The management of the Athens water resource system: Methodology and implementation

Demetris Koutsoyiannis

Department of Water Resources, Faculty of Civil Engineering,
National Technical University of Athens

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School of Civil and Environmental Engineering, Georgia Institute of Technology

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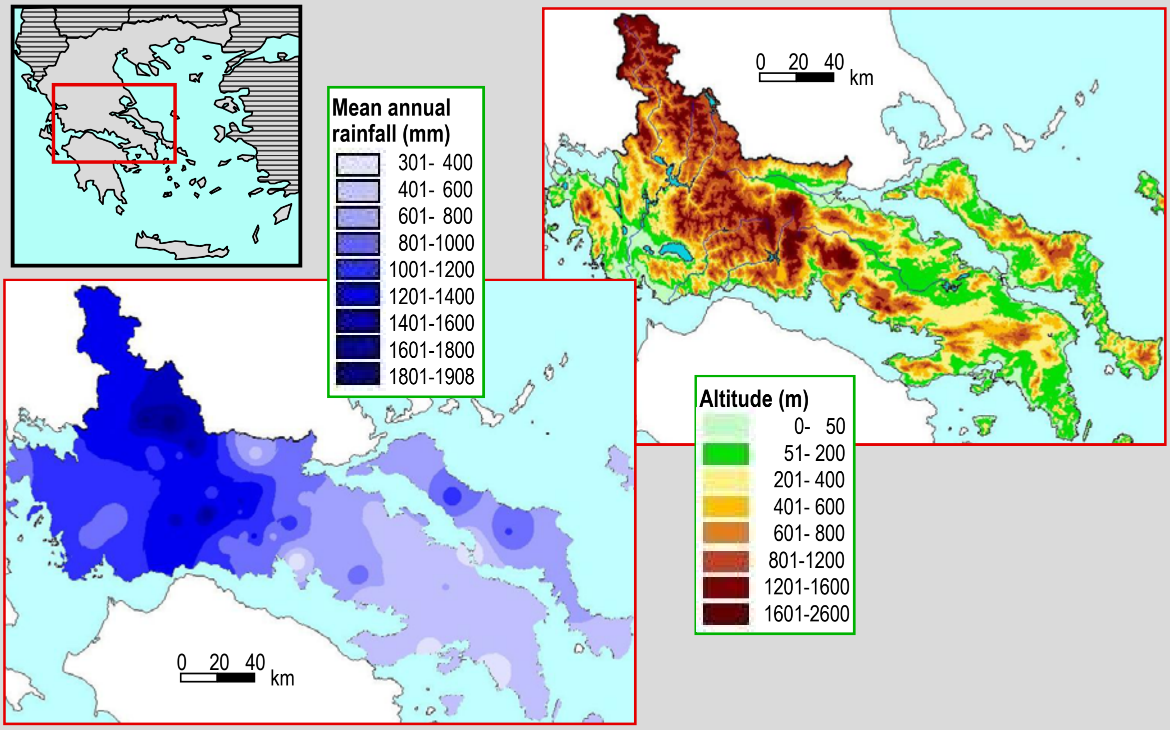
Acknowledgments

Ὕσον, ὕσον Ζεῦ κατὰ τῆς ἀρούρης τῶν Ἀθηναίων

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



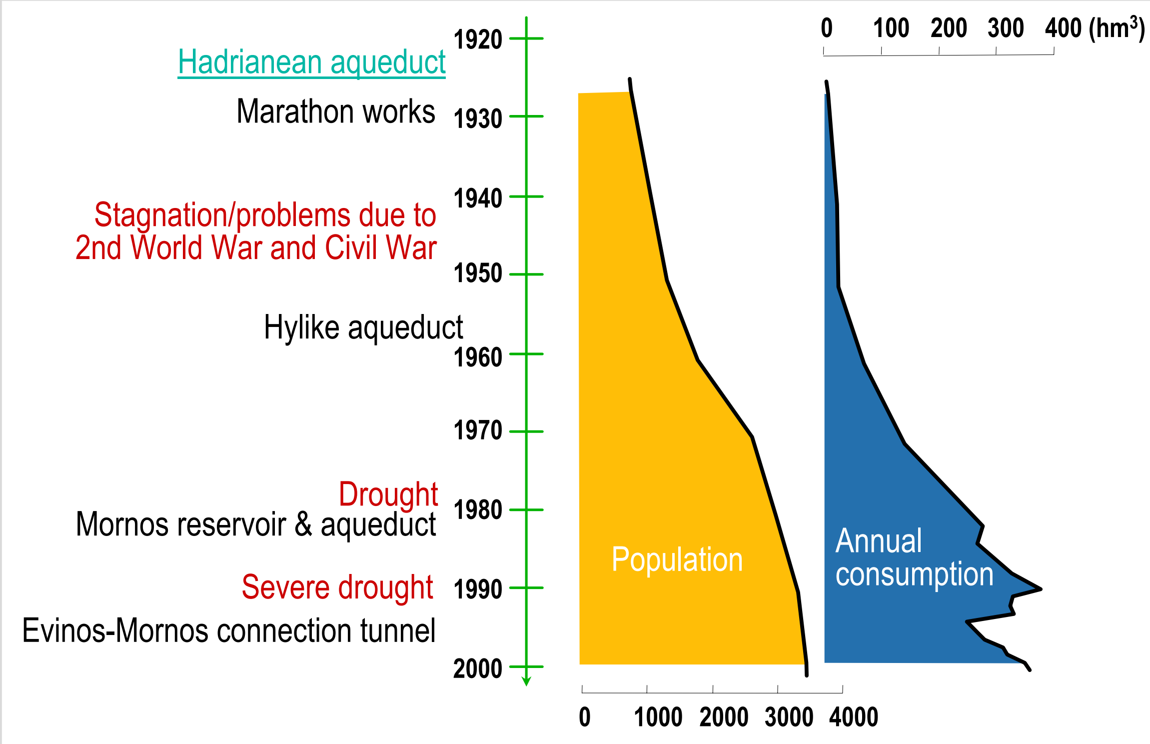
Parts of the presentation

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

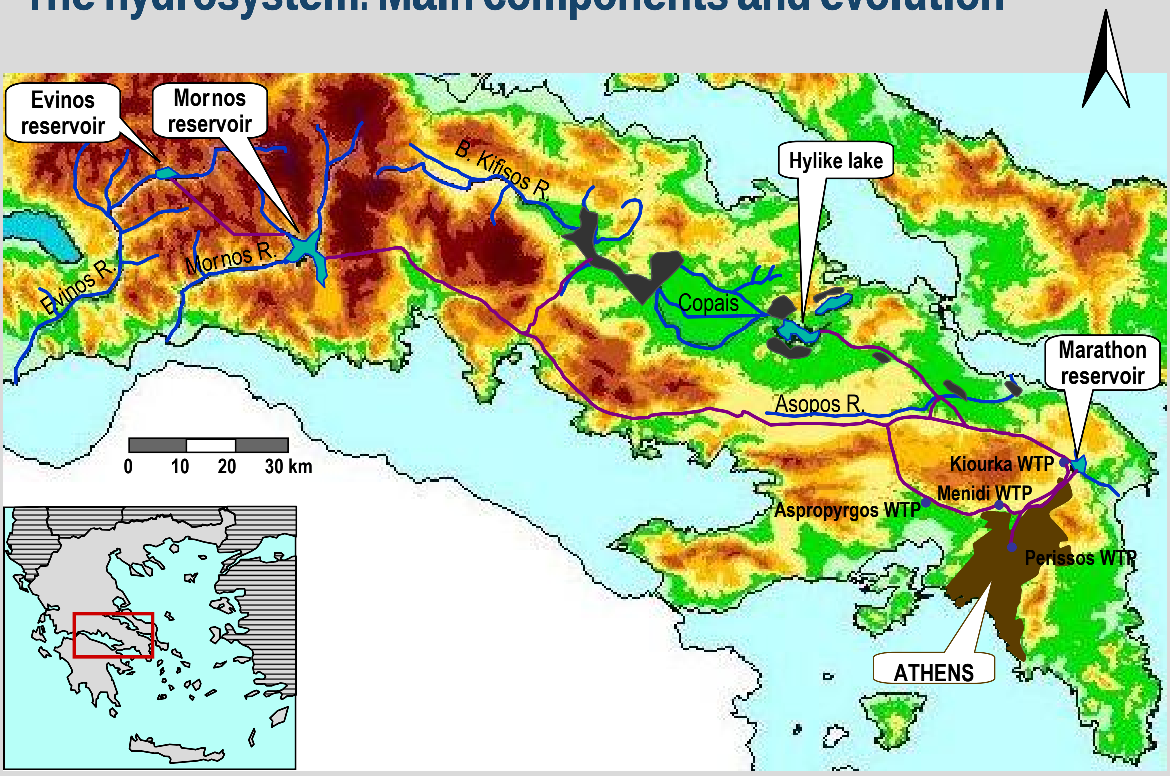
2. Hydrosystem operation issues
   Parameterization – Simulation – Optimization

