Lecture given in the context of TUM visiting activities

Athens, 5 October 2016

The water supply system of Athens: Management complexities and modelling challenges vs. low risk & cost decisions

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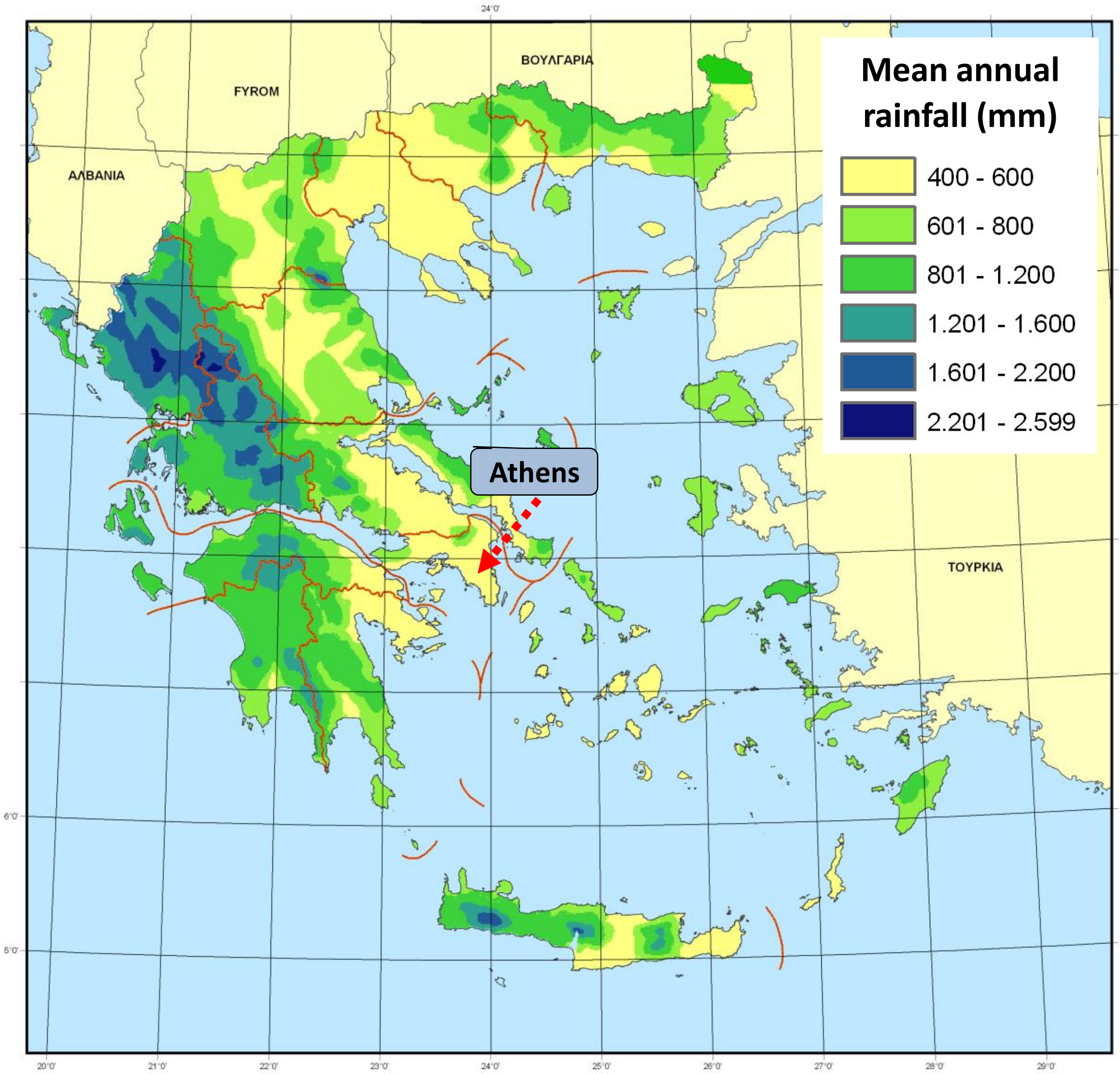
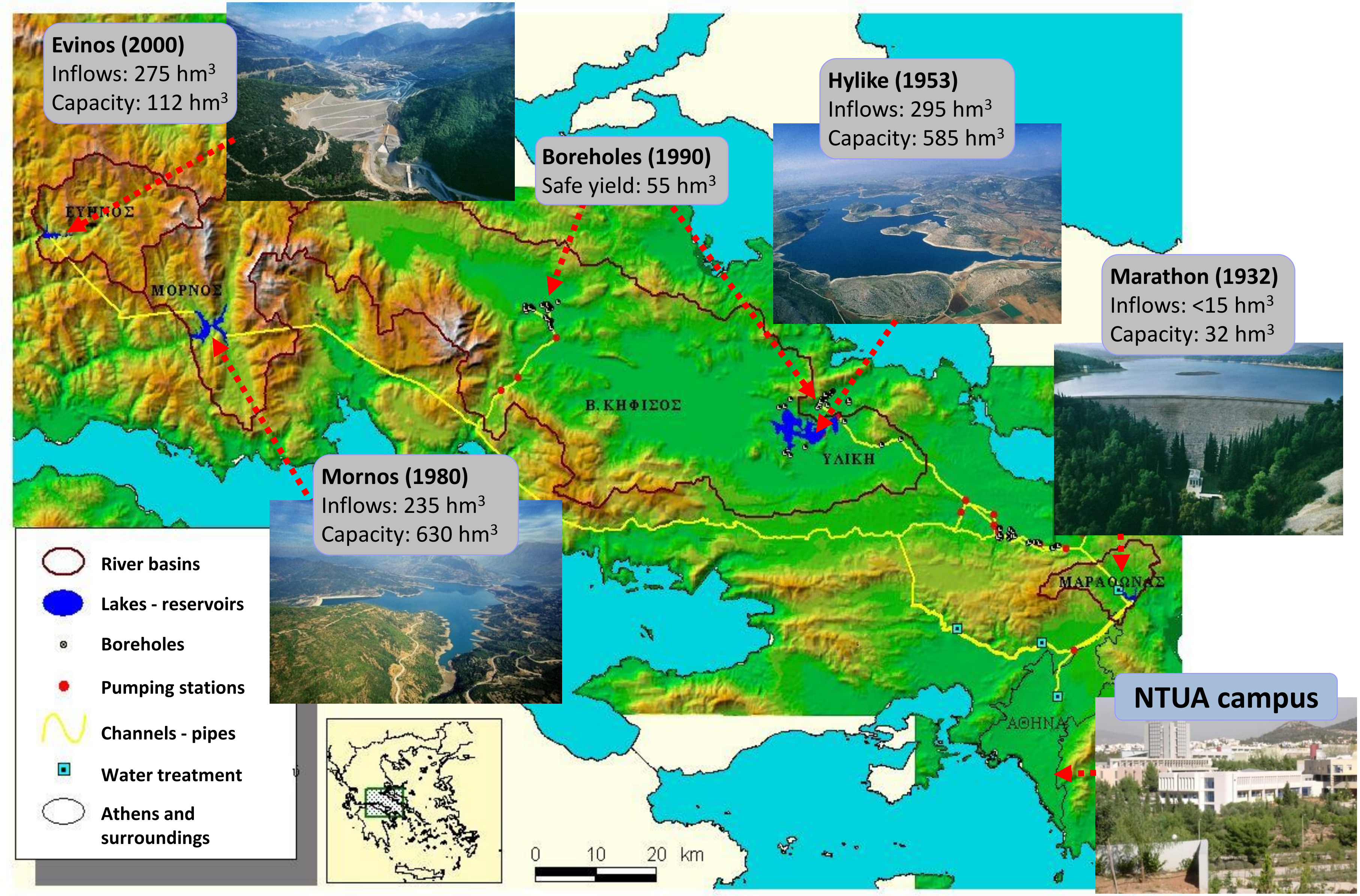
The hydrological "paradox" of Greece

- While Western Greece is very prosperous in water recourses (wet climate, mountainous topography), it is weakly developed.
- Eastern Greece attracts most of the population (~40% in Athens) and the economic activities, but is poor in water, due to its semi-arid hydroclimatic regime.
- Large transfer projects are essential to restore both water and energy "equilibrium" across the country.



