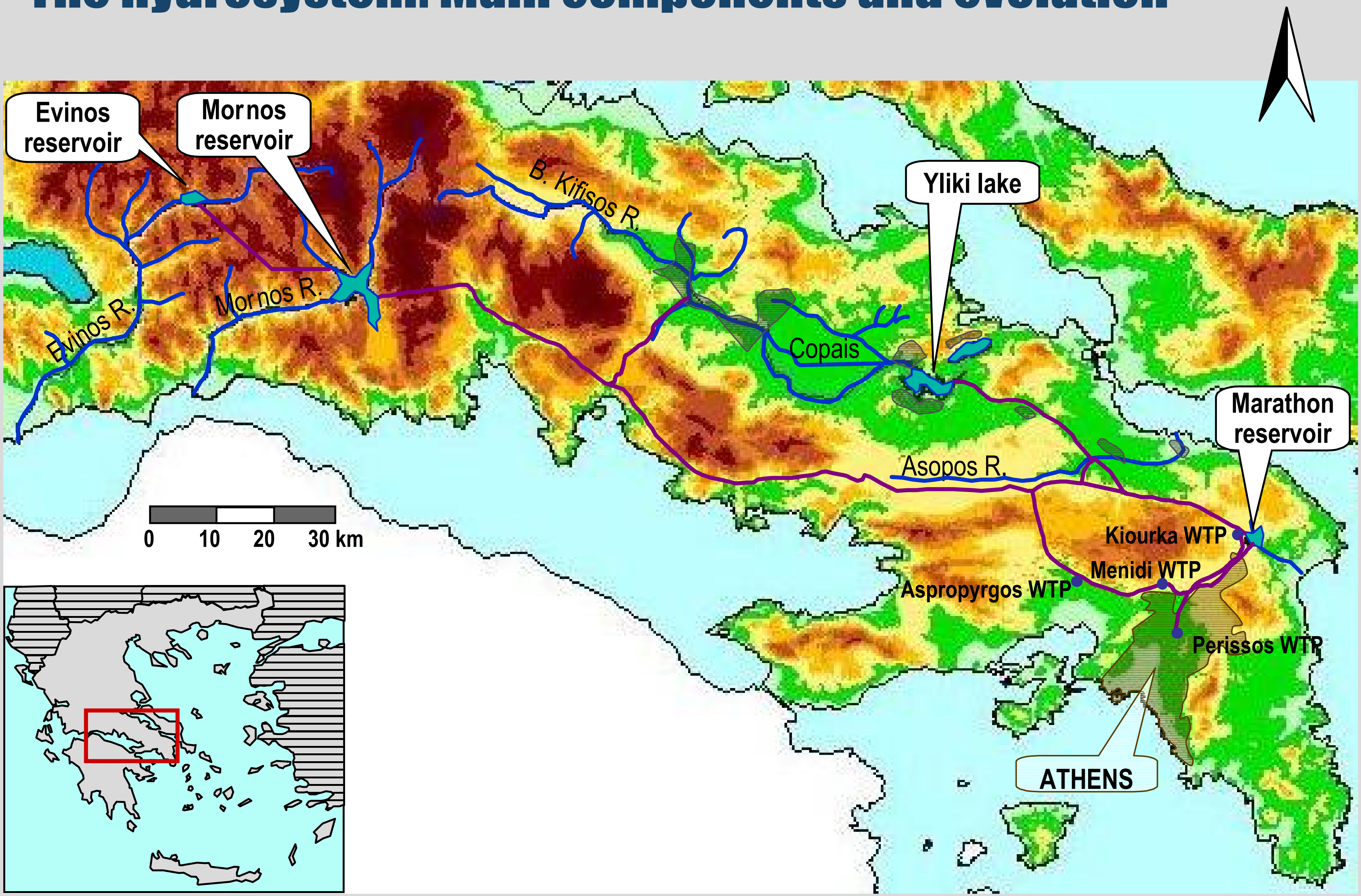
2. The project: *Modernisation of the supervision and management of the water resource system of Athens*
   - Objectives
   - Components

3. The methodology
   - General aspects
   - Specific problems

Evolution of water consumption – Milestones



The hydrosystem: Main components and evolution

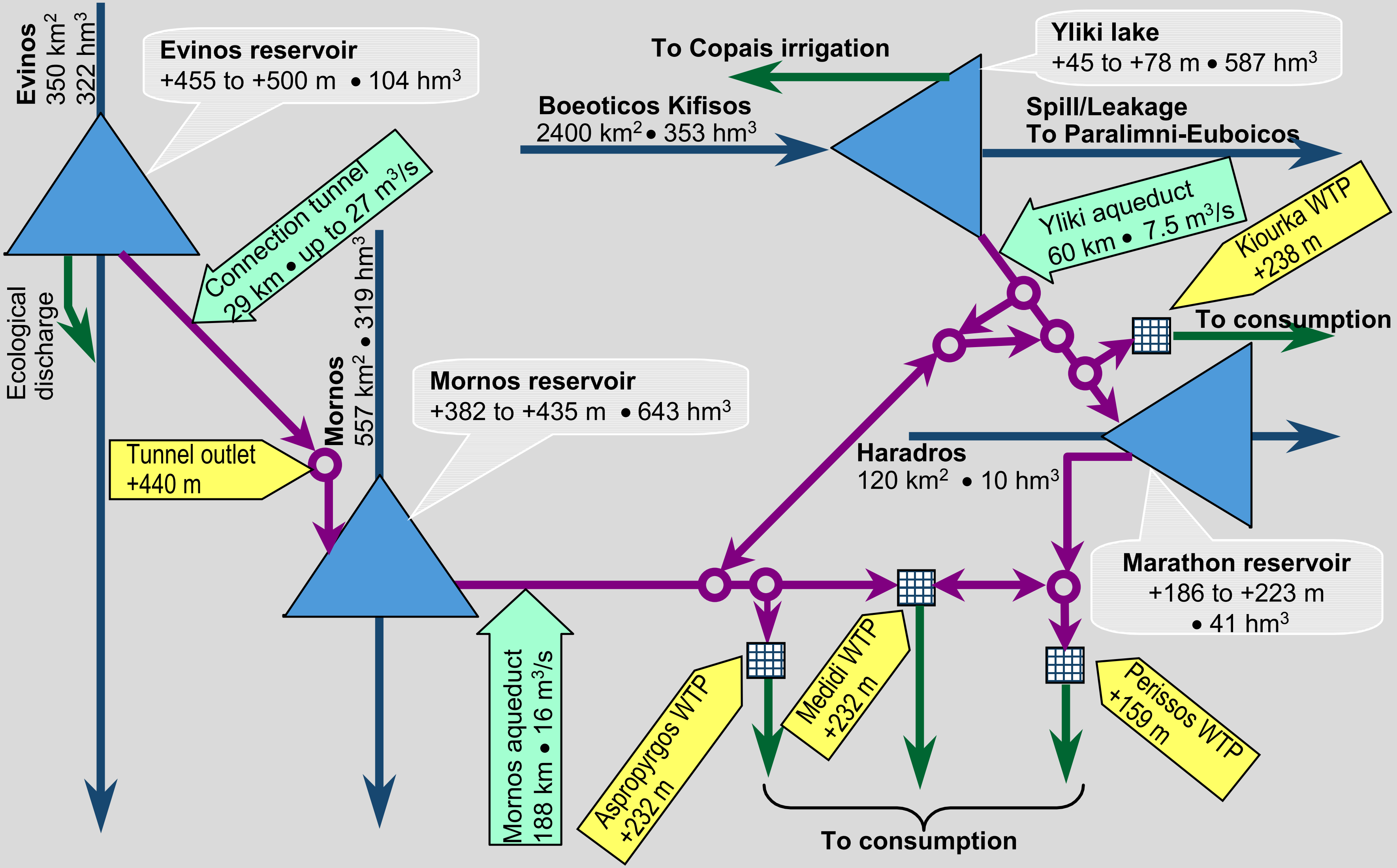


Classification of water resources

	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*

- Objectives:
  - Supervision
  - Measurement
  - Mathematical modelling and simulation
  - Optimisation