3. Decision support tool integration
   Data acquisition – Software systems – Management plans

Evolution of water consumption – Milestones



The hydrosystem: Main components and evolution

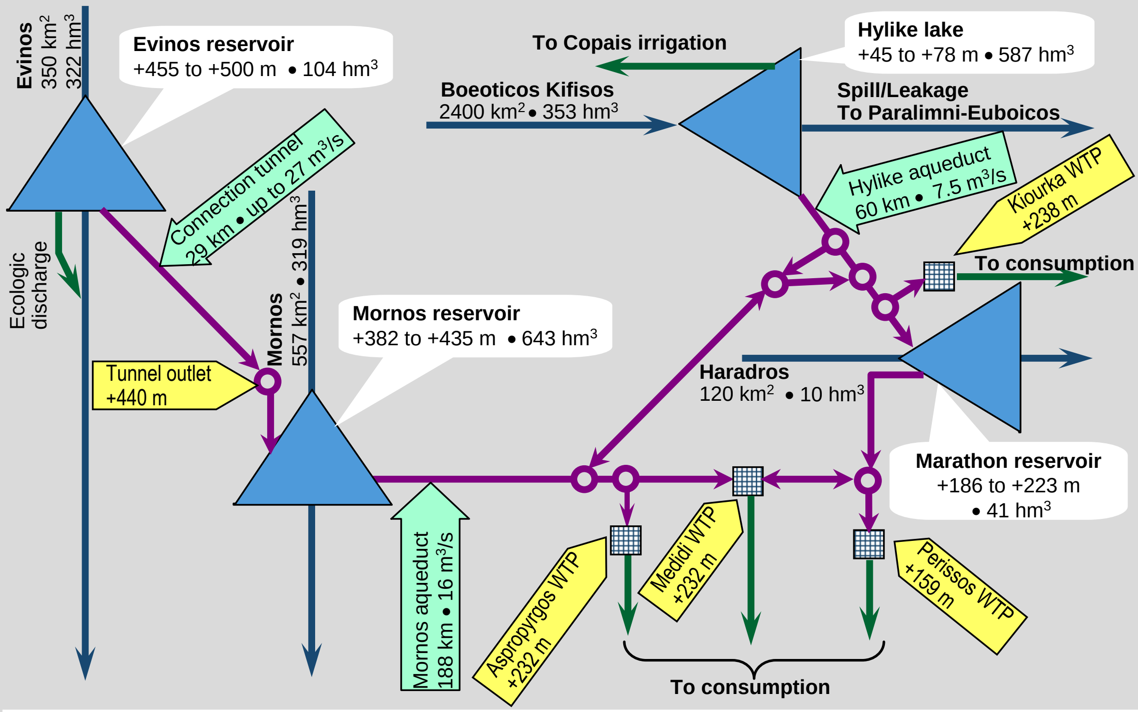


Classification of water resources

Basin	SURFACE WATER Primary (Reservoirs)	SURFACE WATER Secondary (Reservoirs)	GROUNDWATER Backup (Boreholes)
Evinos 350 km²	Evinos 322 hm³/y		
Mornos 557 km²	Mornos 319 hm³/y		
Boeoticos Kifisos – Yliki 2400 km²		Yliki 353 hm³/y	B. Kifisos, middle course 136 hm³/y Yliki region 85 hm³/y
Haradros 120 km²		Marathon 10 hm³/y	
North Parnetha			Viliza 26 hm³/y Mavrosouvala 36 hm³/y

Area	Inflow	Pumping capacity	High spill	High leakage	Pumping

Hydrosystem: Current structure



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

2. Hydrosystem operation issues
Parameterization – Simulation – Optimization

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)

{1,2,4}

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
  - Hydroclimatic inputs: Climate change
- Adequacy/safety under exceptional events – Required measures
  - Damages
  - Special demand occasions (e.g. 2004 Olympic Games)

The methodology: General aspects

Question 1: Simulation **or** optimization?

- Simulation **versus** optimization (water resources literature and practice)
- Simulation methods **for** optimization (more mathematical literature)

Answer: Optimization coupled with simulation

Main advantages
- Determination of optimal policies
- Incorporation of mathematical optimization techniques

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

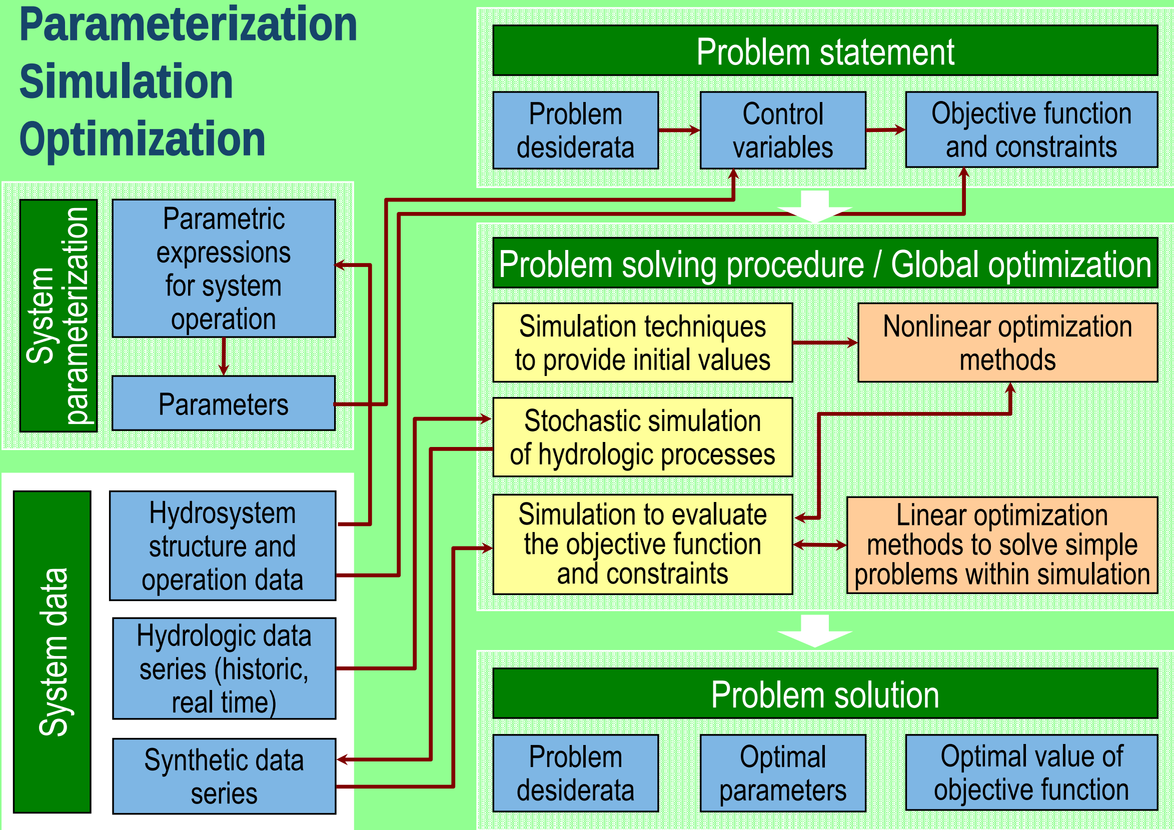
Question 2: Which are the control (decision) variables?

- Typically: Releases from system components in each time step

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

{3,5}

Parameterization
Simulation
Optimization



Introduction to the parametric reservoir operation rule – Some analytical solutions

Maximize 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, 1997)

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

Conveyance rule (Nalbantis & Koutsoyiannis, 1997)

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

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

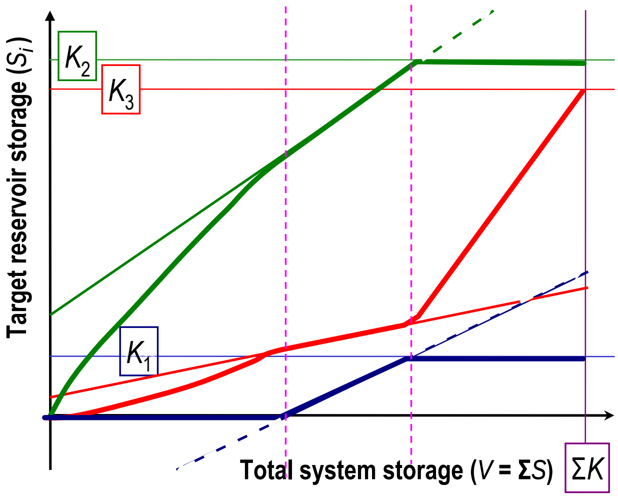
$S_i^* = a_i + b_i V$ (parameters a_i, b_i)
subject to $\Sigma a_i = 0$, $\Sigma b_i = 1$,
since $\Sigma S_i^* = V$

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

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



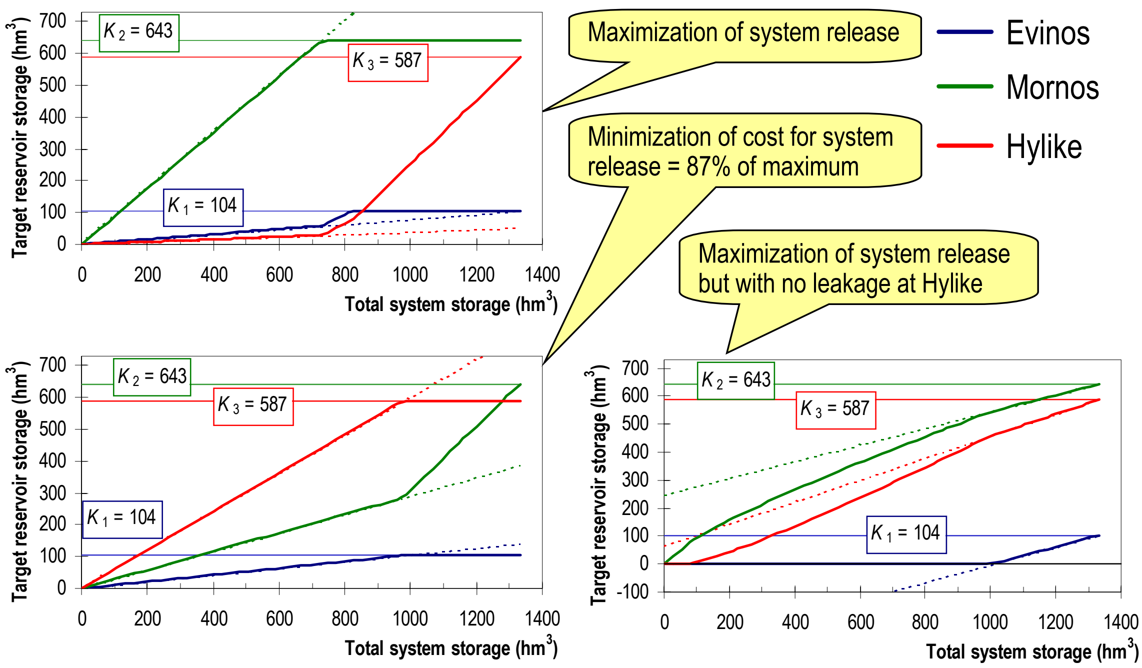
Two parameters per reservoir (a_i, b_i) = **Control variables**
Parameter values **determined by optimization** – depending on the objective function
Parameters may depend also on season (e.g., refilling-emptying period, or months)
2 × (reservoirs – 1) × seasons total parameters for the reservoir system

A comparison with non-parametric optimization

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 optimization	Parametric rule based optimization
Number of control variables: 1000 × 12 monthly releases × (3 – 1) reservoirs + 1 (problem target) = 24001	Number of control variables: 2 parameters/reservoir/ season × (3 – 1) reservoirs × 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 (perfect foresight)	Control variables do not depend on inflow series but on their statistical properties No assumption of known inflows
The optimization model needs continuous runs with updated data	Once parameters are optimized, the system can be operated without running the model