The water supply system of Athens (~ 4000 km^2)



Evinos (2000)
Inflows: 275 hm^3
Capacity: 112 hm^3

Boreholes (1990)
Safe yield: 55 hm^3

Hylike (1953)
Inflows: 295 hm^3
Capacity: 585 hm^3

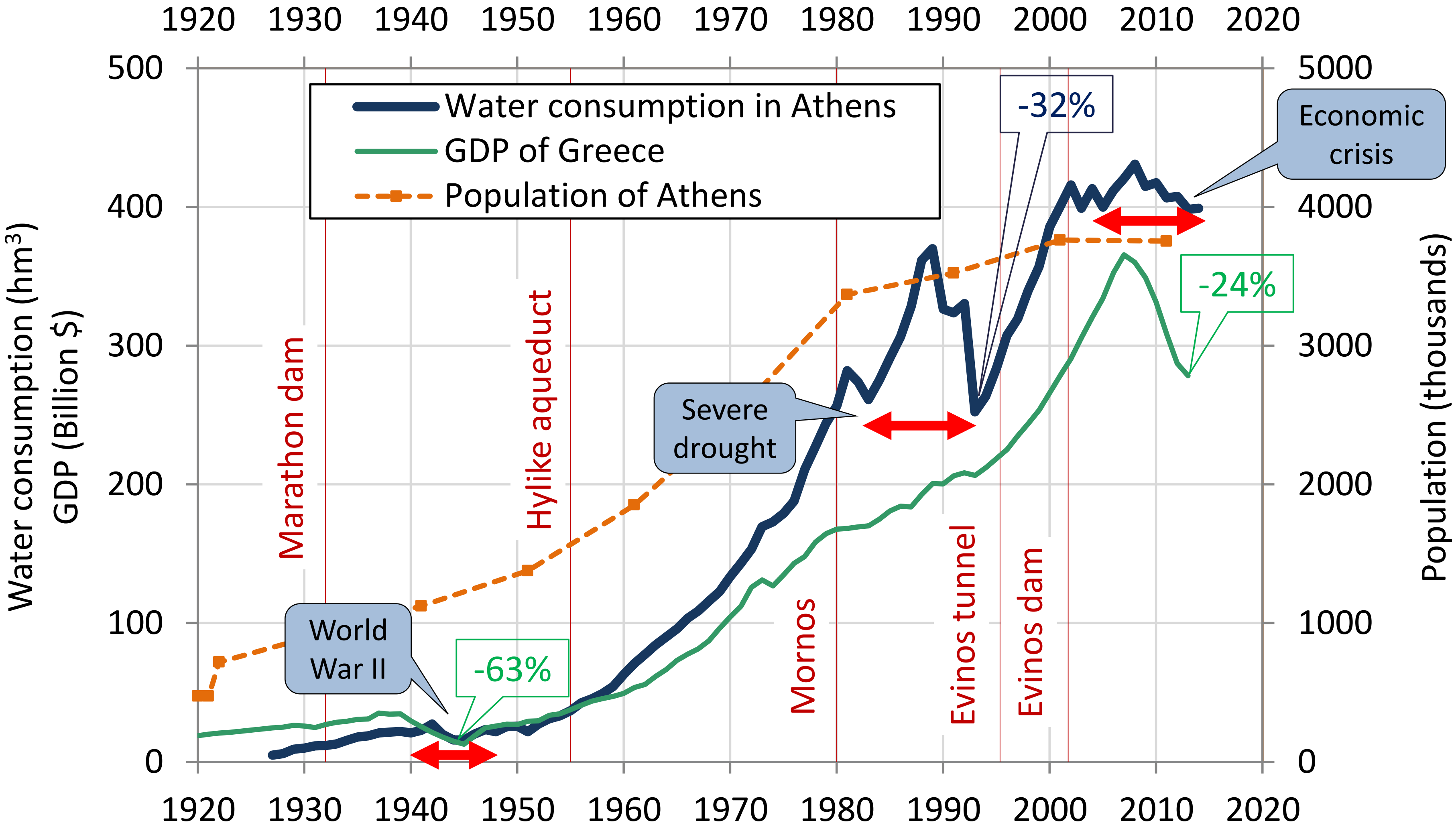
Marathon (1932)
Inflows: <15 hm^3
Capacity: 32 hm^3

Mornos (1980)
Inflows: 235 hm^3
Capacity: 630 hm^3

NTUA campus

- ○ **River basins**
- ● **Lakes - reservoirs**
- ⊗ **Boreholes**
- ● **Pumping stations**
- ∿ **Channels - pipes**
- ▣ **Water treatment**
- ○ **Athens and surroundings**

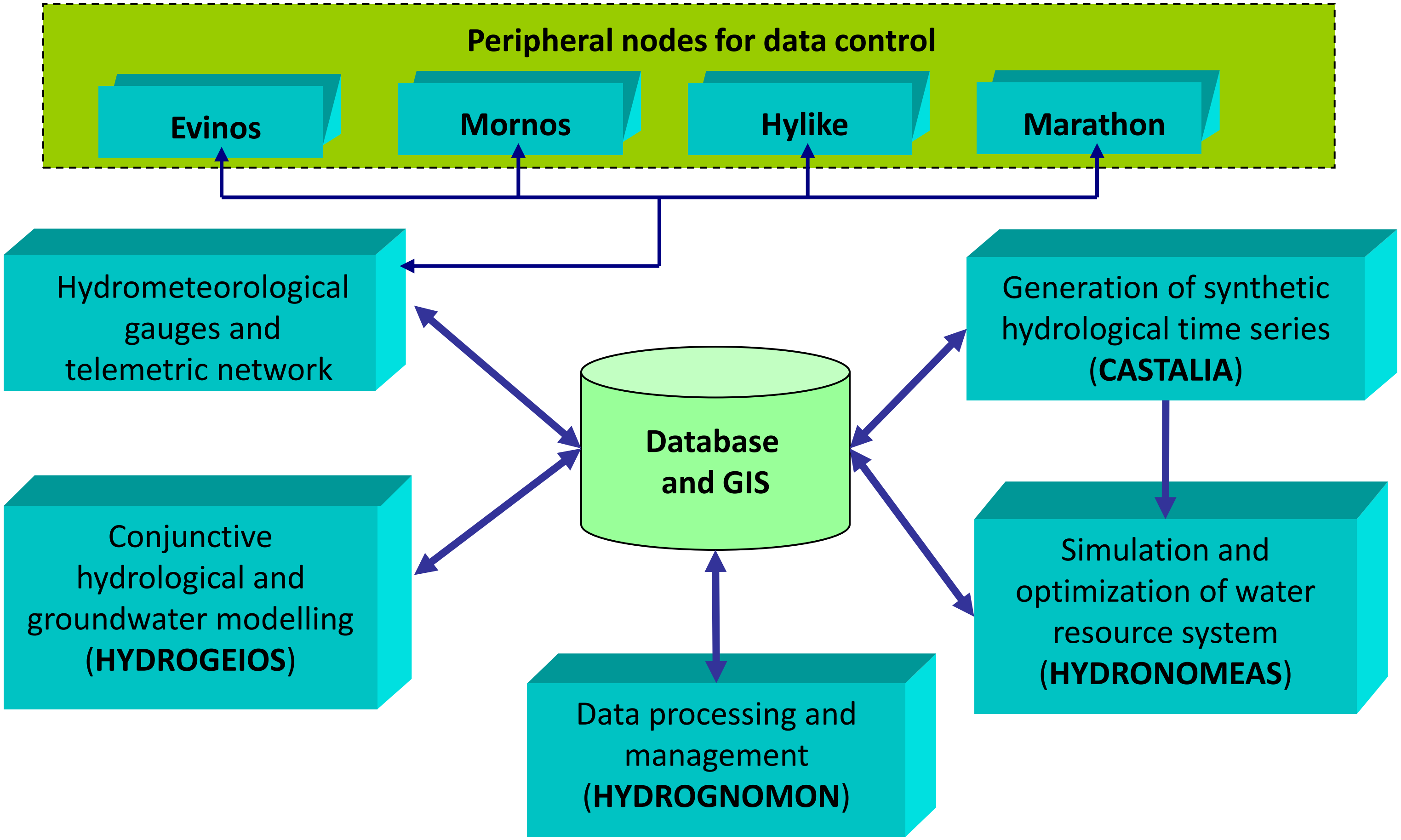
Providing drinking water to Athens: Evolution of annual demand, population, GDP and water recourses



Management challenges and complexity issues

- Conflicting objectives
  - Operational cost, mainly due to pumping (to be minimized)
  - Long-term reliability (at least 99%, on annual basis)
- Multiple water resources & water paths
  - Four reservoirs (total useful capacity 1360 hm^3, mean annual inflow 820 hm^3)
  - ~100 boreholes, used as emergency resources (estimated safe yield 50 hm^3)
  - Multiple water conveyance options, some of them through pumping
  - Four water treatment plants, multiple water distribution options
- Multiple water uses
  - Drinking water to Athens (450 hm^3, also considering water conveyance leakages)
  - Local water uses across the water conveyance network (50 hm^3)
  - Environmental flows through Evinos dam (30 hm^3) – first established EF in Greece
  - Hydroelectric energy through small hydropower plants (Mornos aqueduct)
- Multiple sources of uncertainty
  - Non-predictable inflows (hydroclimatic uncertainty)
  - Uncertain demands, subject to uncertain socio-economic conditions
  - Operational issues (leakages, malfunction of critical system components)

Architecture of the decision support system (DSS) for the management of Athens water supply



Peripheral nodes for data control

Evinos

Mornos

Hylike

Marathon

Hydrometeorological gauges and telemetric network

Generation of synthetic hydrological time series (**CASTALIA**)

Database and GIS

Conjunctive hydrological and groundwater modelling (**HYDROGEIOS**)