  of the Athens water resource system
- Commissioned by the Athens Water Supply and Sewerage Company (ΕΥΔΑΠ) to the National Technical University of Athens
- Part of the ΕΥΔΑΠ Water Supply Master Plan
- Approved and funded by the EU in the framework of the 2nd Cohesion Fund
- Commenced in June 1999; duration five years in two phases

Unit 5: Cooperation and transfer of knowledge between NTUA and EYDAP

- Setting up of collaboration between NTUA and EYDAP
- Linking/sharing of computational resources
- Seminars and workshops
- Training programmes
- Participation of EYDAP personnel in research work

Unit 4: Development of a decision support system for the integrated management of the system

- Final product
  - Software system in operational use (Core of the project)
- Theoretical basis
  - Parameterisation – Simulation – Optimisation
- Specific characteristics
  - Faithful representation of the real hydrosystem
  - Use of either historical or stochastic data series
  - Determination of optimal system operation
  - Coping with multiple objectives / conflicting uses
  - Wide range of results (water quantities, energy quantities, economical quantities)
  - Evaluation of results in probabilistic terms

Unit 3: Development of a computational system for the estimation and prediction of water resources

- Final products
  - Software system for the stochastic simulation/forecasting of the reservoir inflows (linked to the Decision Support System)
  - Groundwater model for the Beoticos Kifisos – Yliki basin (linked to the Decision Support System)
  - Approximate estimation of the groundwater potential of the remaining backup water resources
- Theoretical basis and characteristics
  - Stochastic model: Generalised mathematical framework of stochastic hydrology + disaggregation models
  - Groundwater model: Distributed model with a coarse (rough) horizontal and vertical grid
  - Specific provision for climatic trends and droughts

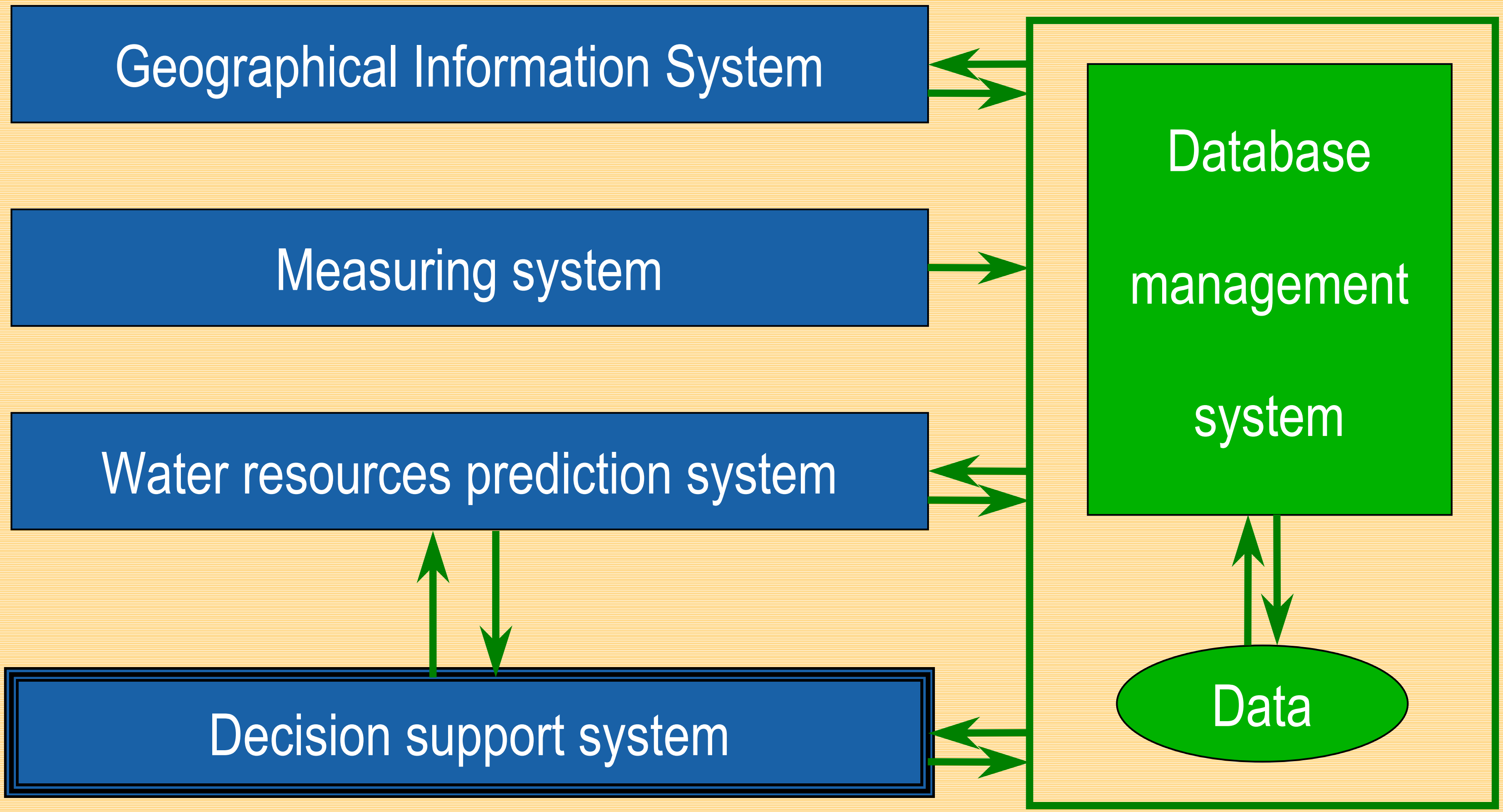
Unit 2: Development of the water resources telemetric measurement system

- Final product
  - Study, installation and operation of an automated telemetric system for measuring hydrological and meteorological variables in the study area
- Objectives
  - Updating of hydrologic and system simulation models with current input data
  - Monitoring of the water resources
- System components
  - Telemetric meteorological stations (4)
  - Telemetric river staff gauges (4)
  - Telemetric reservoir level gauges (4)
  - Conventional river discharge measurement gauges (4)
  - Sub-system for data acquisition, transmission, and processing
  - Connection with measuring devices of aquifers

Unit 1: Development of a Geographical Information System for the hydrosystem visualisation and supervision