Application of the parametric rule – Optimal results

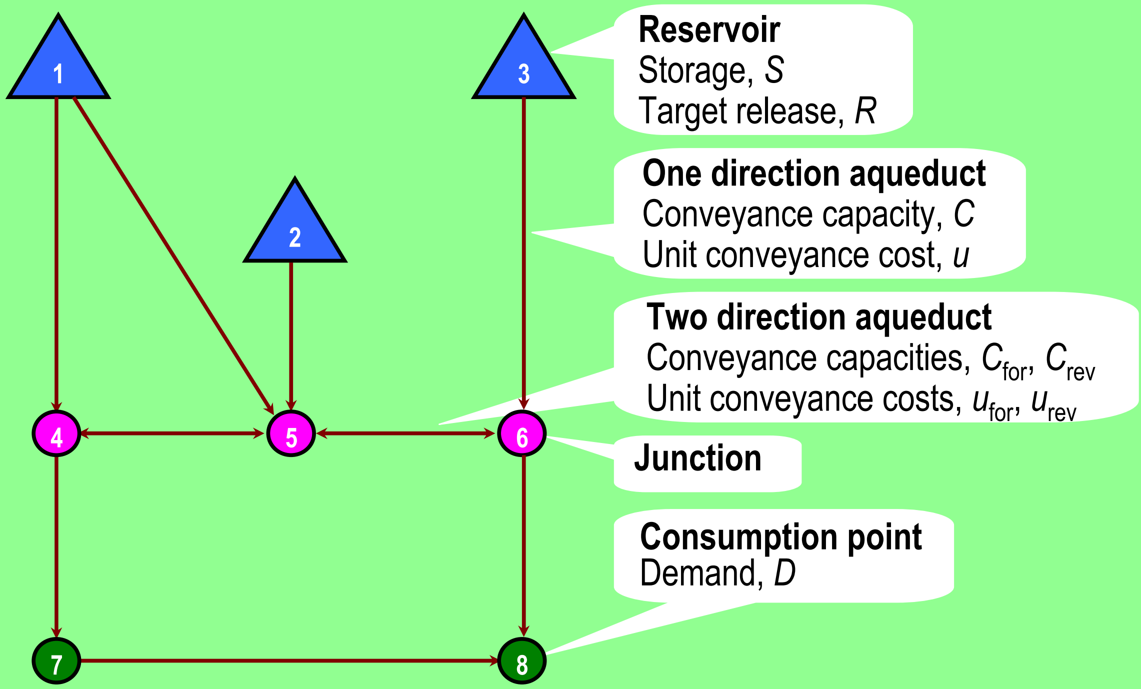


Considering the complete hydrosystem – Simulation

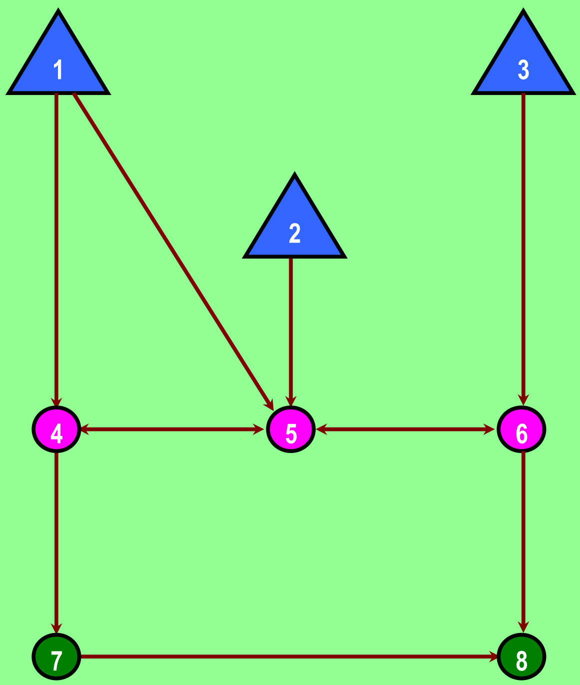
- Assuming that parameters a_i and b_i are known, the **target releases** from each reservoir will be also known in the beginning of each simulation time step
- The **actual releases** depend on several attributes of the hydrosystem (physical constraints)
- Their estimation is done using **simulation**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

PSO approach

Hydrosystem components and attributes



Conveyance problem formulation

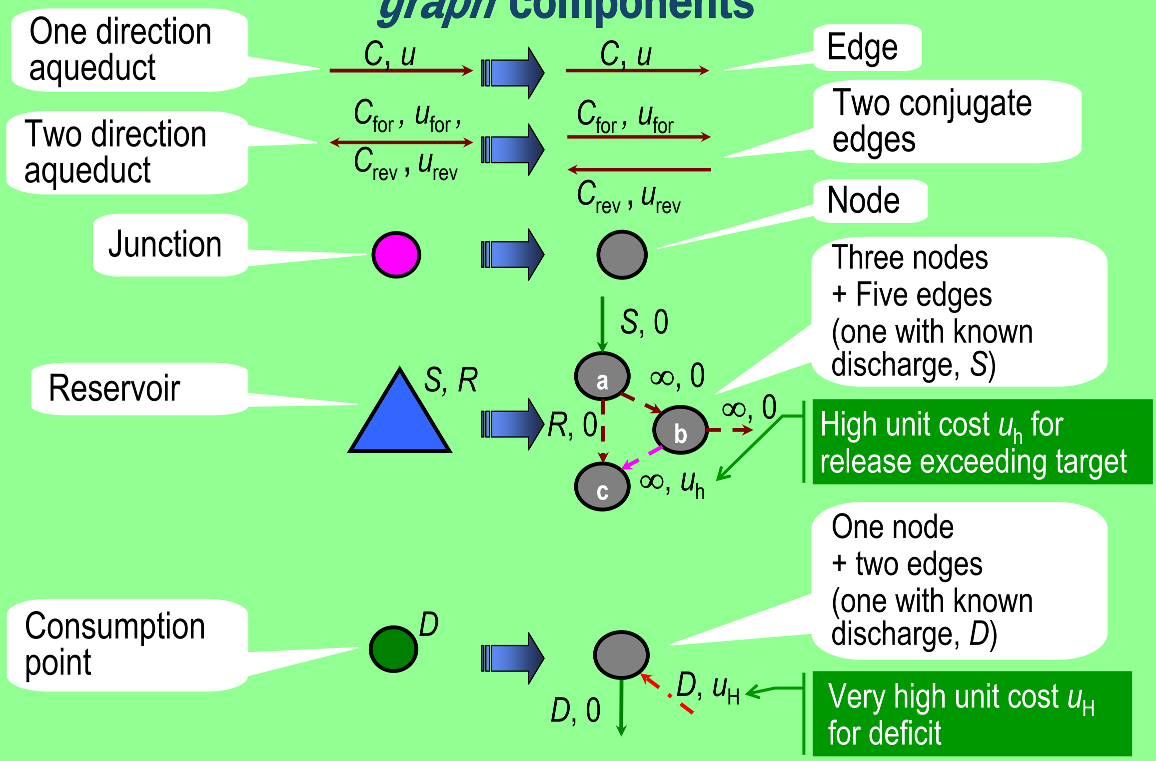


Given:
- Demands (*D*)
- Reservoir storages (*S*),
- Reservoir target releases ($R \leq S$; $\Sigma R = \Sigma D$; from parametric rule)

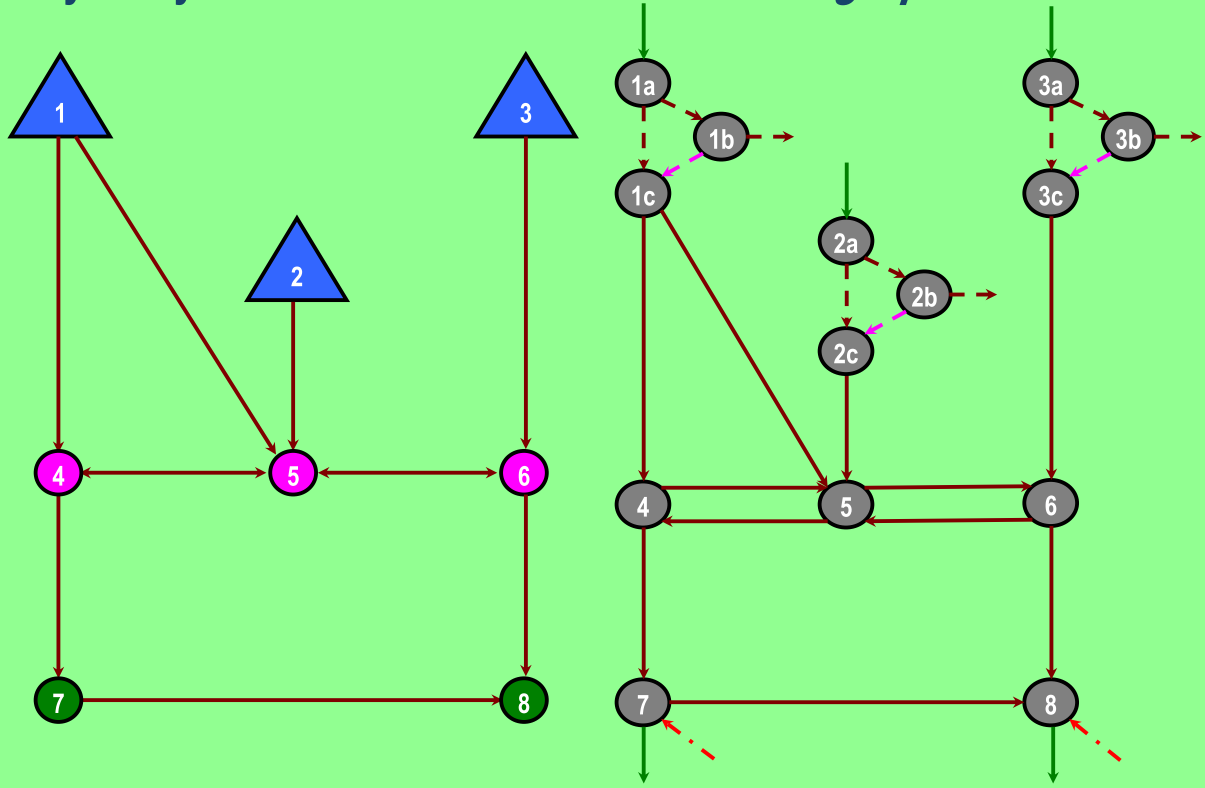
Required:
- Actual (feasible) consumptions (at consumption points)
- Actual (feasible) releases (from reservoirs)
- Aqueduct discharges
- Conveyance cost