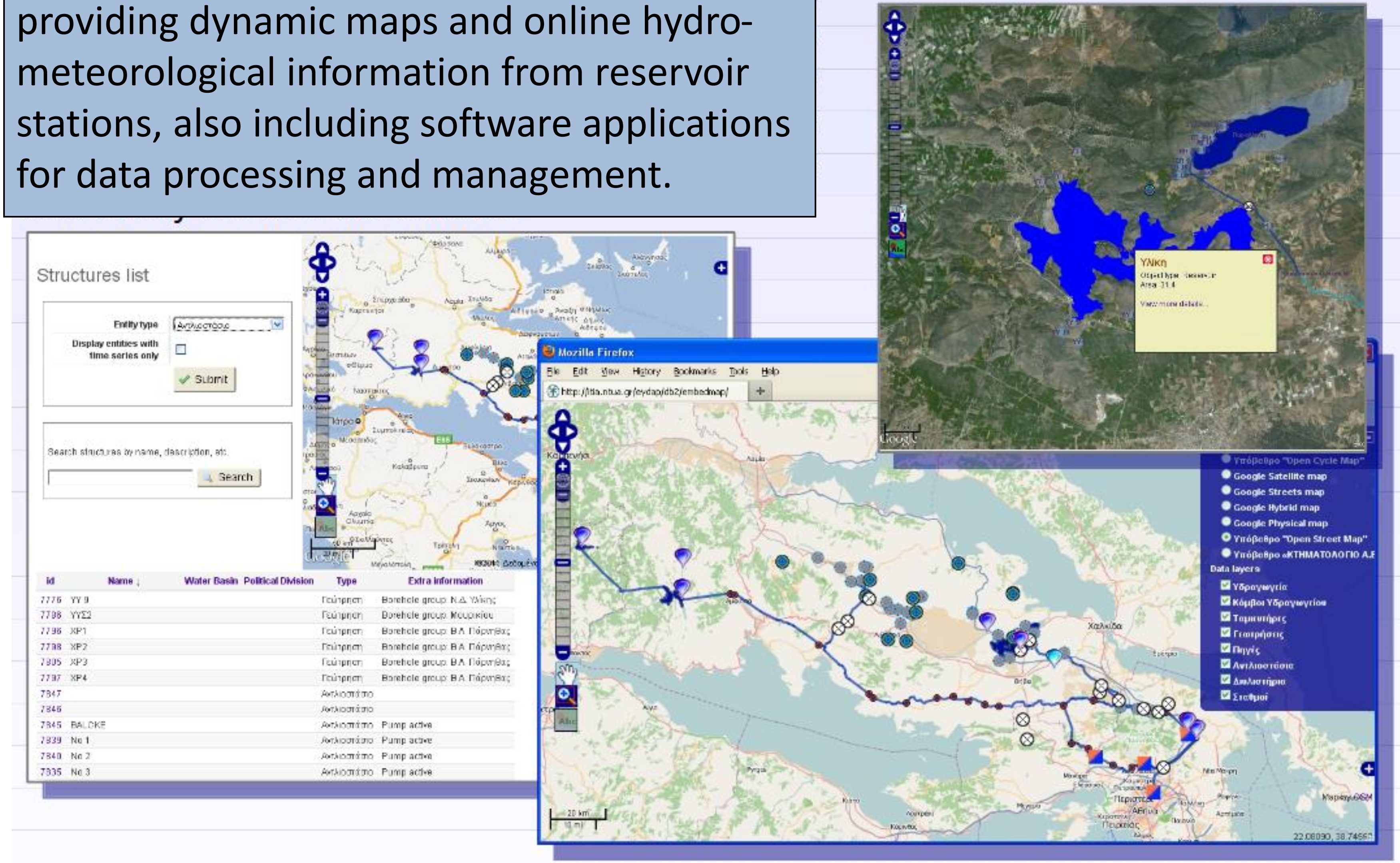
Simulation and optimization of water resource system (**HYDRONOMEAS**)

Data processing and management (**HYDROGNOMON**)

Remark: The DSS was developed during 1999-2003 and upgraded during 2008-2010

Geo-data base

Open database with GIS functionalities, providing dynamic maps and online hydro-meteorological information from reservoir stations, also including software applications for data processing and management.



Structures list

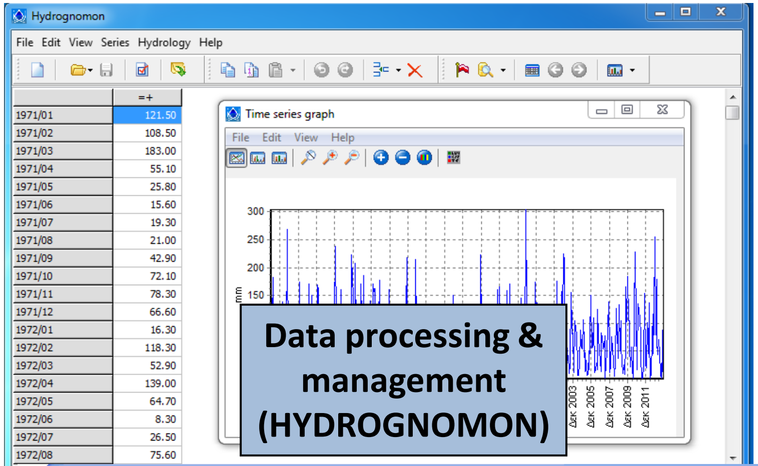
Entity type: Αντλιοστάσιο

Display entities with time series only ☐

Search structures by name, description, etc.

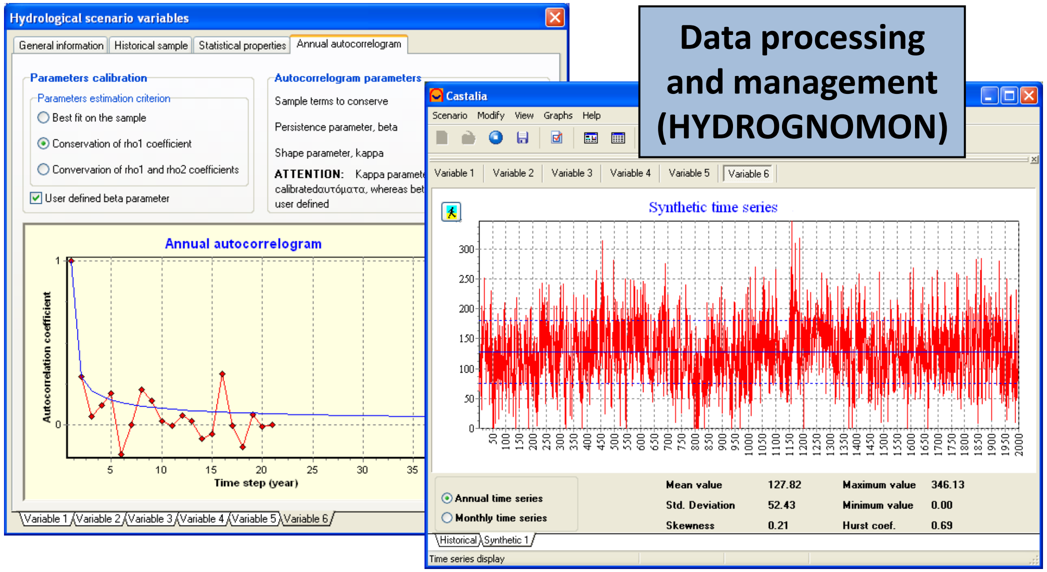
id	Name	Water Basin	Political Division	Type	Extra information
7776	ΥΥ 9			Γεώτρηση	Borehole group: Ν.Δ. Υλίκης
7798	ΥΥΣ2			Γεώτρηση	Borehole group: Μουρικίου
7796	ΧΡ1			Γεώτρηση	Borehole group: Β.Α. Πάρνηθας
7798	ΧΡ2			Γεώτρηση	Borehole group: Β.Α. Πάρνηθας
7805	ΧΡ3			Γεώτρηση	Borehole group: Β.Α. Πάρνηθας
7797	ΧΡ4			Γεώτρηση	Borehole group: Β.Α. Πάρνηθας
7847				Αντλιοστάσιο	
7846				Αντλιοστάσιο	
7845	BALCKE			Αντλιοστάσιο	Pump active
7839	No 1			Αντλιοστάσιο	Pump active
7840	No 2			Αντλιοστάσιο	Pump active
7835	No 3			Αντλιοστάσιο	Pump active

Software tools



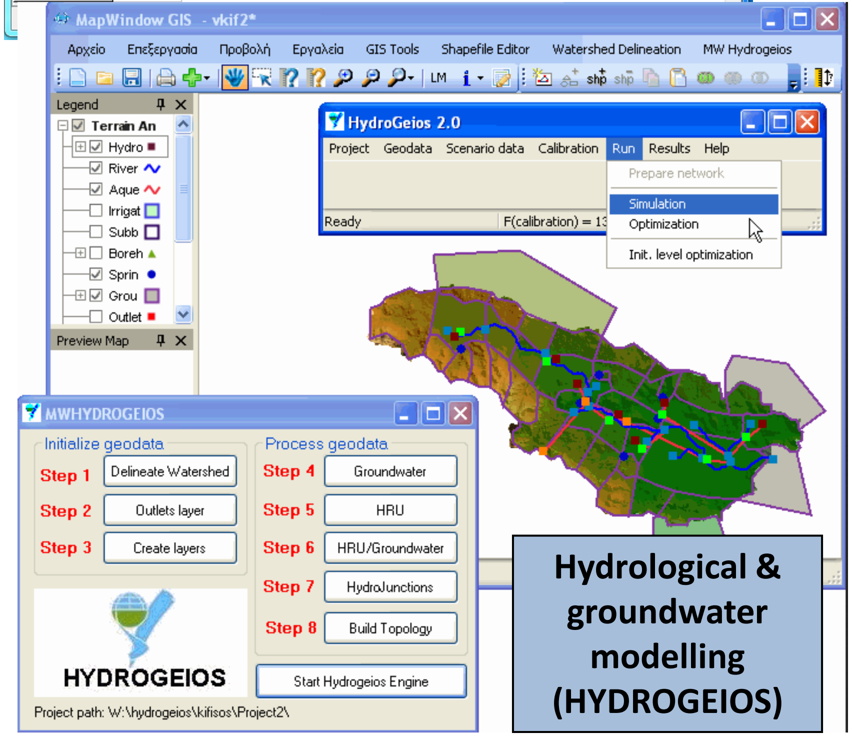
	=+
1971/01	121.50
1971/02	108.50
1971/03	183.00
1971/04	55.10
1971/05	25.80
1971/06	15.60
1971/07	19.30
1971/08	21.00
1971/09	42.90
1971/10	72.10
1971/11	78.30
1971/12	66.60
1972/01	16.30
1972/02	118.30
1972/03	52.90
1972/04	139.00
1972/05	64.70
1972/06	8.30
1972/07	26.50
1972/08	75.60