- Final product
  - Geographical Database with the necessary data and the appropriate software applications, in operational use
- Objectives
  - Storage and retrieval of information of the hydrosystem structure and operation
  - Archiving of hydrologic data series, historical, real time and synthetic
  - Visualisation and supervision of the hydrosystem
- System components
  - Static information subsystem (Geographical locations and characteristics of natural and technical components of the hydrosystem)
  - Dynamic information subsystem (time series, event recordings)
  - Processing and visualisation subsystem (maps, diagrams, tables)

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

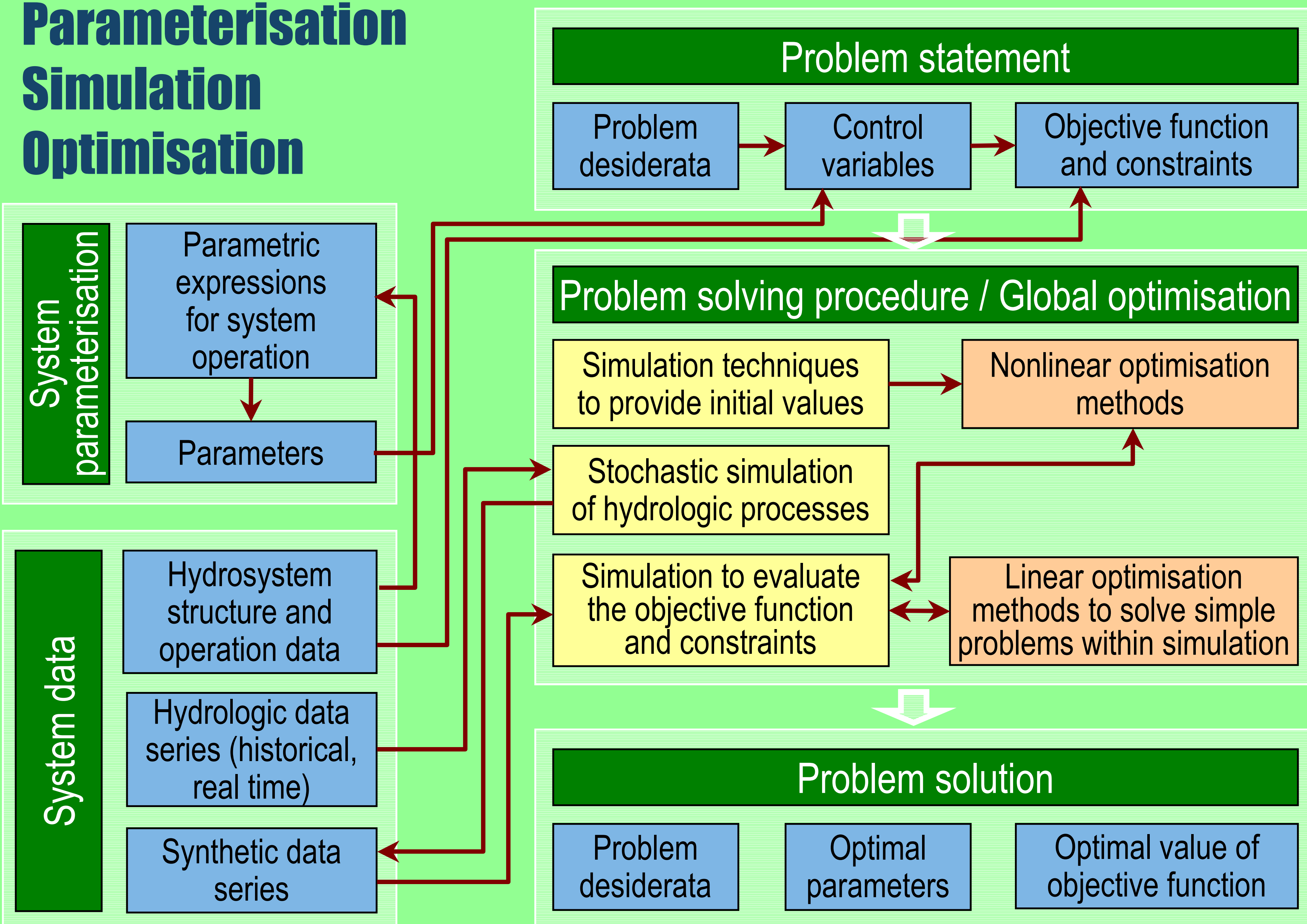
Main advantages
- Detailed and faithful system representation
- Better understanding of the system operation
- Incorporation of stochastic models

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

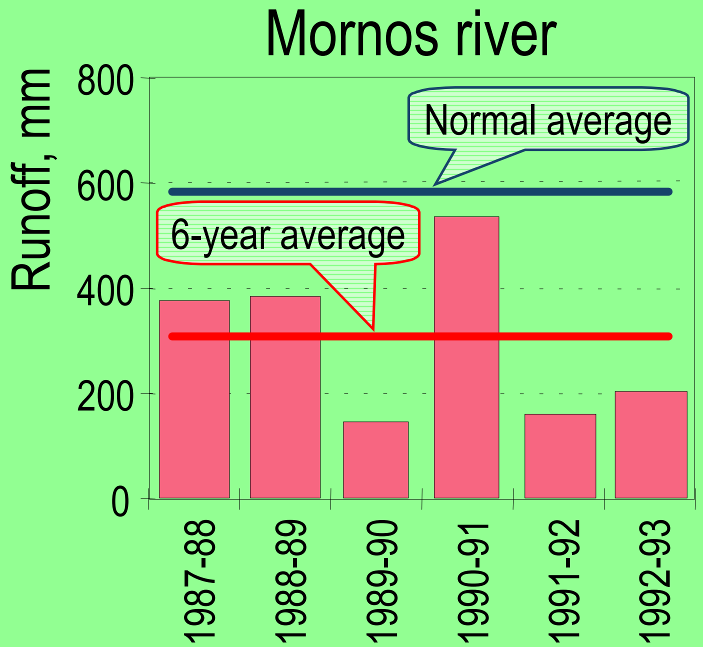


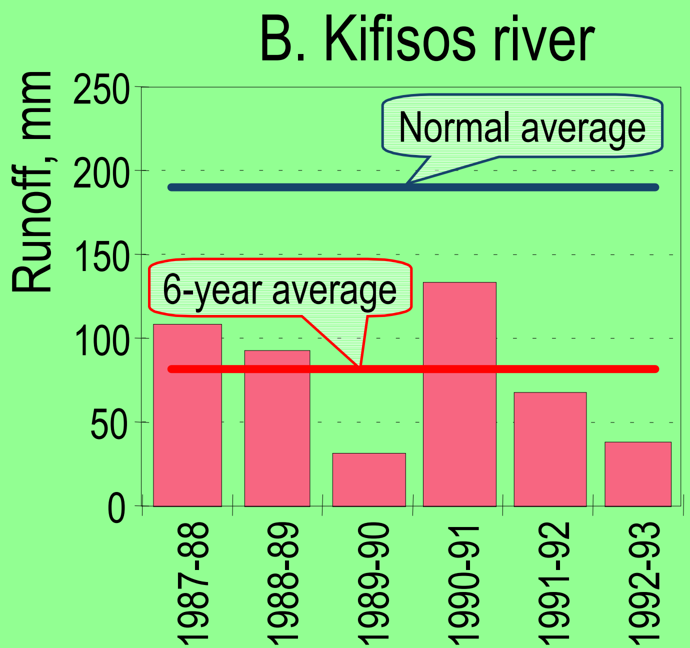
Stochastic simulation/forecasting of hydrologic processes