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

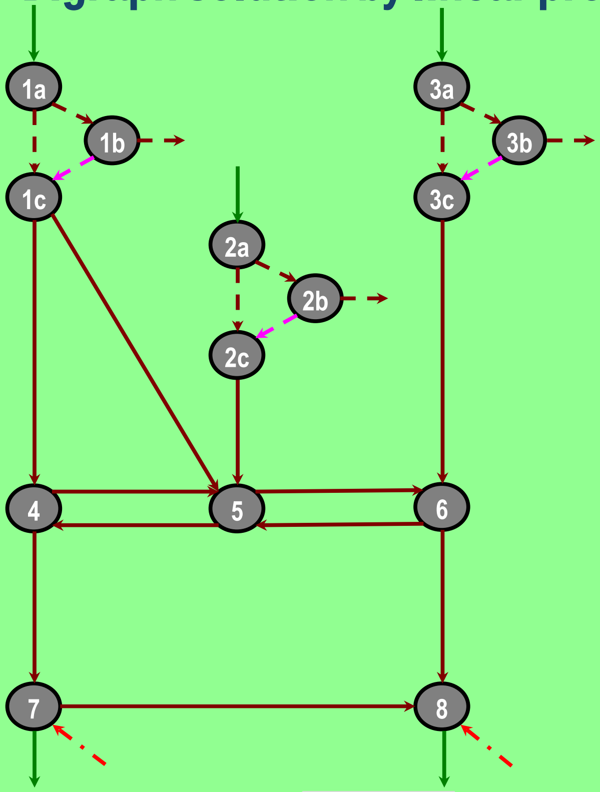
Transformations of hydrosystem components to *graph* components



Hydrosystem and its transformation to *digraph*



Digraph solution by linear programming



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

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

subject to equality constraints for each node *i*

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

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

$$0 \le Q_{ij} \le C_{ij}$$

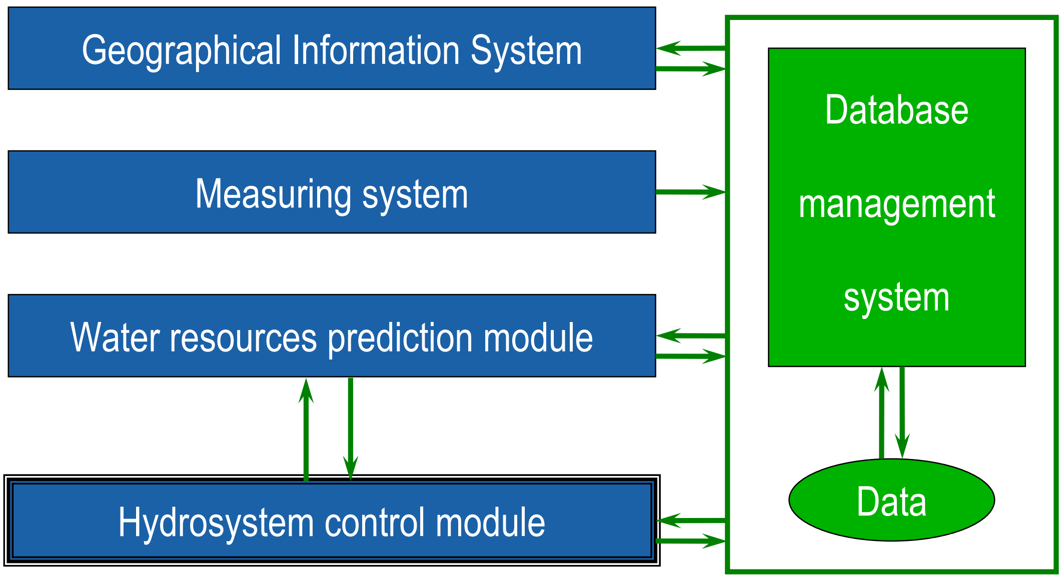
PSO approach

General evaluation and extensions of the parameterization-simulation-optimization method

- Is parametric rule underparametrized?
  - 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) may improve results (slightly)
- How results of parametric rule based optimization compare to those of nonparametric optimization methods?
  - Generally, they are not inferior
  - In the non realistic case of *perfect foresight*, high dimensional methods may outperform parametric method *with no foresight* (slightly, up to about 2%)
  - In practice, in complex nonlinear problems the parametric method yields better solutions due to more effective locating of global optimum
- Is the parameterization appropriate for all water uses and hydrosystems?
  - Yes, but different parameterizations may be needed for different components (e.g. aquifers)
  - Successful application to hydropower systems

3. Decision support tool integration
Data acquisition – Software systems – Management plans

Decision support tool structure



Measuring system

Central data base (archiving and processing of data)

Central data collection unit (daily transmission by phone)

Evinos Peripheral Data Center

Mornos Peripheral Data Center

Hylike Peripheral Data Center

Marathon Peripheral Data Center

Meteorological station (10 min step)
Rainfall, Temperature, Humidity, Wind, Radiation, Sunshine duration

Reservoir elevation gage (1 h time step)

River level gage (10 min time step)

River flow measuring station (~once a month)

Data management and processing: Time series manipulation

FROM ASCII TO DB → telemetric raw data

telemetric raw data → RANGE CHECK TIME CONSISTENCY → raw data irregular time step

raw data irregular time step → FIXING OF TIME STEP → 10 minute processed data

10 minute processed data → AGGREGATION → hourly aggregated data

hourly aggregated data → AGGREGATION → daily aggregated data

daily aggregated data → COALITION OF SEVERAL SENSORS → daily coalesced data

daily coalesced data → INFILLING OF MISSING VALUES FROM OTHER STATIONS → daily filled data

daily filled data → AGGREGATION → monthly aggregated data

monthly aggregated data → INFILLING OF MISSING VALUES FROM OTHER STATIONS → monthly filled data

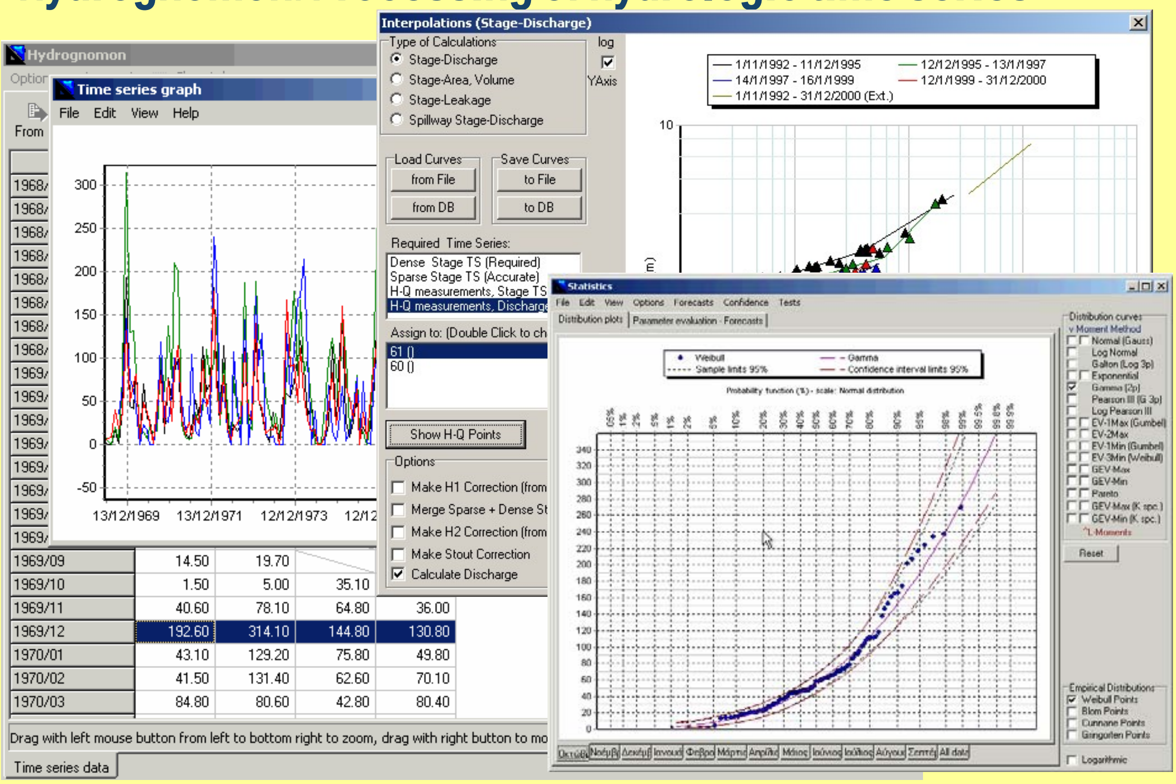
monthly filled data → AGGREGATION → annual aggregated data

METEOROLOGICAL STATIONS
More than 100 time series per station
About one million records per station per year