Data processing & management (HYDROGNOMON)



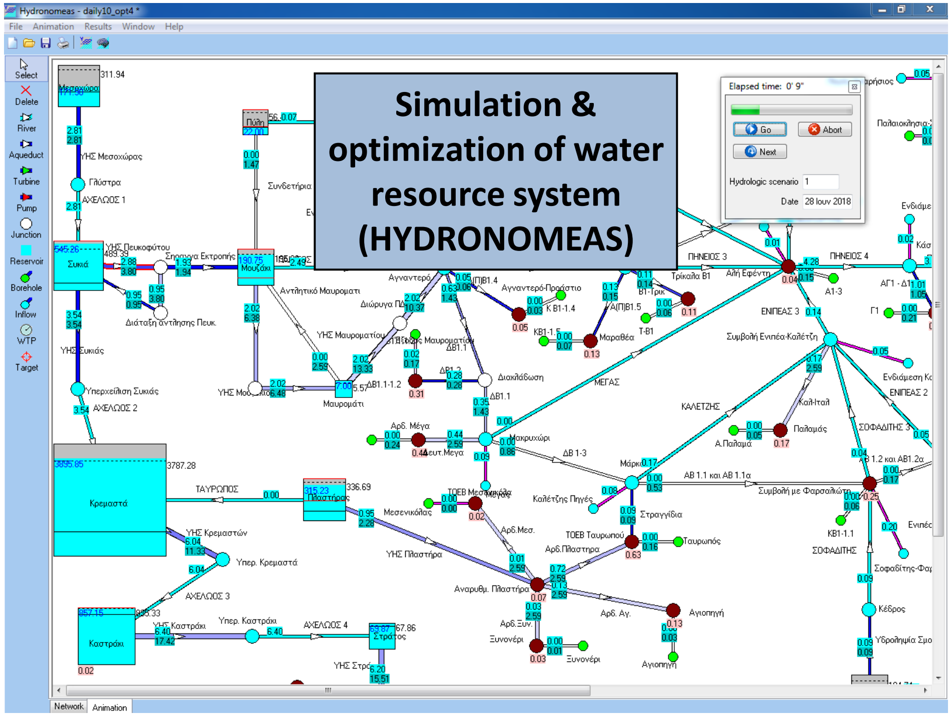
Mean value 127.82
Std. Deviation 52.43
Skewness 0.21
Maximum value 346.13
Minimum value 0.00
Hurst coef. 0.69

Data processing and management (HYDROGNOMON)



Project path: W:\hydrogeios\kifisos\Project2\

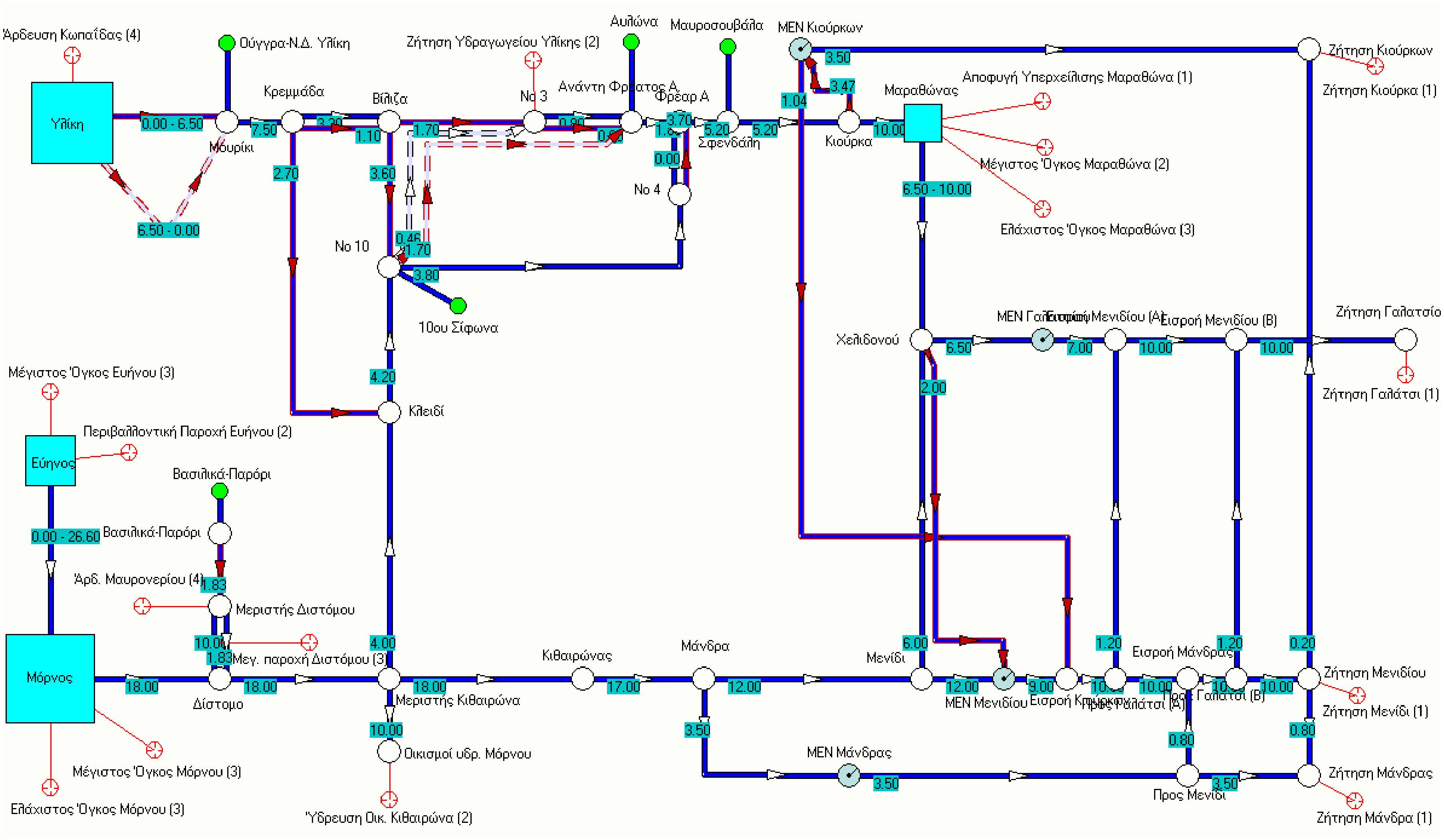
Hydrological & groundwater modelling (HYDROGEIOS)



Hydrologic scenario 1
Date 28 Ιουν 2018

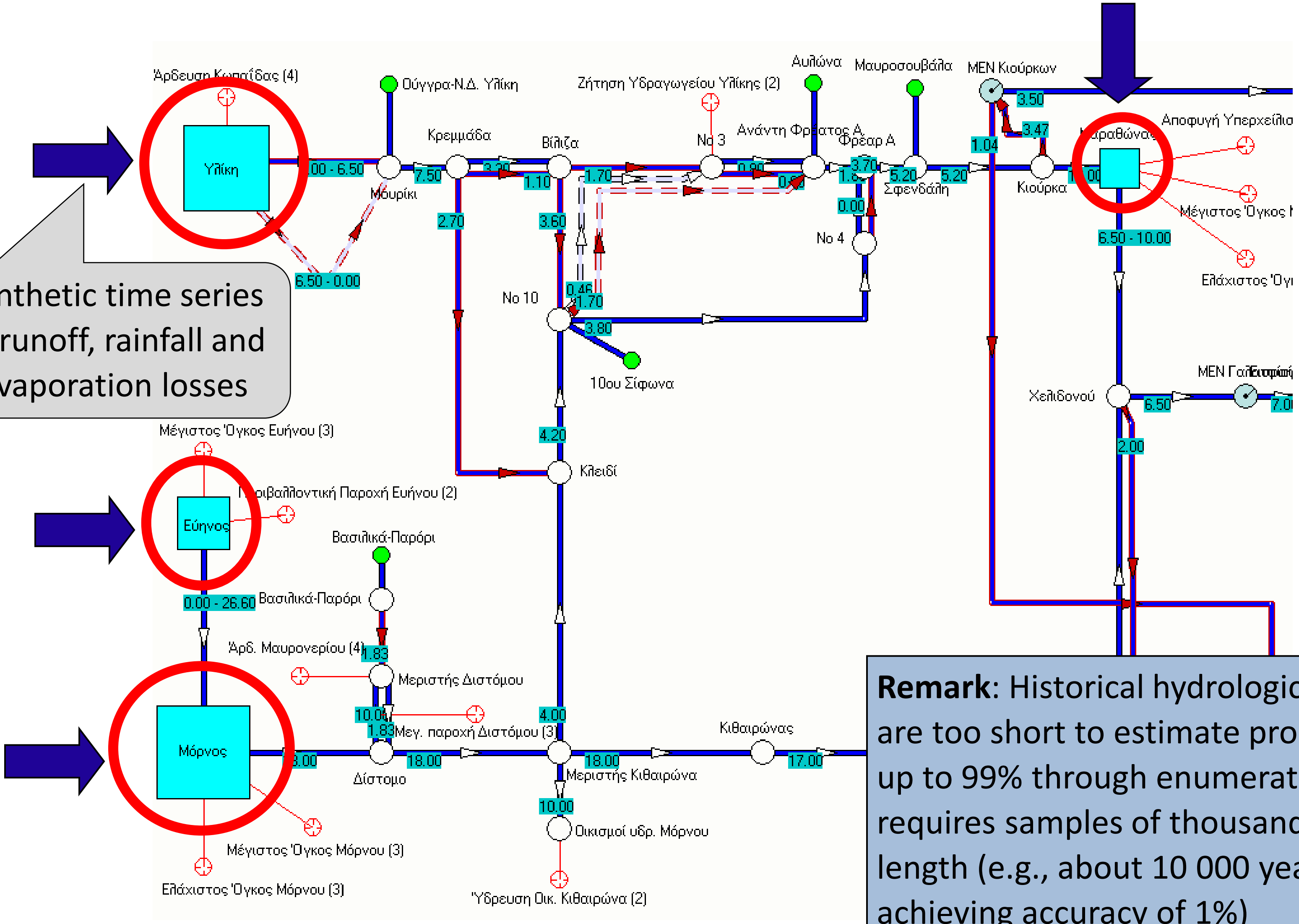
Simulation & optimization of water resource system (HYDRONOMEAS)