- 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 draught – Preservation of long-term persistence





Specification of the *Kastalia* stochastic simulation software (under development)

- 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:
- Case b: no conveyance restrictions; significant leakages; insignificant spills
  - Solution:
- Case c: restricted conveyance capacity; insignificant spills; no leakages
  - Solution:

Space rule
(Bower et al., 1962)

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

Leakage rule (Nalbantis & Koutsoyiannis, 1996)

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

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

$S_i^* = a_i + b_i V$ – parameters a_i, b_i

subject to $\Sigma a_i = 0$, $\Sigma b_i = 1$,

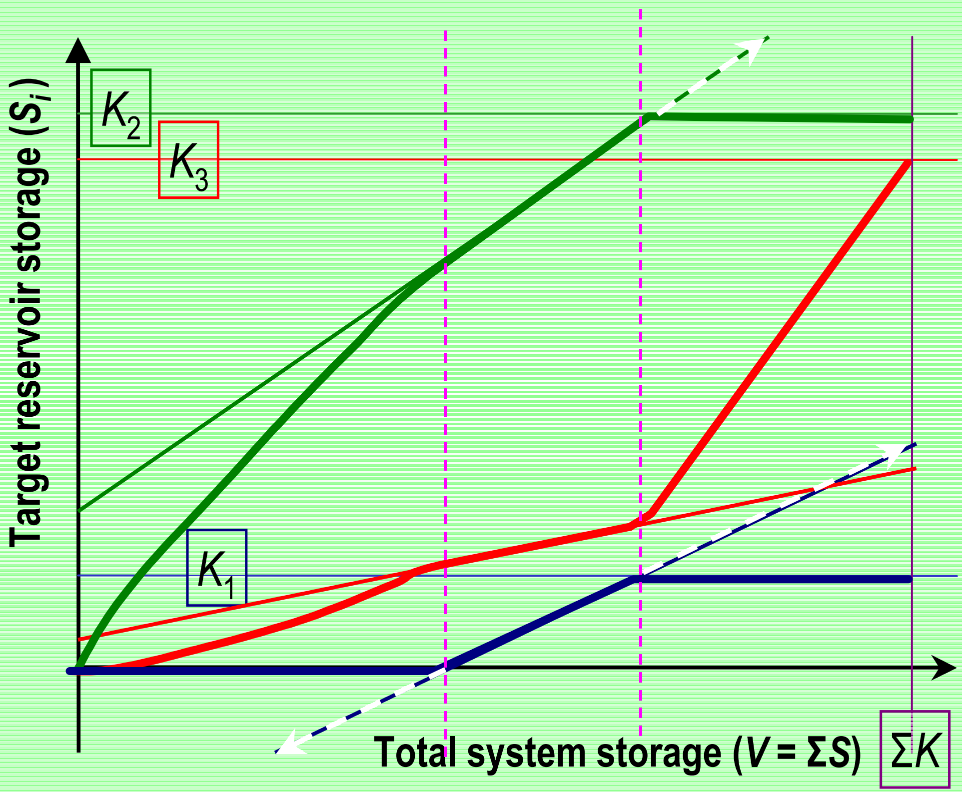
since $\Sigma S_i^* = V$

Corrected for physical constraints

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

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)

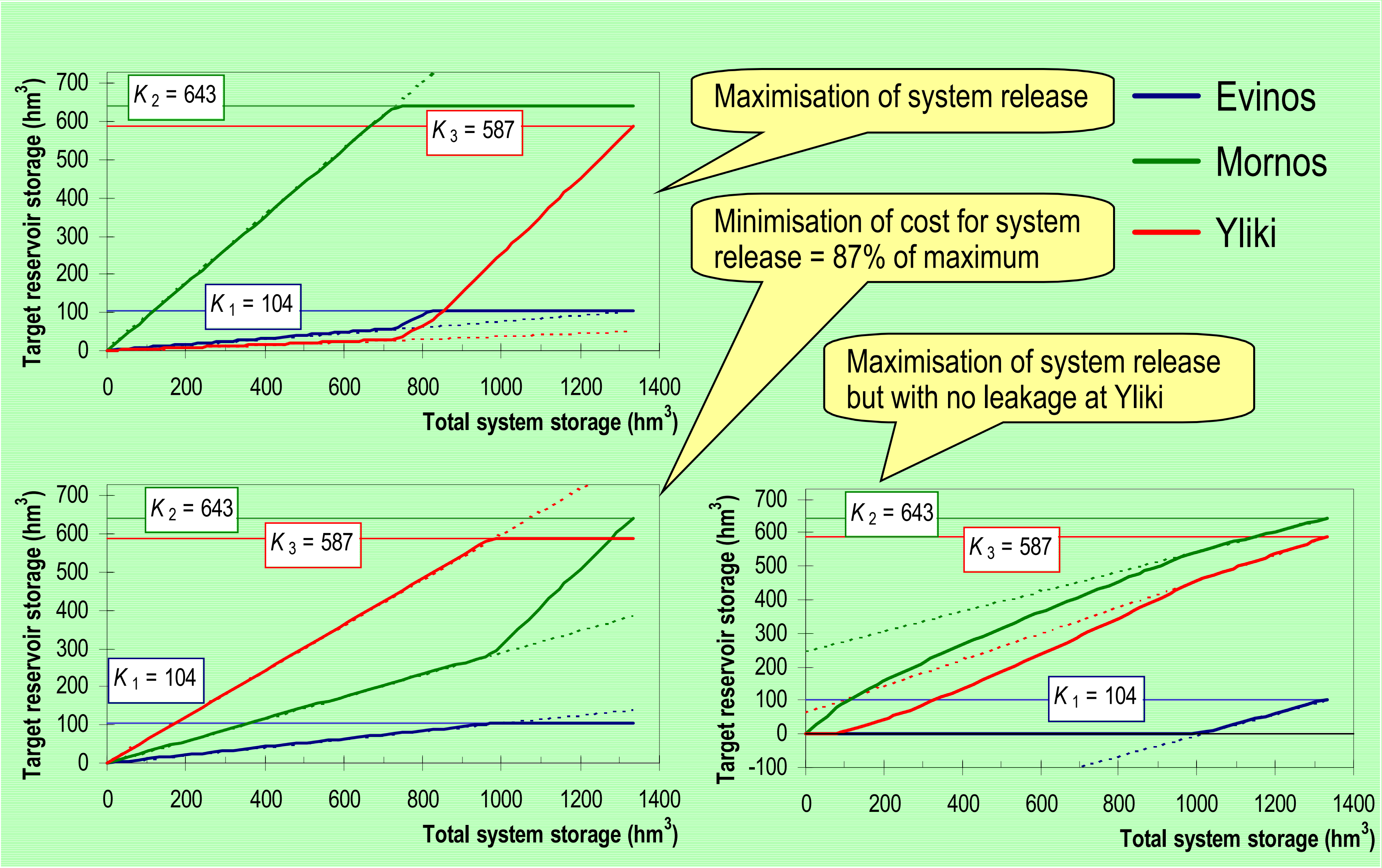
2 × (reservoirs – 1) × seasons total parameters for the reservoir system

A comparison with a conventional optimisation method

Problem: Find the maximum release that can be ensured by a system of **3 reservoirs** with **reliability 99%** (probability of failure 1%). Use **1000 years** of simulated data with **monthly time step**. Assume **steady state** conditions.