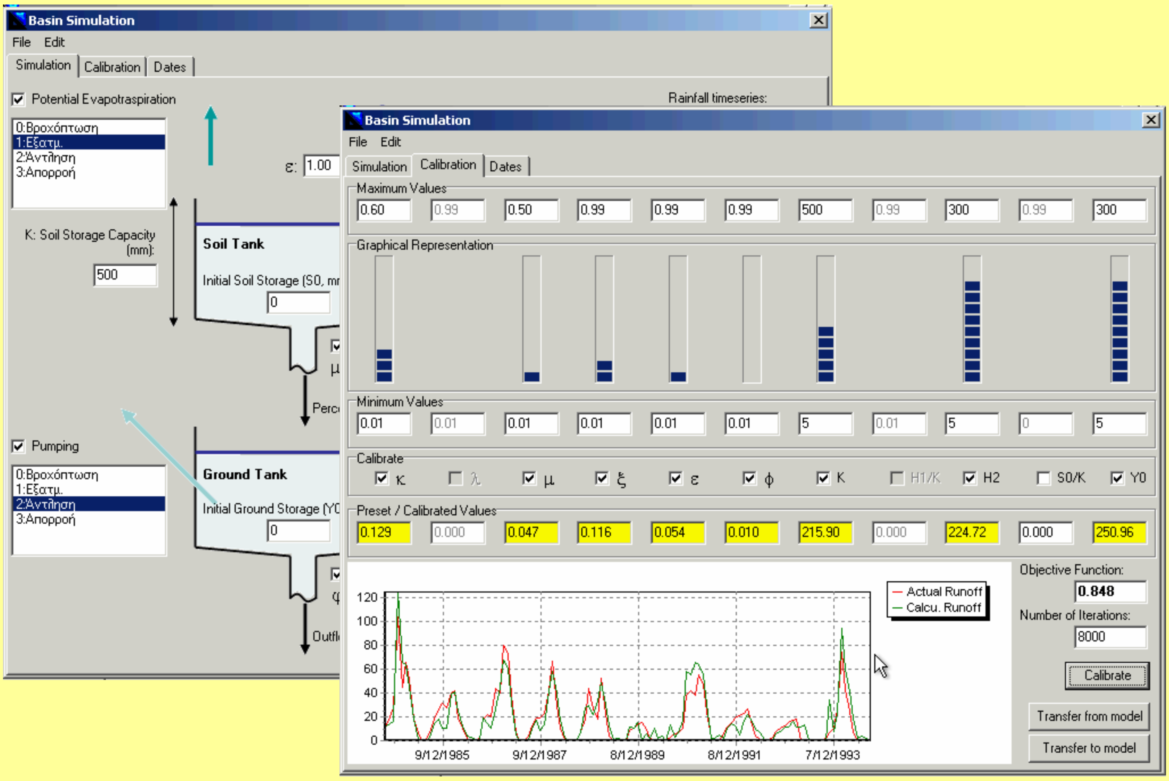
Software system characteristics

- All models written from scratch
- Basic development tool: **Delphi** (Object Pascal)
- Database: **Oracle** (more recently: **PostgreSQL**)
- Geographic system: **ArcView**
- Basic software units
  - **Hydrognomon**: Database management, processing of hydrologic data
  - **Castalia**: Stochastic hydrologic simulator
  - **Hydrogeios**: Simulation of surface and ground water processes
  - **Hydronomeas**: Hydrosystem control

Hydrognomon: Processing of hydrologic time series

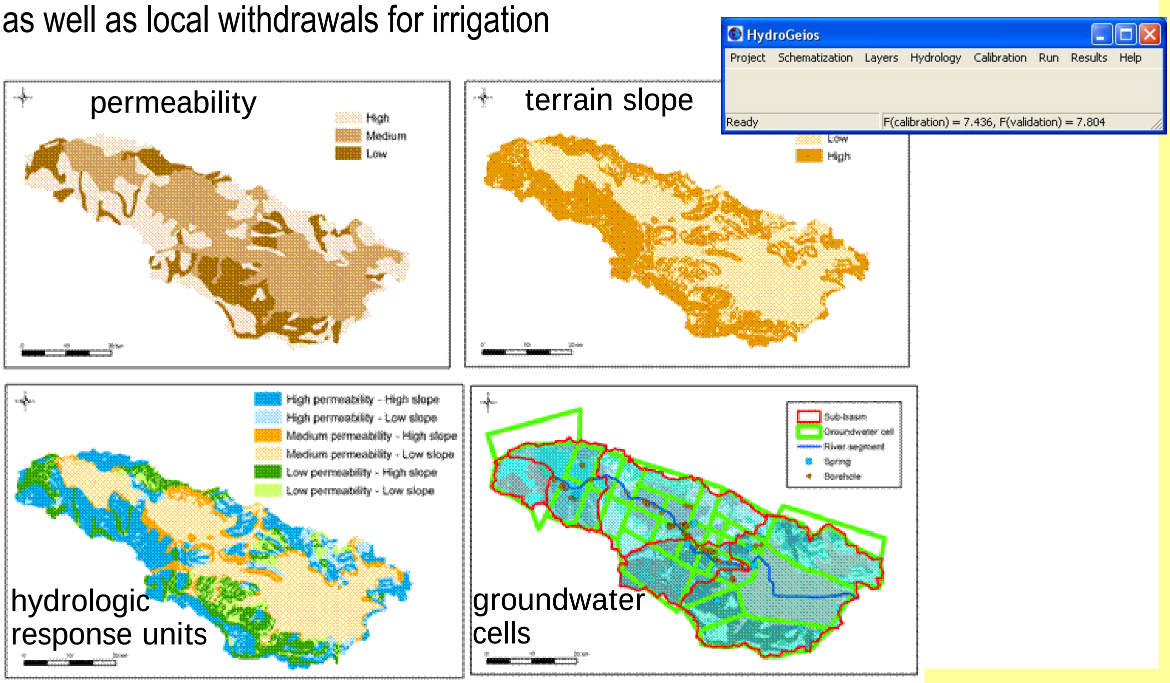


Hydrognomon: Automatic lumped hydrologic modeling

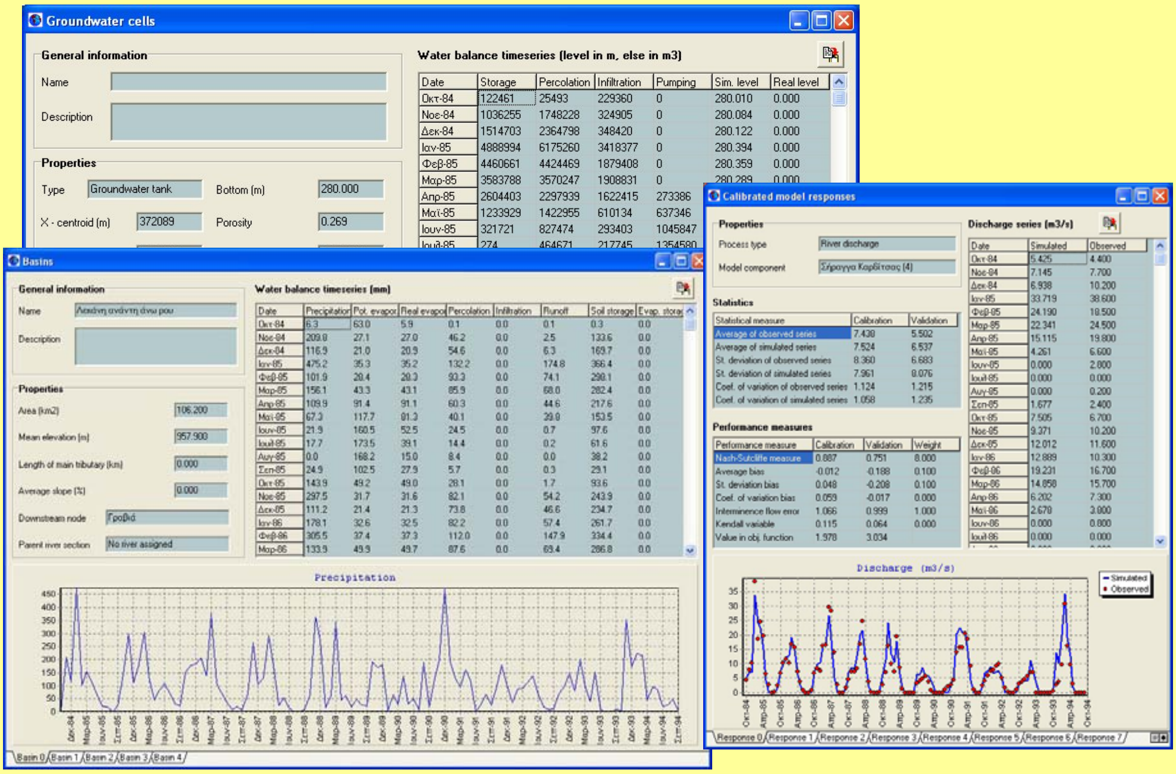


Hydrogeios: Detailed geo-hydrologic modeling

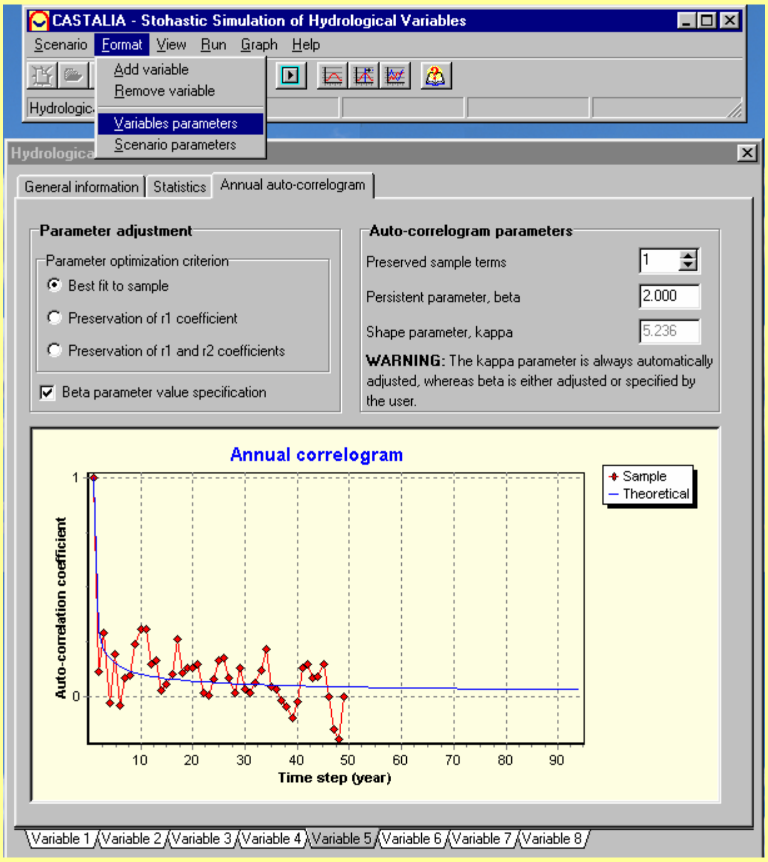
Hydrogeios is a hydrologic model of the entire hydrologic cycle, designed to describe both surface and subsurface processes, and especially karstic processes, as well as local withdrawals for irrigation