Schematization of the water resource system



Representation of the water resource system in the graphical environment of **Hydronomeas**

Modelling task 1: Generation of hydrological inputs

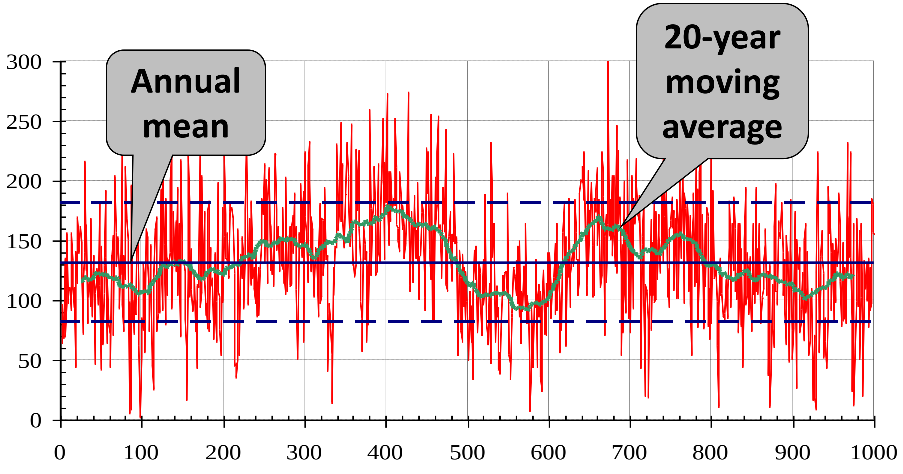


Synthetic time series of runoff, rainfall and evaporation losses

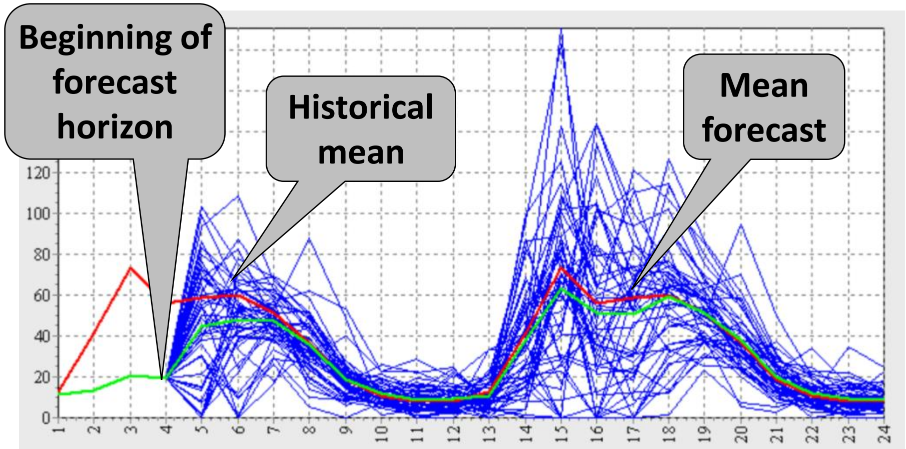
Remark: Historical hydrological records are too short to estimate probabilities up to 99% through enumeration; this requires samples of thousands of years length (e.g., about 10 000 years, for achieving accuracy of 1%)

The stochastic model Castalia

- Multivariate stochastic modelling, to represent multiple processes at multiple locations that are inherently correlated;
- Preservation of marginal statistics up to third order (asymmetry);
- Preservation of temporal and spatial correlations;
- Multiple time scales of preservation, from annual (preservation of over-year scaling, i.e. the Hurst phenomenon) to monthly (preservation of periodicity);
- Operation in steady-state simulation mode (synthetic series of very long horizon) and forecast mode, conditioned to present and past data (terminating simulation; “ensemble” series, representing multiple hydrological scenarios for relatively small horizons).



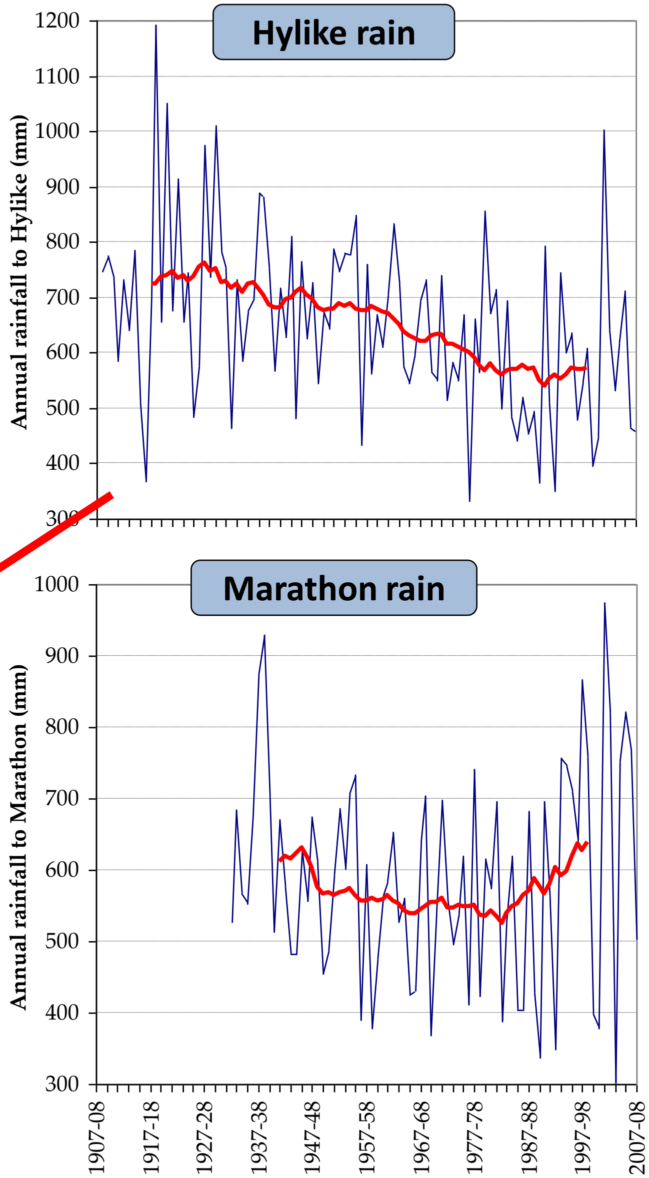
Annual time series for steady-state simulation

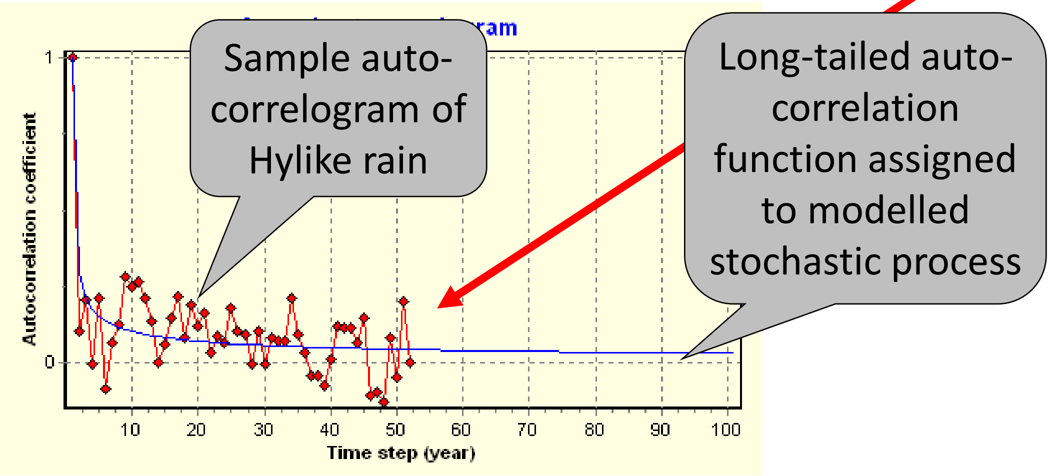


Monthly time series for terminating simulation

Representing the Hurst-Kolmogorov behaviour

- Historical data exhibit peculiarities, such as fluctuations at multiple scales and trends, which cannot be represented through short-memory schemes, such as ARMA-type models.
- Persistent droughts and changing climate are typical aspects of this behaviour, which is crucial to be represented in water management models.
- The Hurst-Kolmogorov dynamics, explained through the principle of **maximum entropy**, is easily formulated in terms of the variance and autocorrelation of the stochastic process.