Non-parametric optimisation	Parametric rule based optimisation
Number of control variables: 1000×12 monthly releases $\times (3 - 1)$ reservoirs + 1 (problem target) = 24001	Number of control variables: 2 parameters/reservoir/ season $\times (3 - 1)$ reservoirs $\times$ 2 seasons + 1 (problem target) = 9 (as an order of magnitude)
Cannot be combined with simulation All physical constraints of the system must be entered as problem constraints	Can be combined with simulation Physical constraints of the system are handled by the simulation model
Control variables depend on inflow series Implicit assumption of known inflows (infinite forecast lead time, 100% accuracy)	Control variables do not depend on inflow series but on their statistical properties No assumption of known inflows
The optimisation model needs continuous runs with updated data	Once parameters are optimised, the system can be operated without running the model

Application of the parametric rule – Optimal results



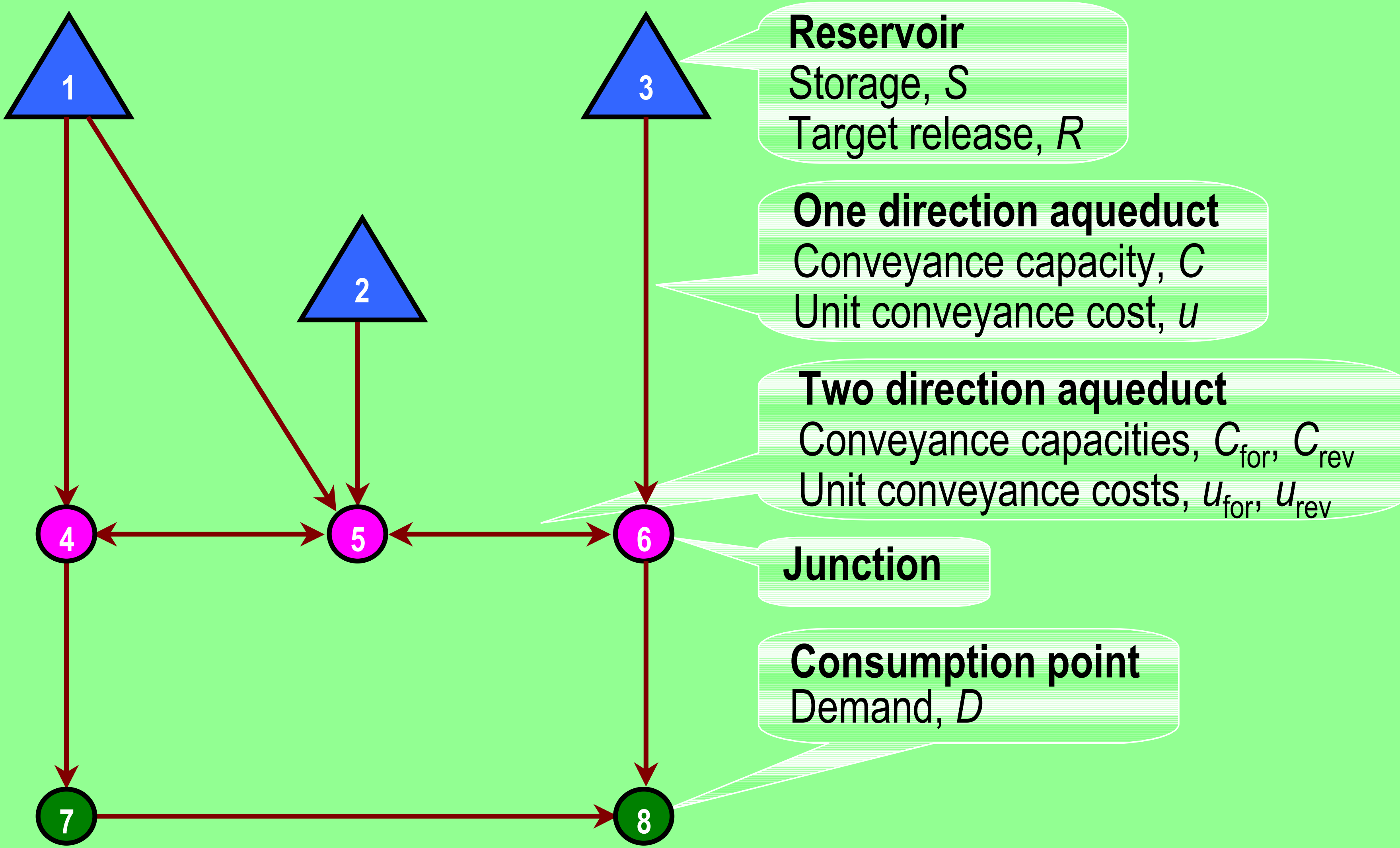
Justification, verification, and extensions of the parametric rule

- Is parametric rule underparametrised?
  - Nonlinear expressions with three parameters per reservoir did not outperform
  - Homogeneous linear expressions (one parameter per reservoir, $a_i = 0$) result in almost same optimal solutions
  - Considering seasonality (2 seasons) seems to improve results (slightly)
- How results of parametric rule based optimisation compare to those of nonparametric optimisation methods?
  - Investigation is under way using
    - Full nonparametric optimisation models (based on evolutionary algorithms) on simple systems with a few years time horizon
    - Existing control models on real systems
- Is the parameterisation appropriate for all water uses?
  - Yes, but extensions may be needed for non-consumptive water uses
  - Successful application to hydropower systems (one more parameter per hydropower station)