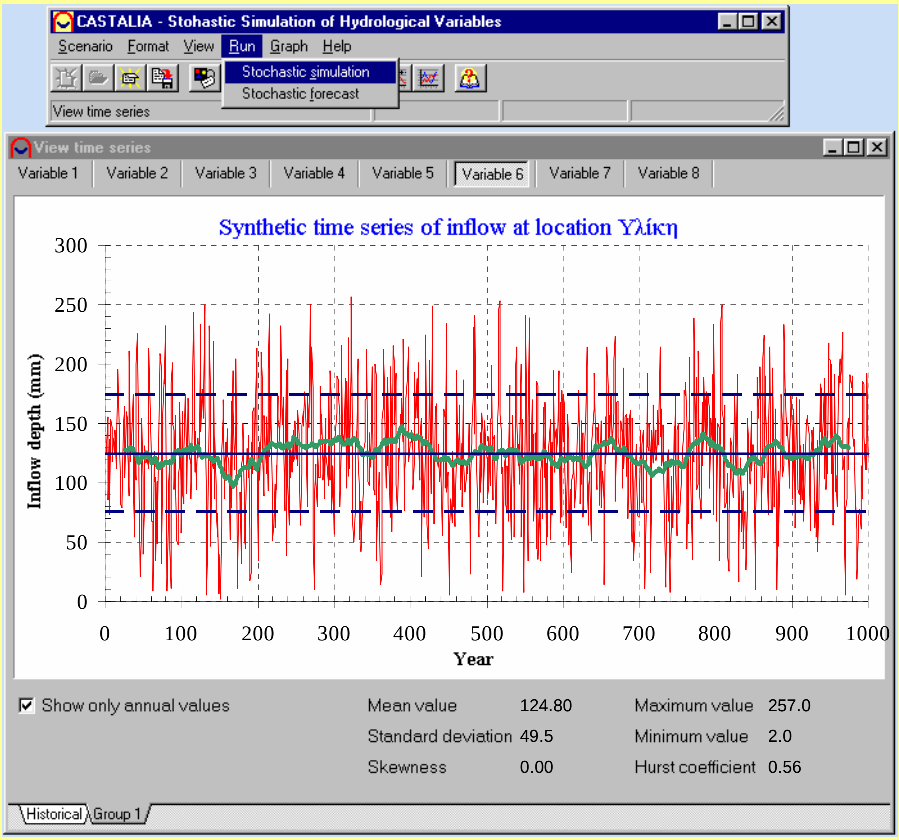
Hydrogeios calibration: vector nonlinear optimization



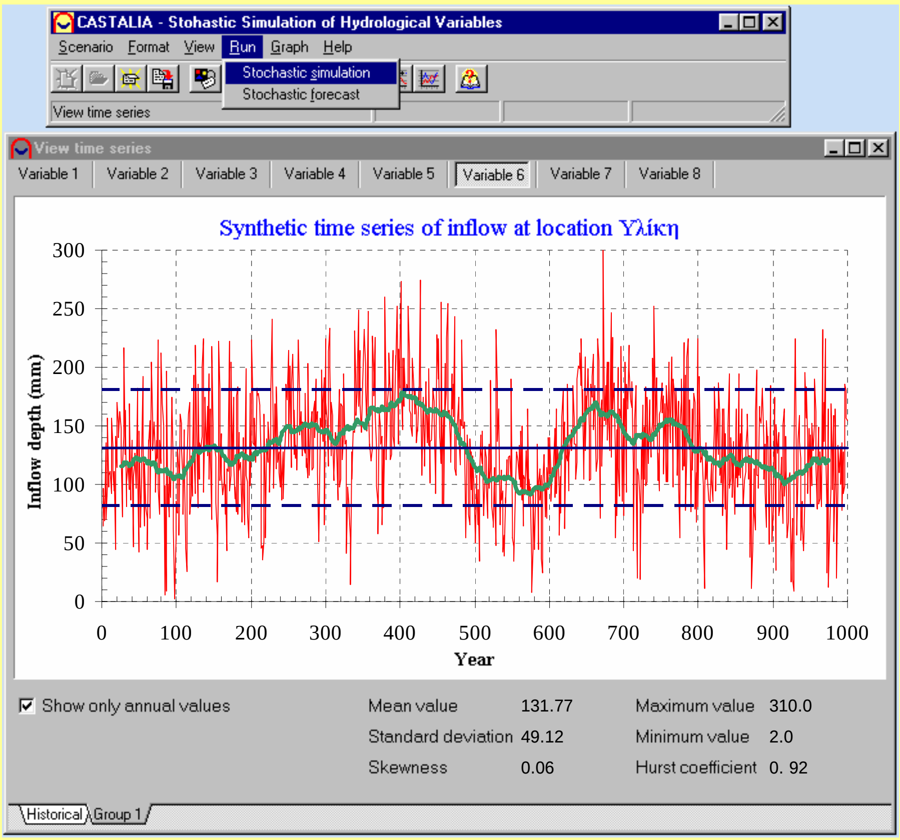
Castalia:
Parameter estimation-Parameters of autocorrelation and persistence



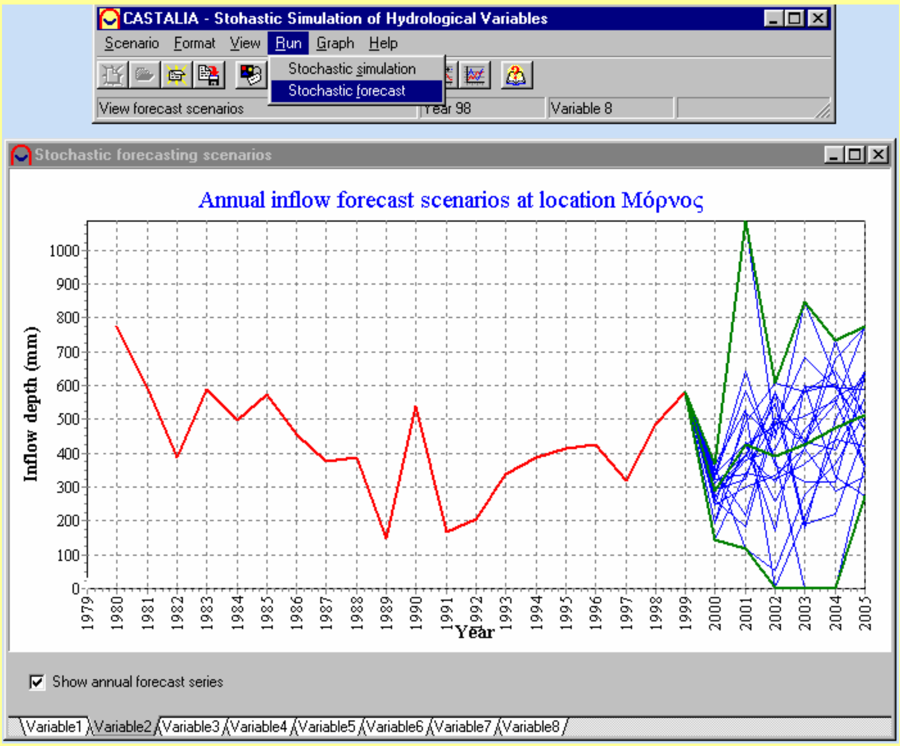
Castalia: Stochastic simulation without long term persistence



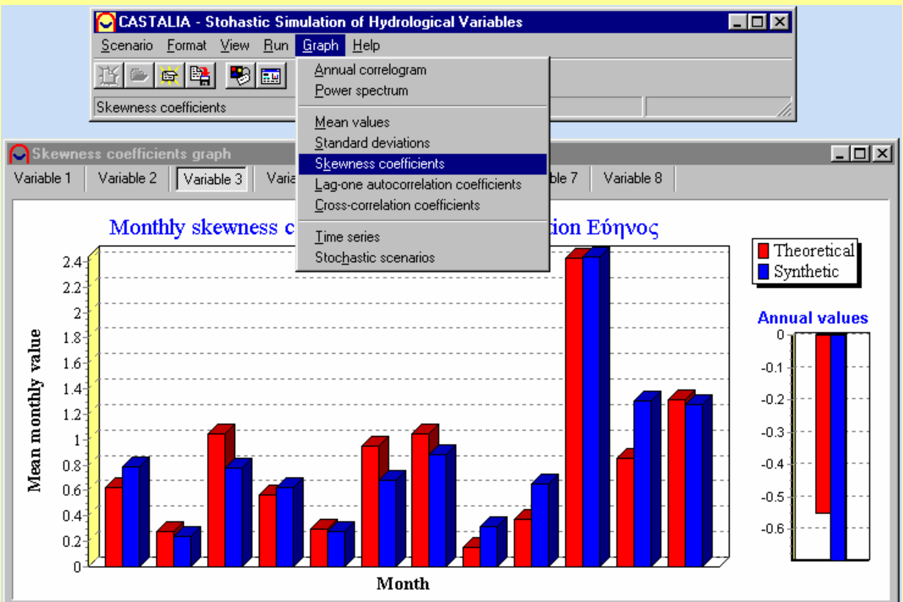
Castalia: Stochastic simulation with long term persistence