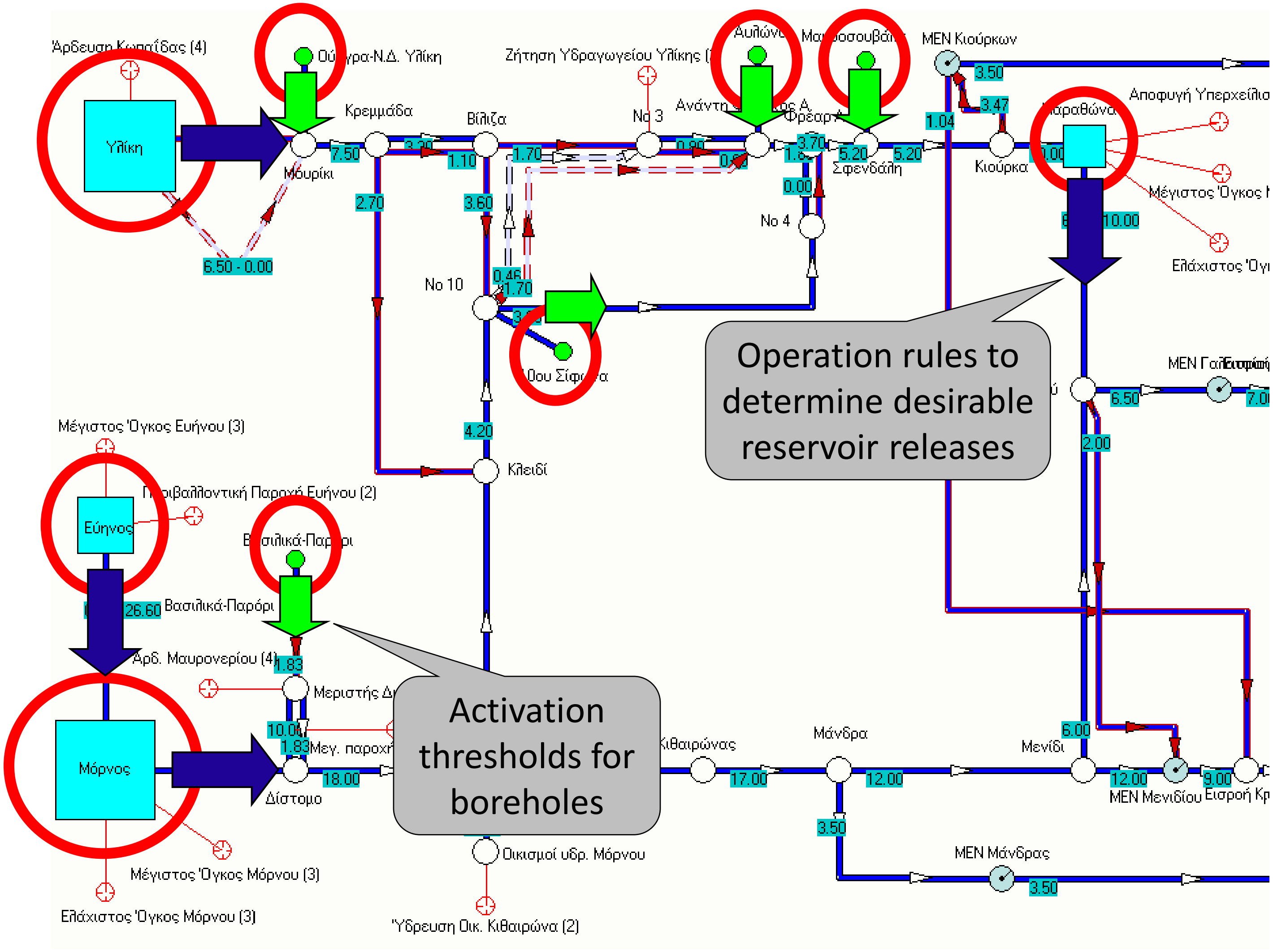




Sample auto-correlogram of Hylike rain

Long-tailed auto-correlation function assigned to modelled stochastic process

Modelling task 2: Establishment of a systematic control policy for reservoirs and boreholes

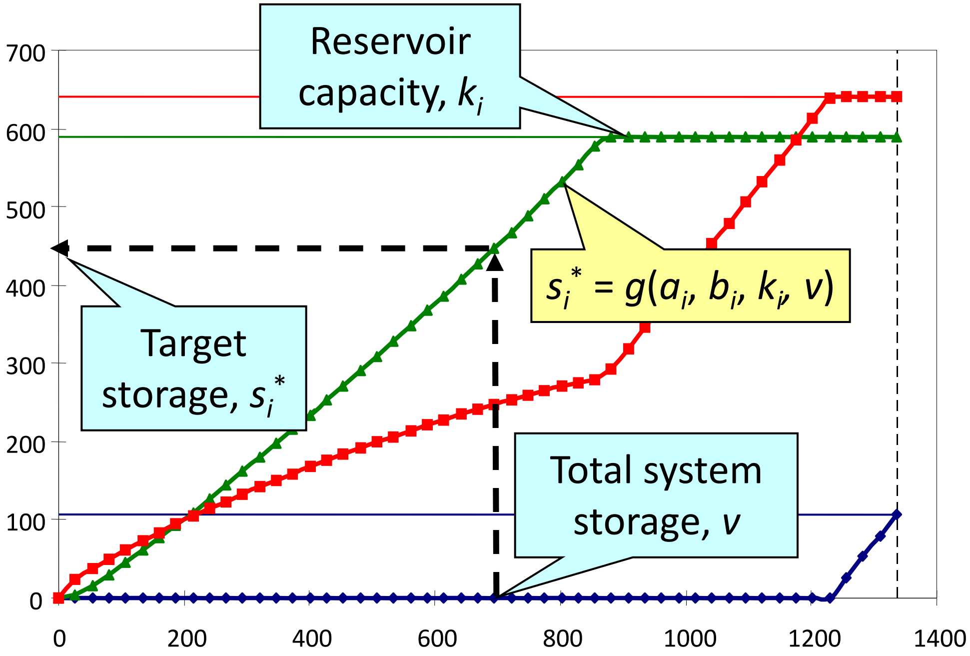


Operation rules to determine desirable reservoir releases

Activation thresholds for boreholes

Operation rules for multi-reservoir systems

- The rules are nomographs that specify the desirable allocation of reservoir resources and the corresponding releases on a monthly basis, as function of:
  - the estimated total storage of the system at the end of month;
  - the capacities of all reservoirs (physical constraints);
  - any other kind of storage constraints, imposed by the user.