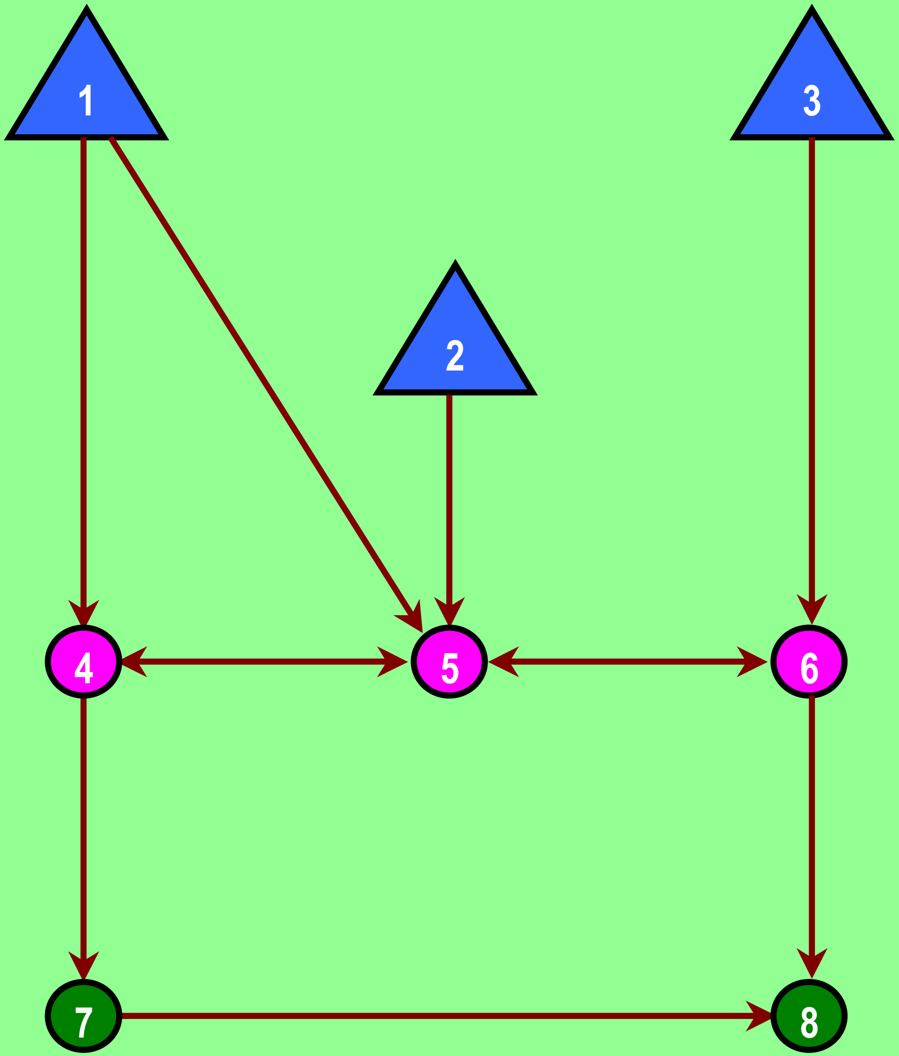
Considering the complete hydrosystem – Simulation

- 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)

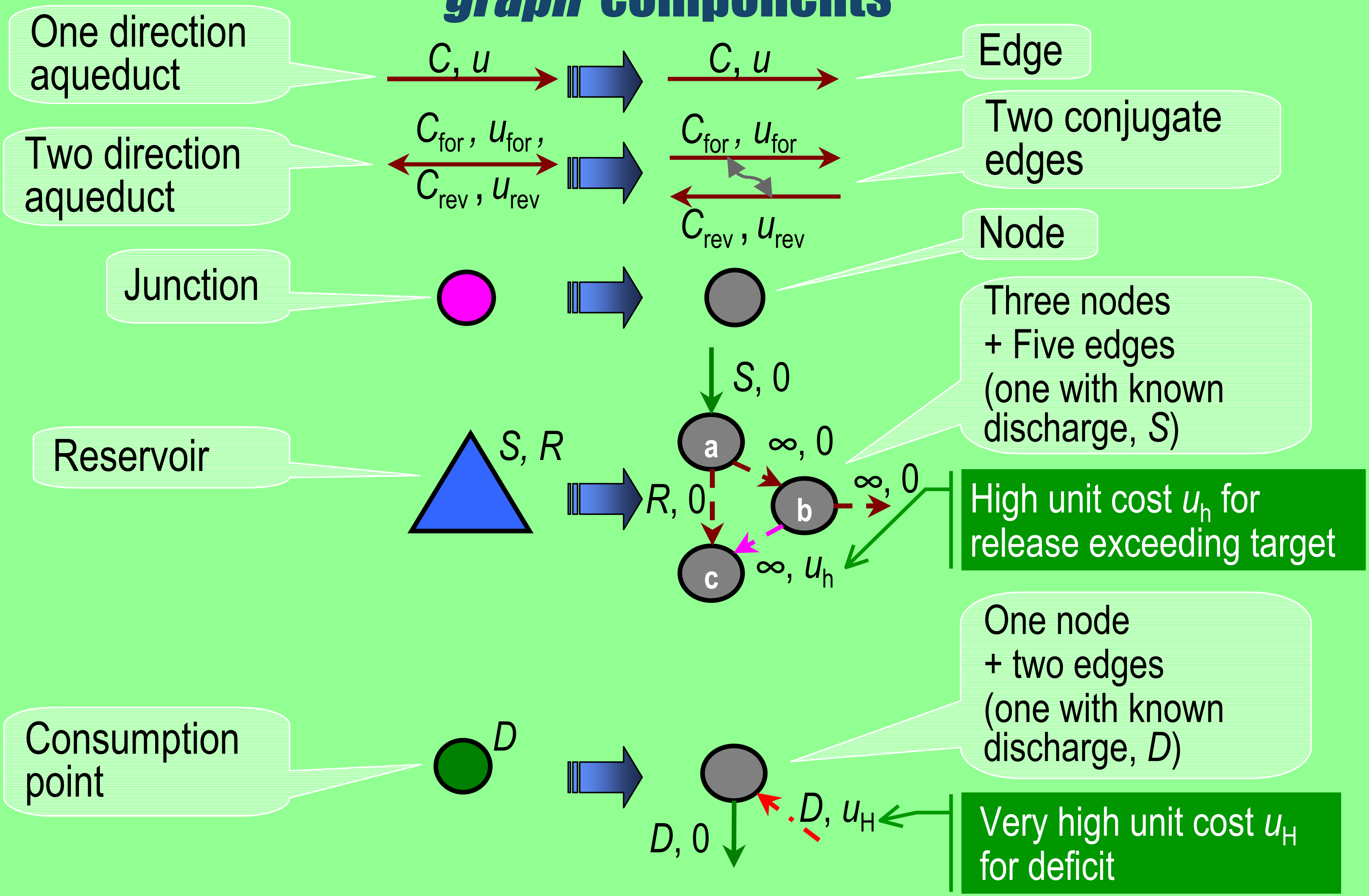
Required:

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

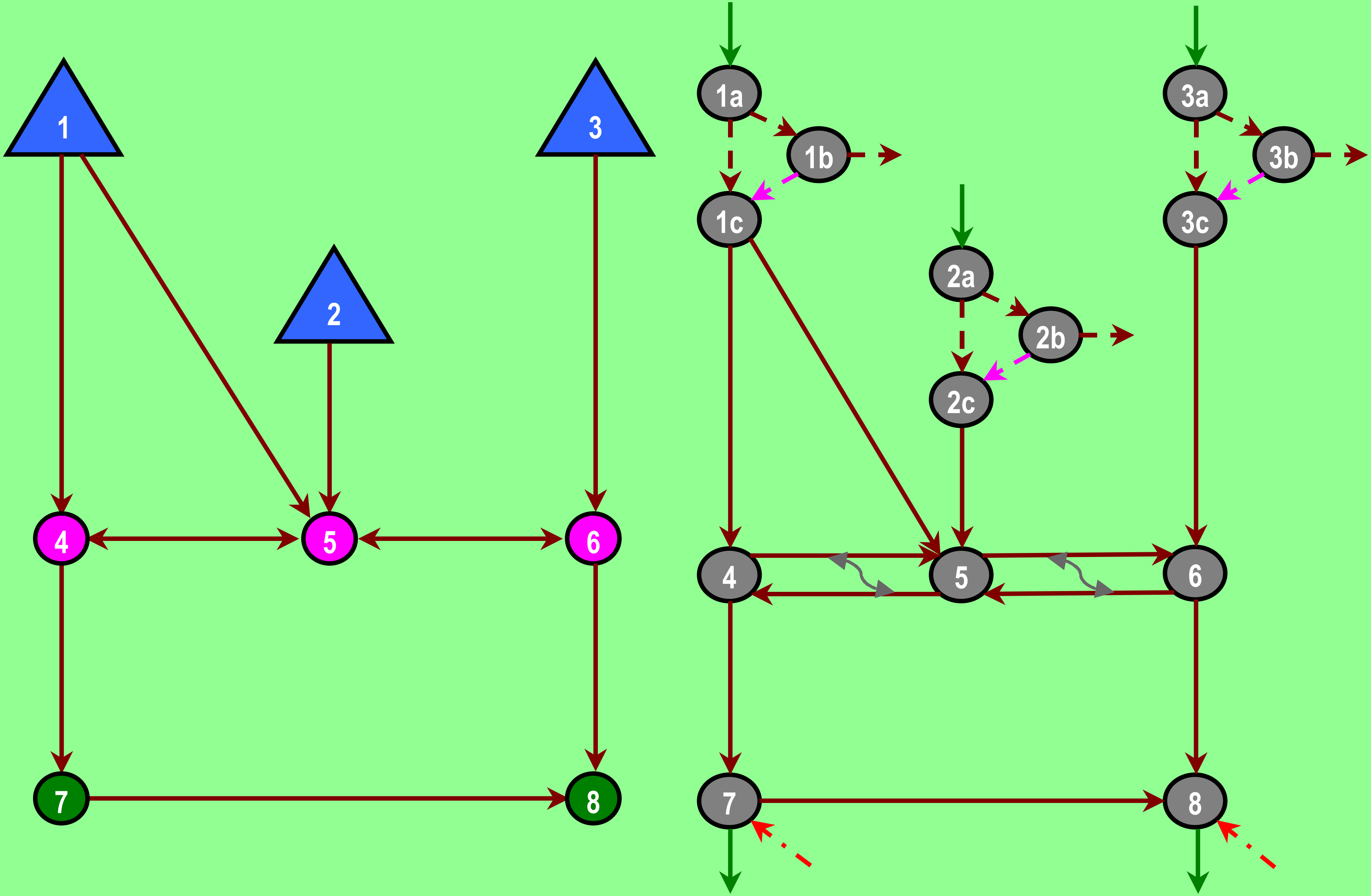
Conditions:

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

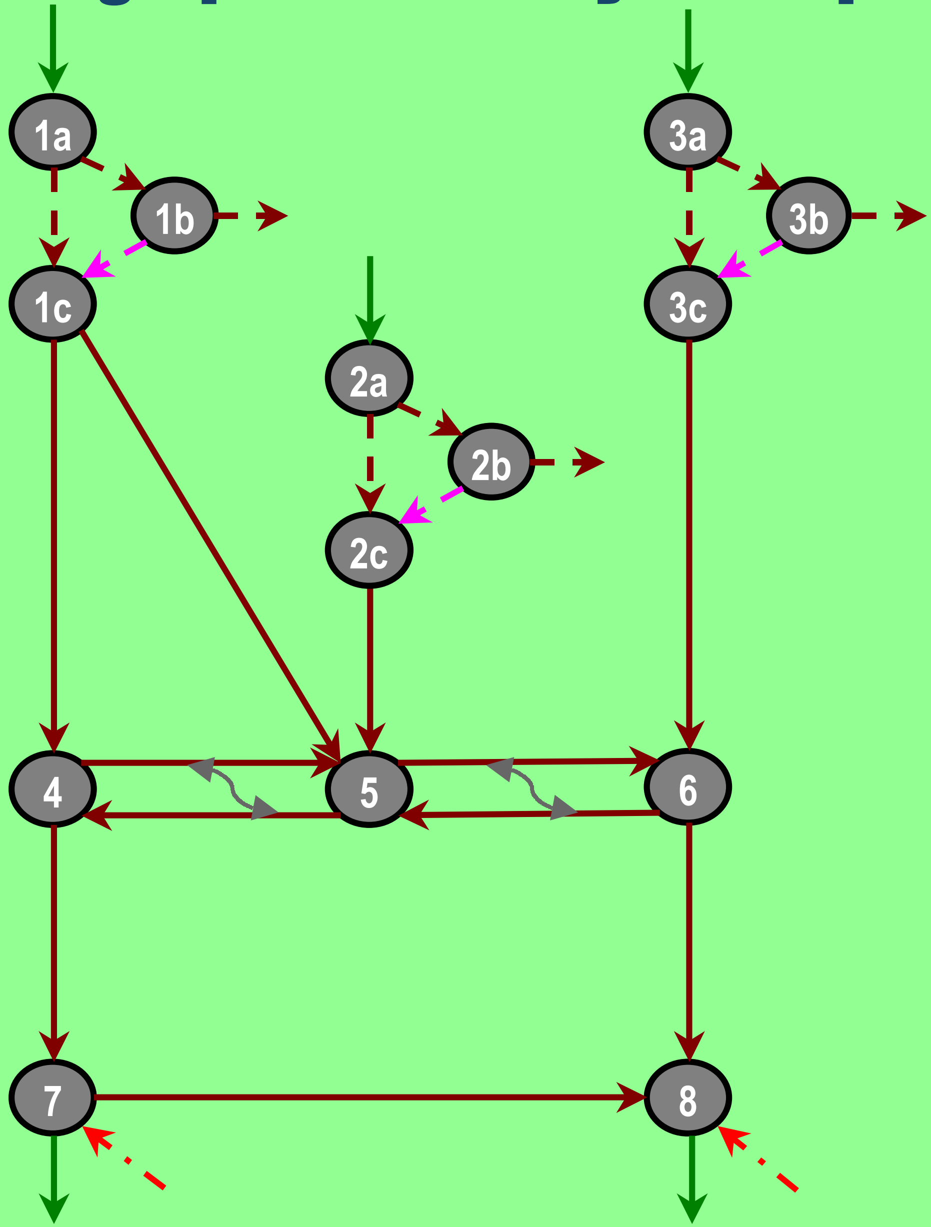
Transformations of hydrosystem components to *graph* components



Hydrosystem and its transformation to *digraph*



Digraph solution by linear programming



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

$$TC = \Sigma_{ij}\, u_{ij}\, Q_{ij}$$

subject to equality constraints for each node i

$$\Sigma_j\, Q_{ij} - \Sigma_j\, Q_{ji} = 0$$

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 Athens water resource system seems to be sufficient for the visible future unless major changes occur in
   - the climate, or
   - the demography.
2. The ongoing project is expected to
   - provide better insights of the system and its components' interactions,
   - improve its operation and management, and
   - assist the handling of future crisis situations.

   More have do be done about
   - water demand management, and
   - more detailed studies of groundwater resources.
3. The methodologies being developed are focusing on
   - the parameterisation-simulation-optimisation approach, and
   - the stochastic modelling of hydrological processes.