Castalia: Stochastic forecasting with long term persistence

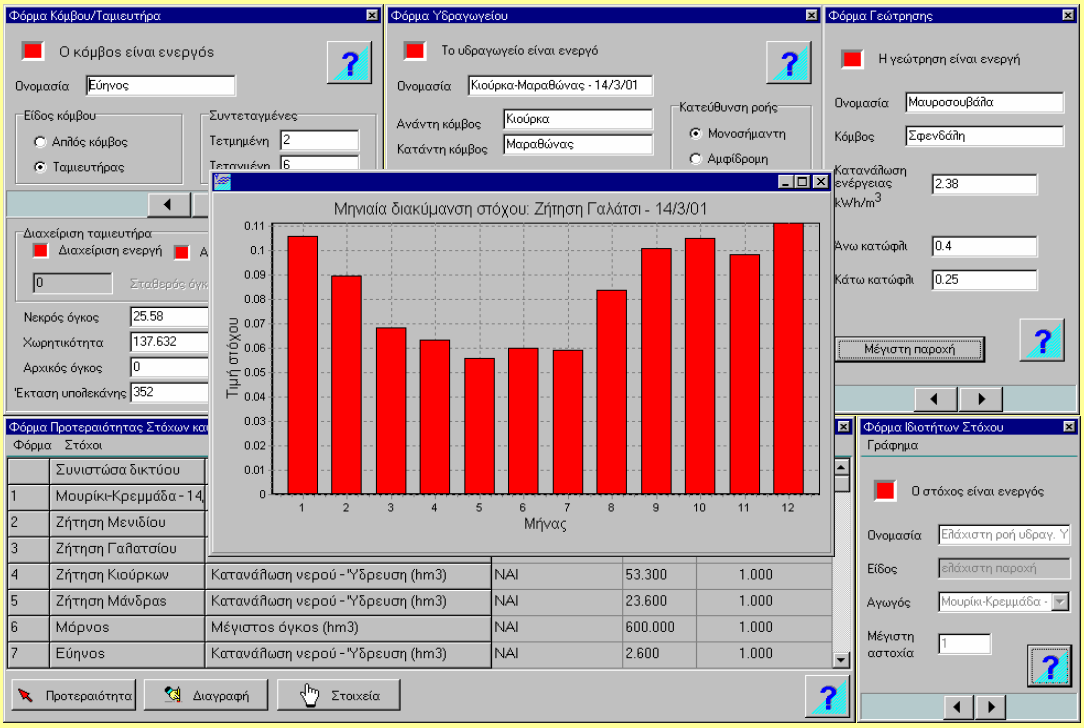


Castalia: Preservation of marginal statistics – Skewness

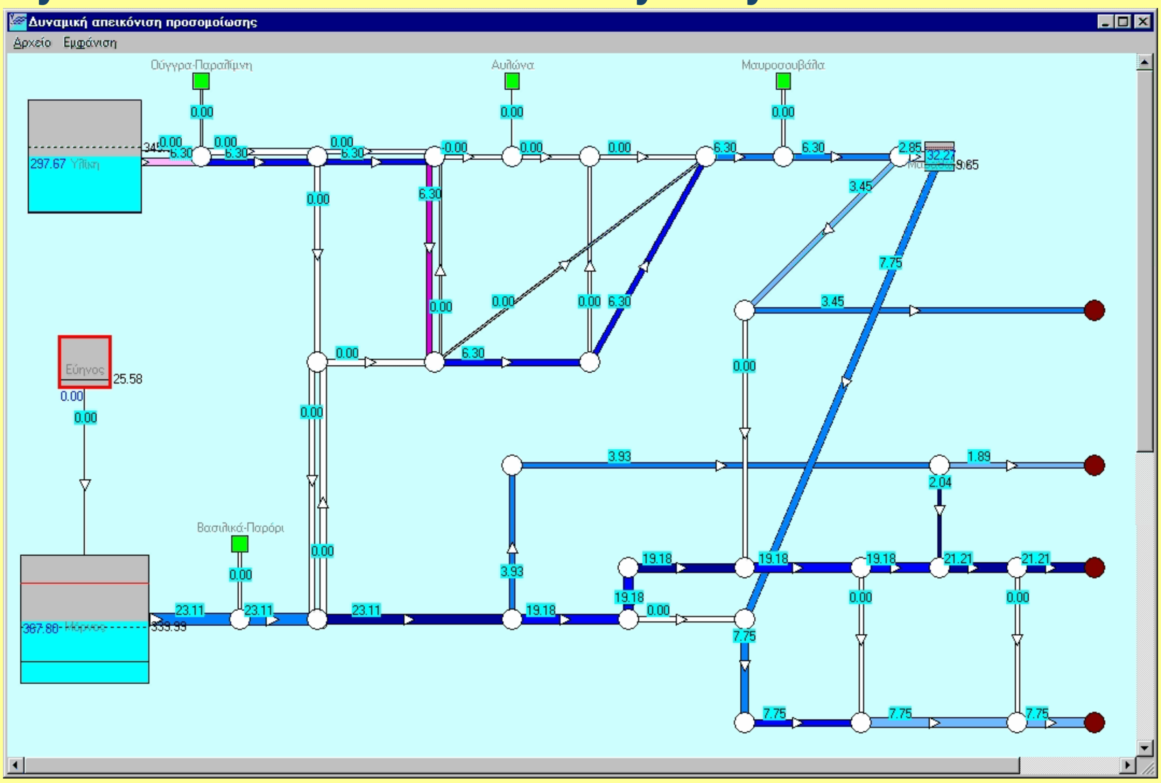


Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Theoretical	0.624	0.275	1.041	0.566	0.299	0.949	1.046	0.156	0.375	2.427	0.856	1.313	-0.550
Synthetic	0.791	0.236	0.779	0.628	0.274	0.680	0.884	0.315	0.651	2.437	1.306	1.273	-0.697

Hydronomeas: Hydrosystem data management

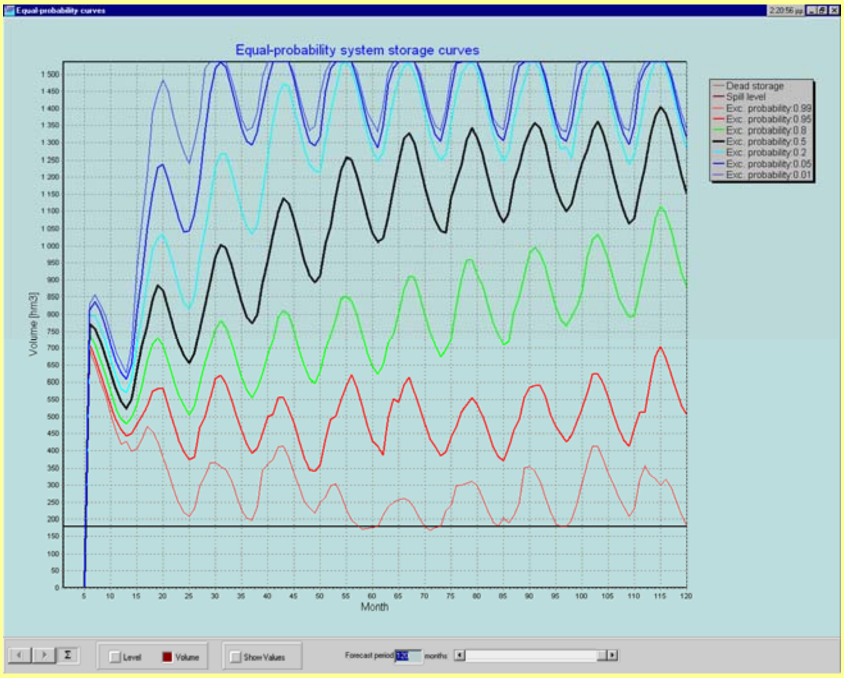


Hydronomeas: Visualization of hydrosystem simulation



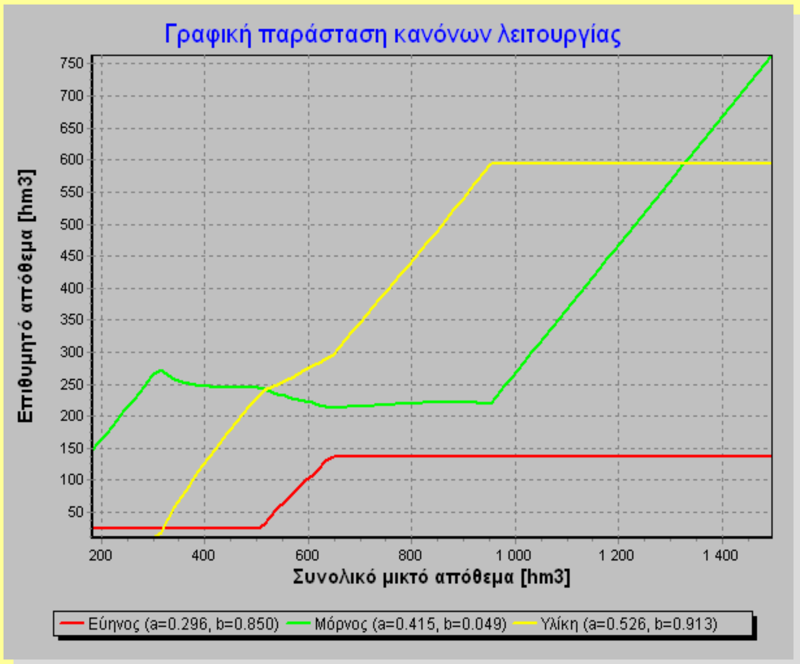
Hydronomeas: Stochastic forecast of hydrosystem storage

Evolution of quantiles of system storage (for several levels of probability of exceedance) for the next 10 years as a result of 200 terminating simulations with long-term persistence



Hydronomeas: Optimal hydrosystem control rules

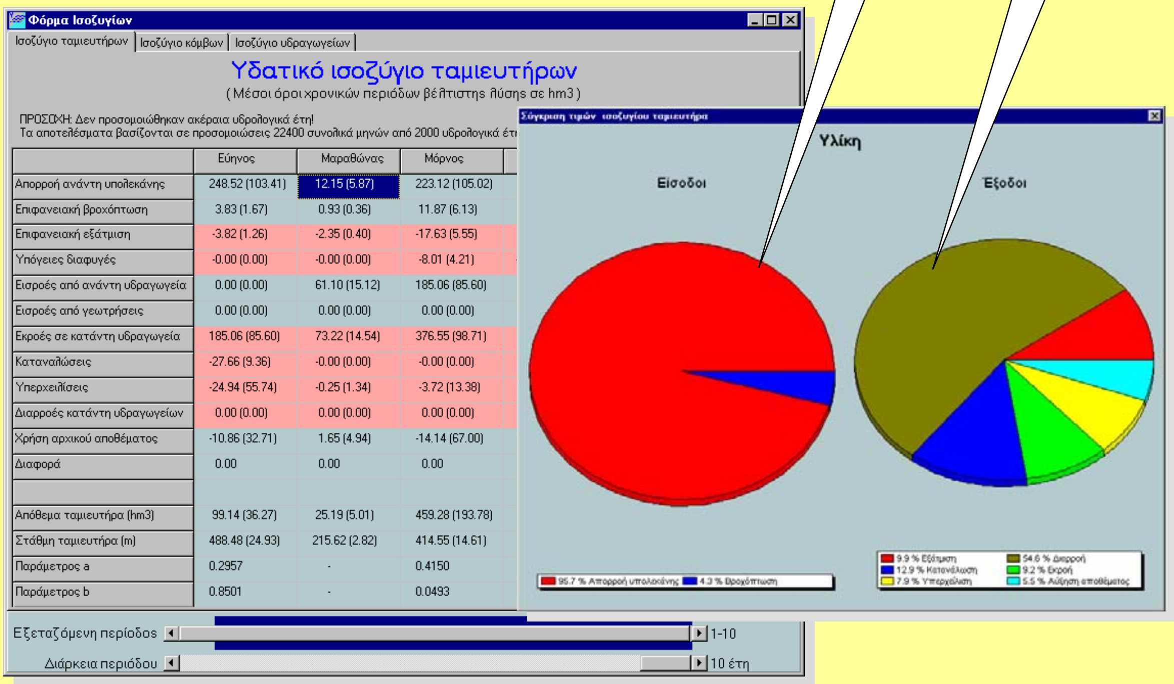
Target allocation of total reservoir storage per each reservoir