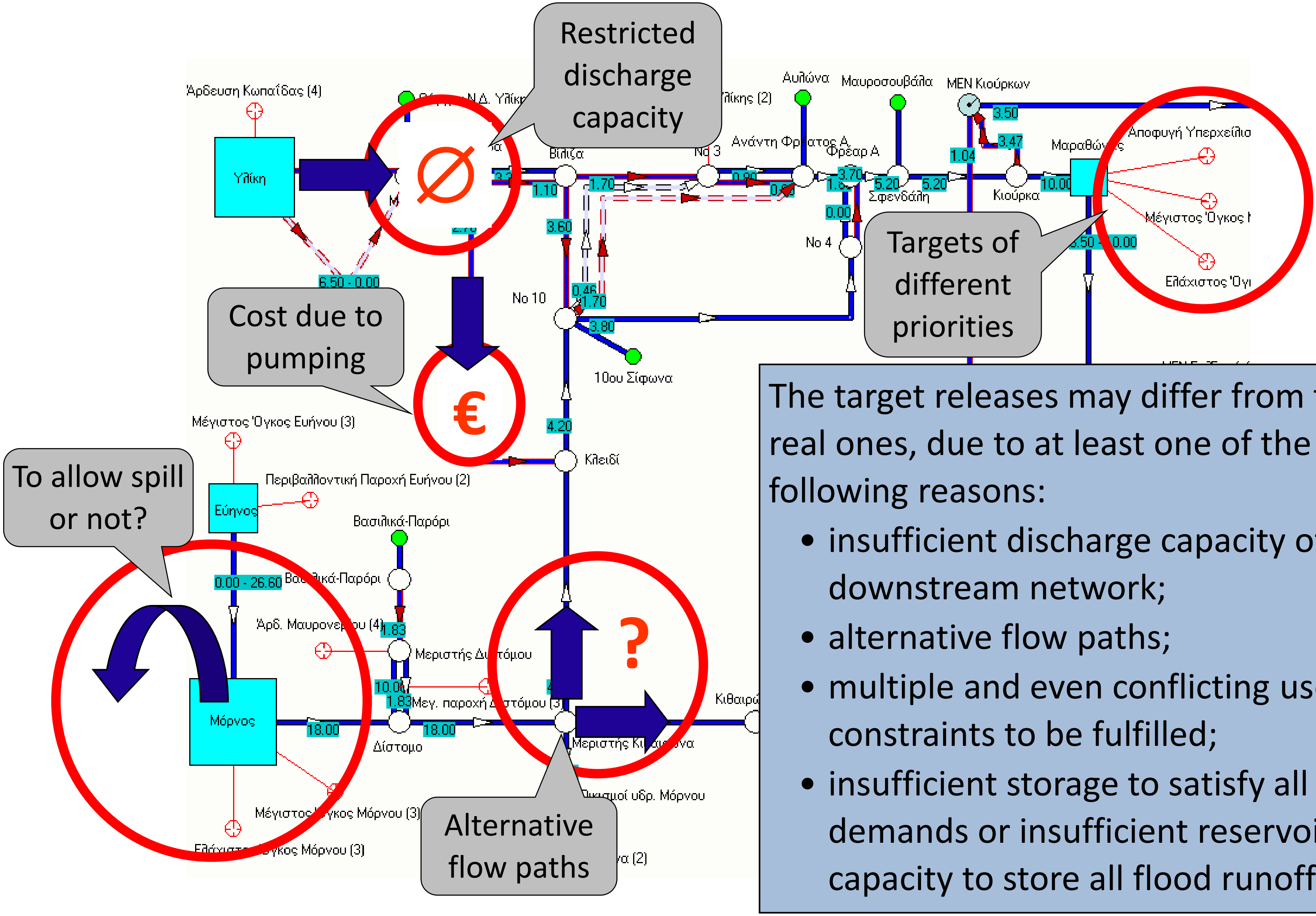


- Since inflows are projected through simulation, the target releases are easily estimated, on the basis on the actual storages and the total water demand.
- The rules are mathematically expressed using two parameters per reservoir, thus ensuring a **parsimonious parameterization** of the related optimization problem, where their values depend on the statistical characteristics of inflows.
- In contrast, linear or dynamic programming approaches would require plethora of decision variables, the number of which depend on the control horizon, while their values depend on the sequence of inflows.

Activation thresholds for groundwater control

- Groundwater are assumed auxiliary resources, which should be only activated in case of emergency.
- There are more than a hundred boreholes, which are grouped into five clusters to represent combined abstractions from broader aquifer areas.
- The management policy is specified on the basis of two **threshold-type parameters** per borehole group, i.e. an upper and a lower bound, which express the percentage of total actual reservoir resources to the total capacity. In this context:
  - when the filling ratio of the reservoirs exceeds the upper threshold, the borehole group is not activated;
  - when the filling ratio of the reservoirs is below the lower threshold, the group is activated by priority, without accounting for energy costs;
  - in intermediate states, the group is either activated or not, depending on the minimization of the total energy consumption across the hydrosystem.
- Different threshold values are assigned to the five borehole groups of Athens, thus specifying a desirable hierarchy in their use.

Modelling task 3: Optimal allocation of actual fluxes



Restricted discharge capacity

Cost due to pumping

Targets of different priorities

To allow spill or not?

Alternative flow paths

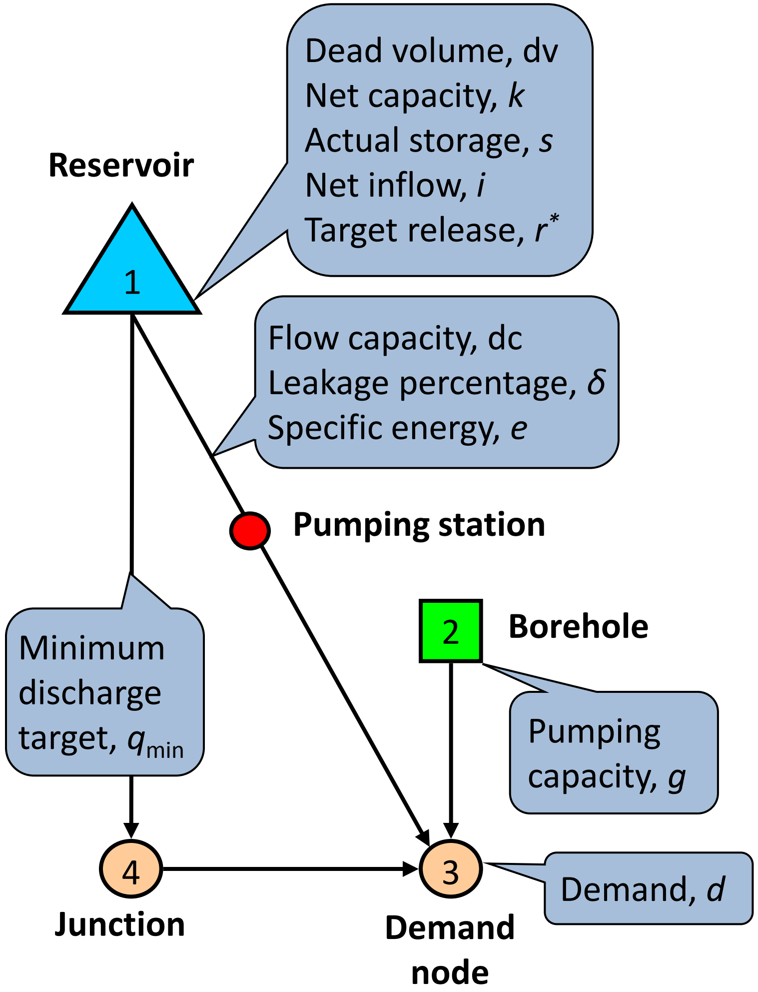
The target releases may differ from the real ones, due to at least one of the following reasons:

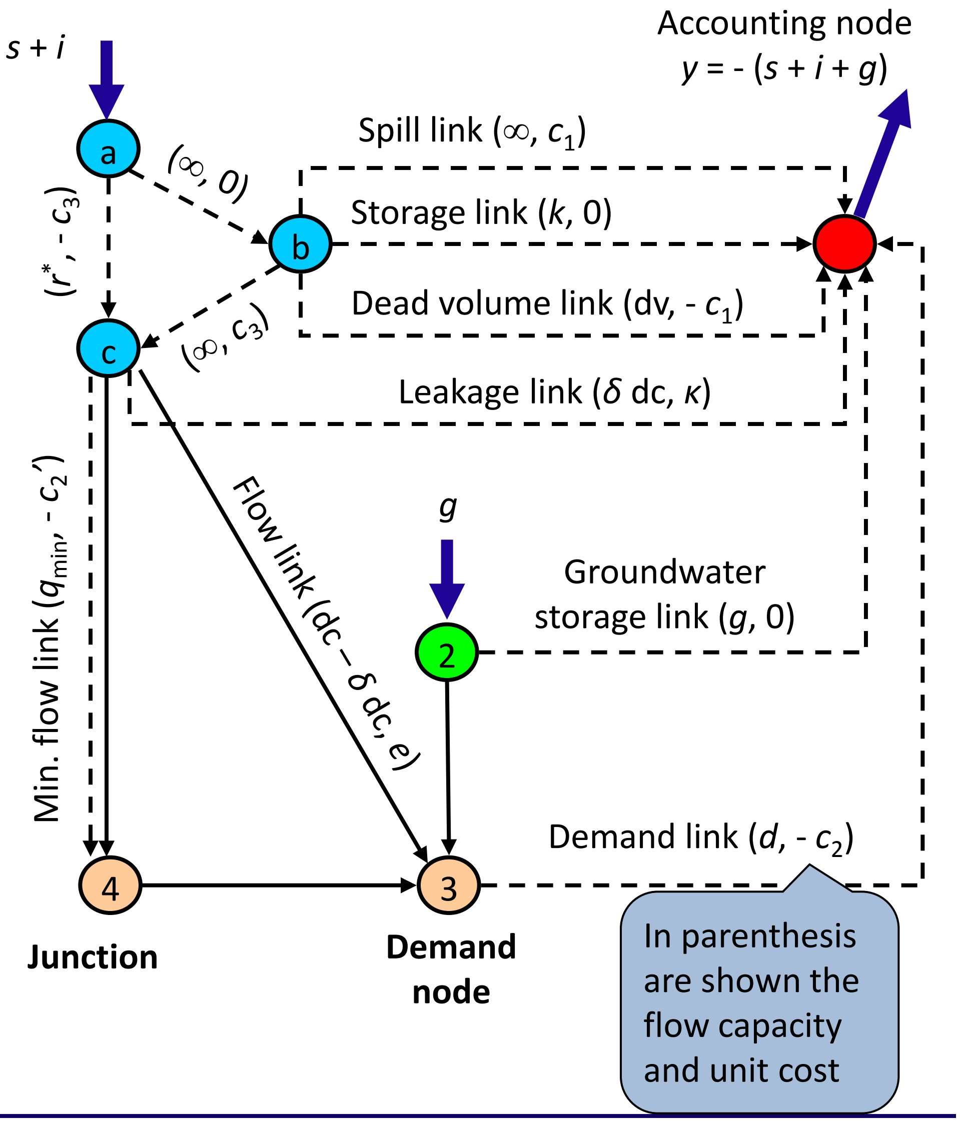
- insufficient discharge capacity of the downstream network;
- alternative flow paths;
- multiple and even conflicting uses and constraints to be fulfilled;
- insufficient storage to satisfy all demands or insufficient reservoir capacity to store all flood runoff.

Network linear programming approach for the flow allocation problem

- The real-world system is described through a conceptual graph, whose dummy properties are conveyance capacities and unit costs.
- All hydrosystem fluxes are represented as control variables of a **network linear programming** (NLP) problem, whose objective is the minimization of the total transportation cost through the graph.
- Artificial costs are set either to prohibit undesirable fluxes (positive costs) or to force the model fulfilling water demands for various uses (negative costs).
- Real costs are expressed in energy terms, by means of specific energy (kWh/m^3).
- The assignment of unit costs, real and artificial, is based on a recursive algorithm that implements the following requirements:
  - strict satisfaction of all physical constraints (storage and flow capacities);
  - satisfaction of demands and constraints, preserving their hierarchy;
  - minimization of departures between actual and target abstractions;
  - minimization of total energy consumption.
- The specific mathematical structure of NLP allows for using accurate and exceptionally fast solvers.