   Their evaluation includes
   - preliminary tests with encouraging results so far, and
   - final (future) operational tests in the demanding water resource system of Athens.

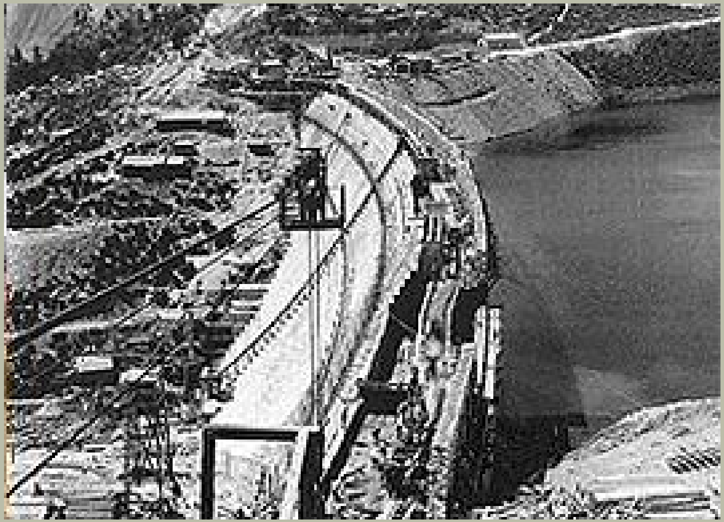
Early stage

The Adrian aqueduct

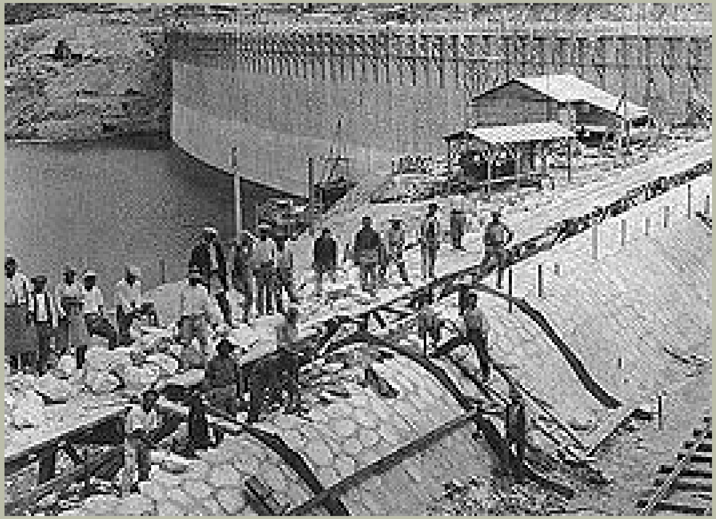
Supplementary water collection and distribution in Athens (early 20th century until 1930s)

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

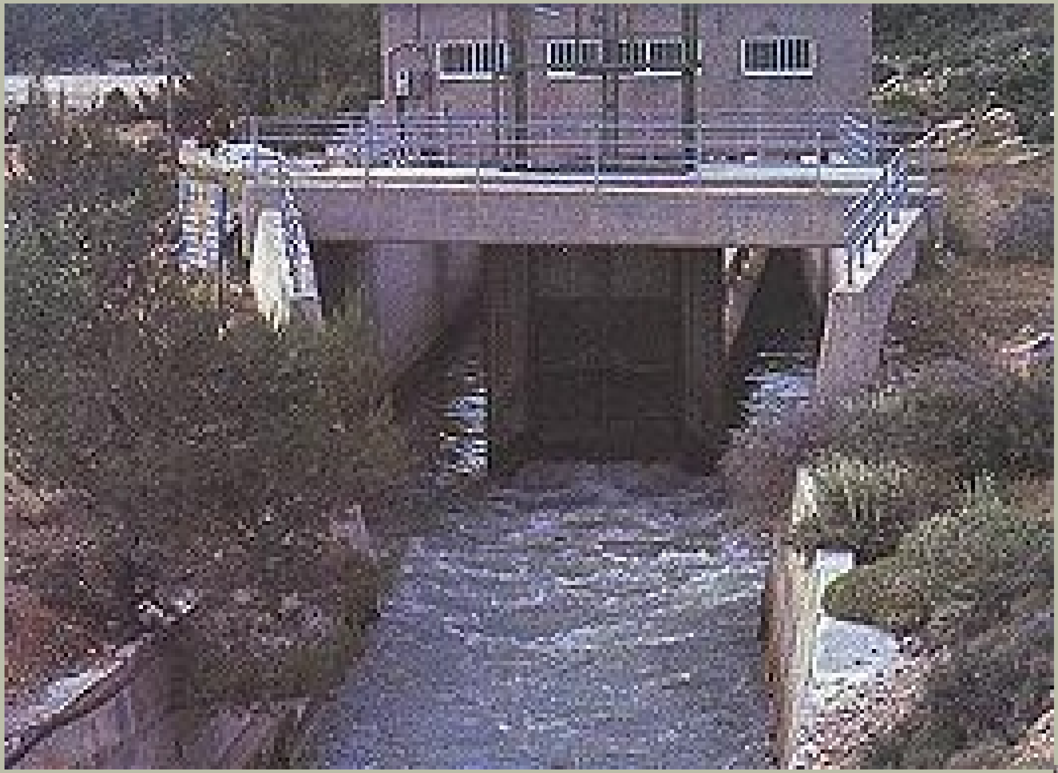
Mornos reservoir

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

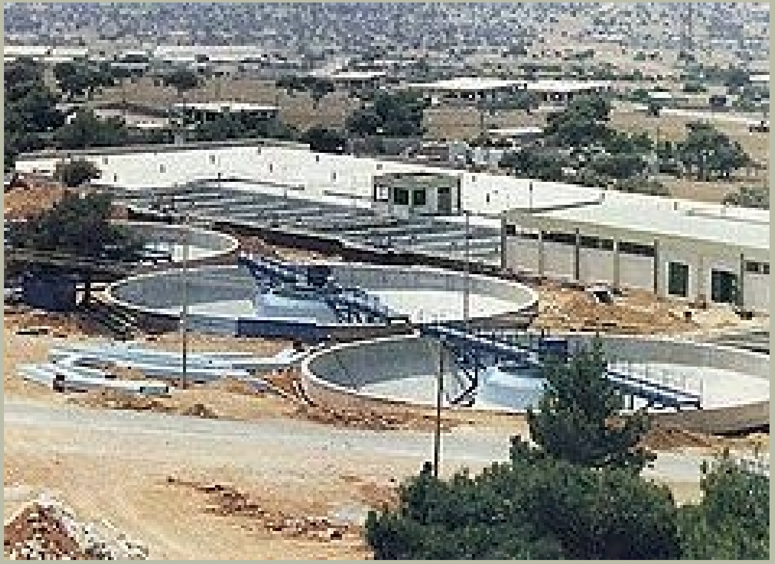
Evinos dam during construction

Construction of the Evinos-Mornos connection tunnel

Treatment plants

Perissos water treatment plant

Aspropyrgos water treatment plant



The Mornos dam and reservoir

The Evinos works at their final phase of construction – July 1999