Hydronomeas: Reservoir balance

Inflows

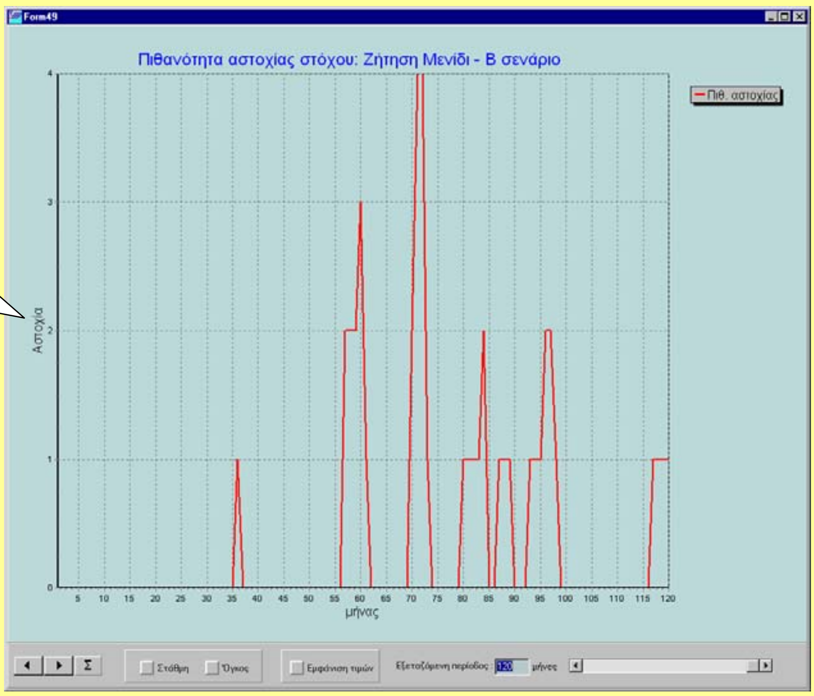
Outflows



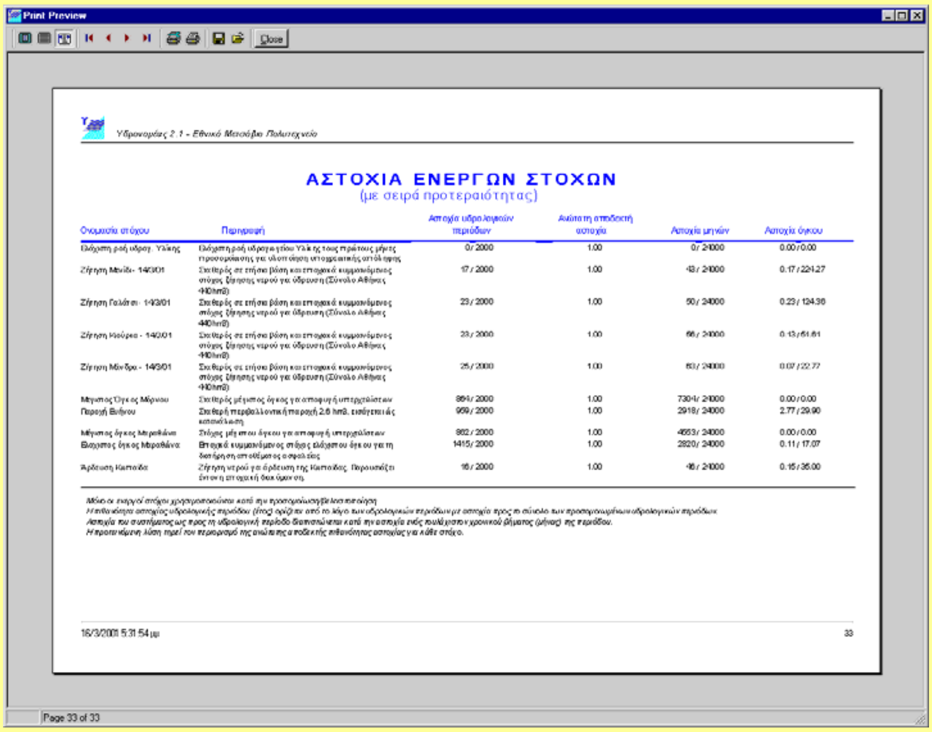
	Εύηνος	Μαραθώνας	Μόρνος
Απορροή ανάντη υπολεκάνης	248.52 (103.41)	12.15 (5.87)	223.12 (105.02)
Επιφανειακή βροχόπτωση	3.83 (1.67)	0.93 (0.36)	11.87 (6.13)
Επιφανειακή εξάτμιση	-3.82 (1.26)	-2.35 (0.40)	-17.63 (5.55)
Υπόγειες διαφυγές	-0.00 (0.00)	-0.00 (0.00)	-8.01 (4.21)
Εισροές από ανάντη υδραγωγεία	0.00 (0.00)	61.10 (15.12)	185.06 (85.60)
Εισροές από γεωτρήσεις	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Εκροές σε κατάντη υδραγωγεία	185.06 (85.60)	73.22 (14.54)	376.55 (98.71)
Καταναλώσεις	-27.66 (9.36)	-0.00 (0.00)	-0.00 (0.00)
Υπερχειλίσεις	-24.94 (55.74)	-0.25 (1.34)	-3.72 (13.38)
Διαρροές κατάντη υδραγωγείων	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Χρήση αρχικού αποθέματος	-10.86 (32.71)	1.65 (4.94)	-14.14 (67.00)
Διαφορά	0.00	0.00	0.00
Απόθεμα ταμιευτήρα (hm3)	99.14 (36.27)	25.19 (5.01)	459.28 (193.78)
Στάθμη ταμιευτήρα (m)	488.48 (24.93)	215.62 (2.82)	414.55 (14.61)
Παράμετρος a	0.2957	-	0.4150
Παράμετρος b	0.8501	-	0.0493

Hydronomeas: Time profile of failure probabilities

Number of failures in a total of 200 stochastic scenarios



Hydronomeas: Reporting



Management plans and every day operation of the hydrosystem

- Every five years a master plan of the water supply of Athens is elaborated (the first was issued in 2000)
- Every year the master plan is revised based on current data and model runs
- Every three months the annual plan is reassessed and, if necessary, updated by new model runs
- Meanwhile, the every day management is based on optimal parametric operation rules
- Models are run for a 10-year lead time to account for long-term effects of today's decisions
- The general management targets are:
  - Adequacy of water resources
  - Adequacy of conveyance system
  - Cost effectiveness
- All management is based on a probabilistic approach of forecasts/risk/reliability assuming:
  - Acceptable reliability 99% on an annual basis
  - Potential for further increase of reliability taking into account elasticity of demand and emergency measures in case of impending failure
- So far, the decision support tool and its modules (thoroughly tested for the Olympics 2004) exhibited good performance

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3. Koutsoyiannis, D., and A. Economou, Evaluation of the parameterization-simulation-optimization approach for the control of reservoir systems, *Water Resources Research*, 39(6), 1170, 1-17, 2003.
4. Koutsoyiannis, D., A. Efstratiadis, and G. Karavokiros, A decision support tool for the management of multi-reservoir systems, *Journal of the American Water Resources Association*, 38(4), 945-958, 2002.
5. Nalbantis, I., and D. Koutsoyiannis, A parametric rule for planning and management of multiple reservoir systems, *Water Resources Research*, 33(9), 2165-2177, 1997.

Acknowledgments

Early stage

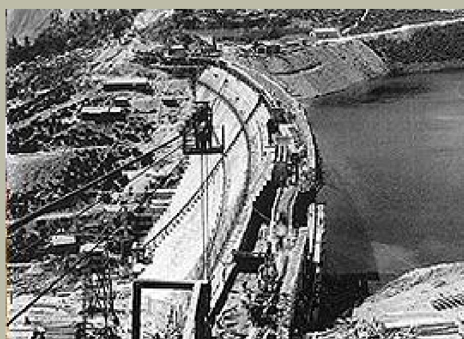
The Hadrianean aqueduct

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

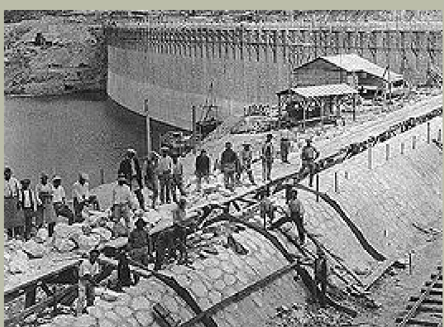
Milestones

Marathon dam

Today



Construction of dam, 1928



Construction of spillway, 1928

Hydrosystem
More pictures

Marathon dam (2)

Devastating flood, 1926

Inauguration of Boyati tunnel, 1928

Marathon spillway in action, 1941

Hydrosystem

Previous pictures

Hylike lake and pumping stations

Hylike lake

Hylike, floating pumping stations

Hylike, main pumping station

Kiourka pumping station

Hydrosystem

Mornos reservoir and aqueduct

Mornos reservoir

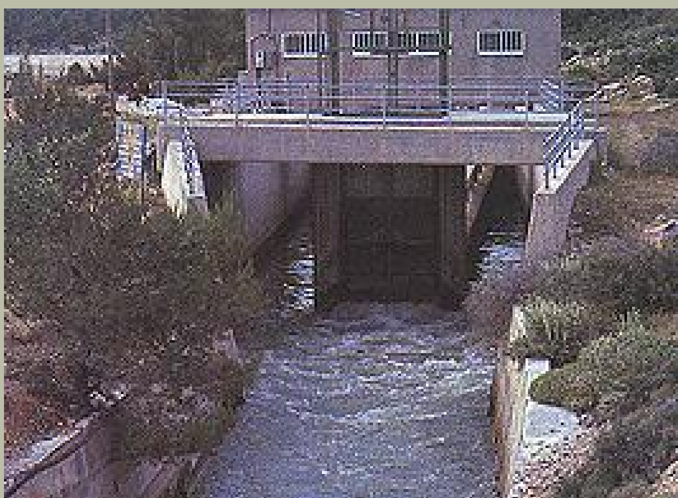
Mornos canal at Delphi

Siphon at Distomo

Mornos canal at Thebes plain

Hydrosystem

Control of Mornos aqueduct



Canal flow control construction

Aqueduct supervizing & control centre

Hydrosystem

Evinos dam and tunnel

Evinos dam during construction

Construction of the Evinos-Mornos connection tunnel

Hydrosystem

Treatment plants

Perissos water treatment plant

Aspropyrgos water treatment plant

Hydrosystem