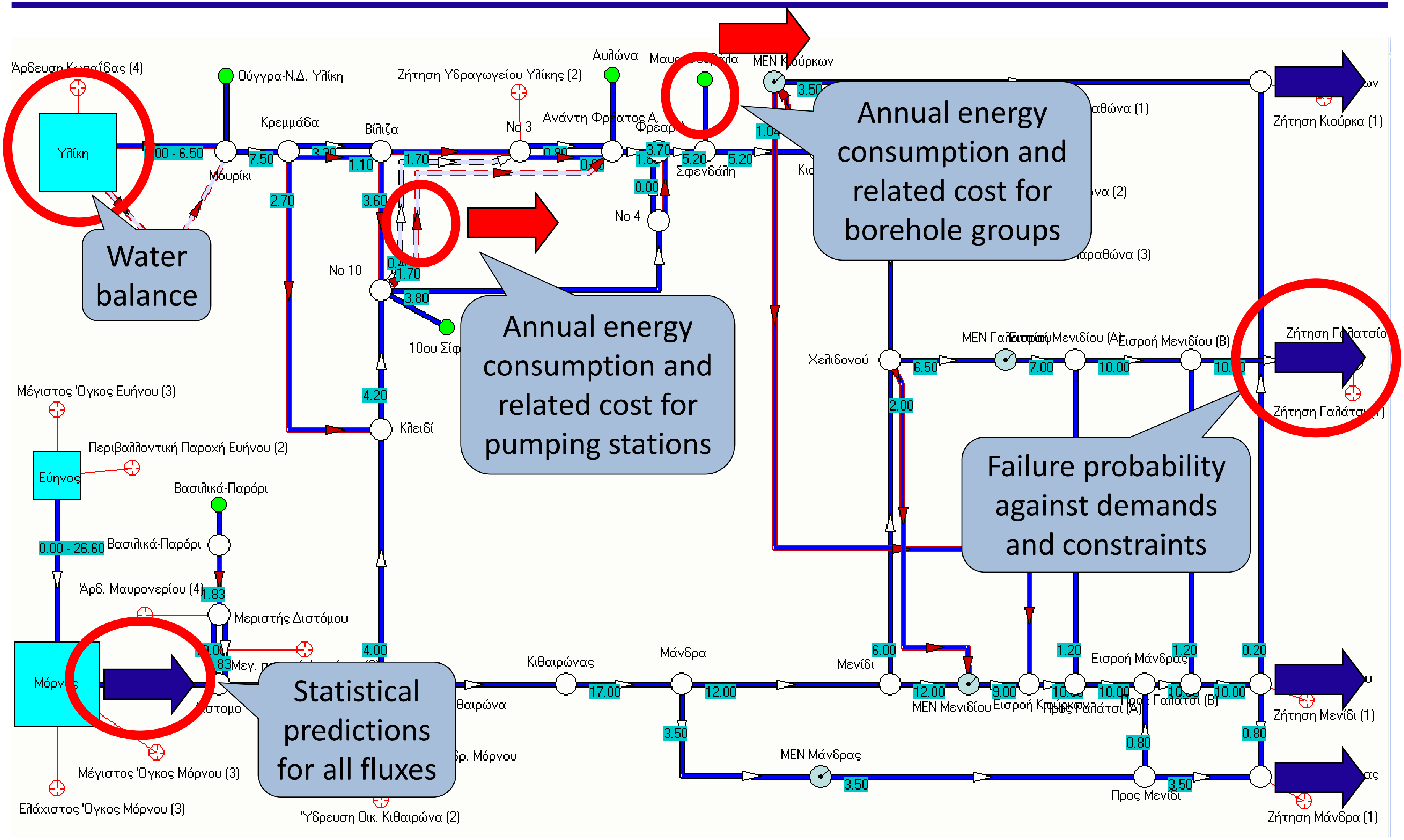
Representation of an elementary water resource system as NLP model





In parenthesis are shown the flow capacity and unit cost

Modelling task 4: Evaluation and optimization of the hydrosystem operation policy



Water balance

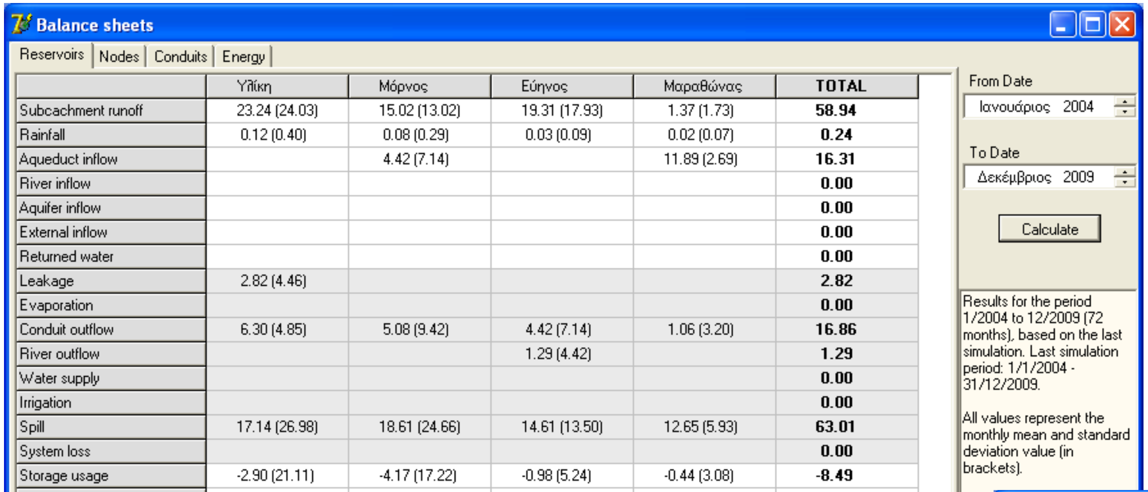
Annual energy consumption and related cost for pumping stations

Annual energy consumption and related cost for borehole groups

Failure probability against demands and constraints

Statistical predictions for all fluxes

Simulation results



	Υλίκη	Μόρνος	Εύηνος	Μαραθώνας	TOTAL
Subcachment runoff	23.24 (24.03)	15.02 (13.02)	19.31 (17.93)	1.37 (1.73)	**58.94**
Rainfall	0.12 (0.40)	0.08 (0.29)	0.03 (0.09)	0.02 (0.07)	**0.24**
Aqueduct inflow		4.42 (7.14)		11.89 (2.69)	**16.31**
River inflow					**0.00**
Aquifer inflow					**0.00**
External inflow					**0.00**
Returned water					**0.00**
Leakage	2.82 (4.46)				**2.82**
Evaporation					**0.00**
Conduit outflow	6.30 (4.85)	5.08 (9.42)	4.42 (7.14)	1.06 (3.20)	**16.86**
River outflow			1.29 (4.42)		**1.29**
Water supply					**0.00**
Irrigation					**0.00**
Spill	17.14 (26.98)	18.61 (24.66)	14.61 (13.50)	12.65 (5.93)	**63.01**
System loss					**0.00**
Storage usage	-2.90 (21.11)	-4.17 (17.22)	-0.98 (5.24)	-0.44 (3.08)	**-8.49**

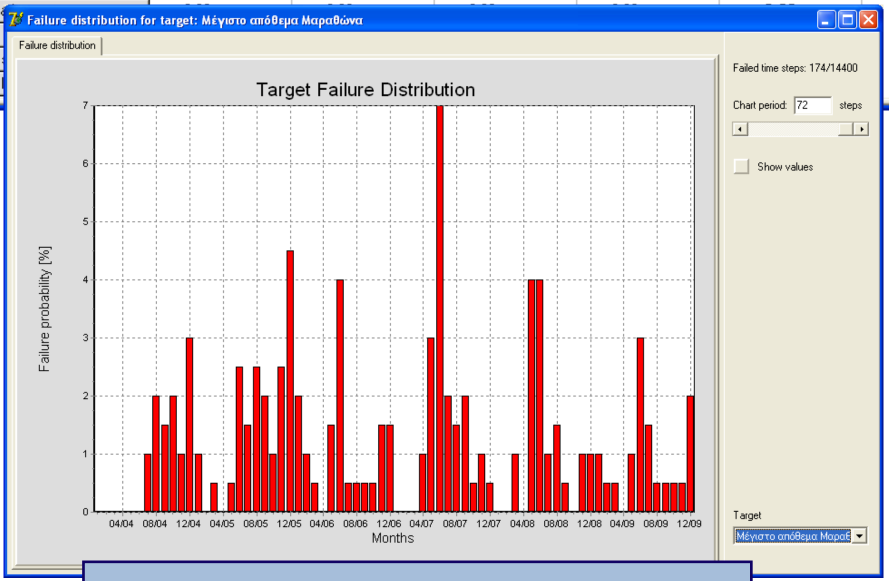
From Date: Ιανουάριος 2004

To Date: Δεκέμβριος 2009

Results for the period 1/2004 to 12/2009 (72 months), based on the last simulation. Last simulation period: 1/1/2004 - 31/12/2009.

All values represent the monthly mean and standard deviation value (in brackets).

Water and energy balance for all system components (mean monthly values and standard deviations)



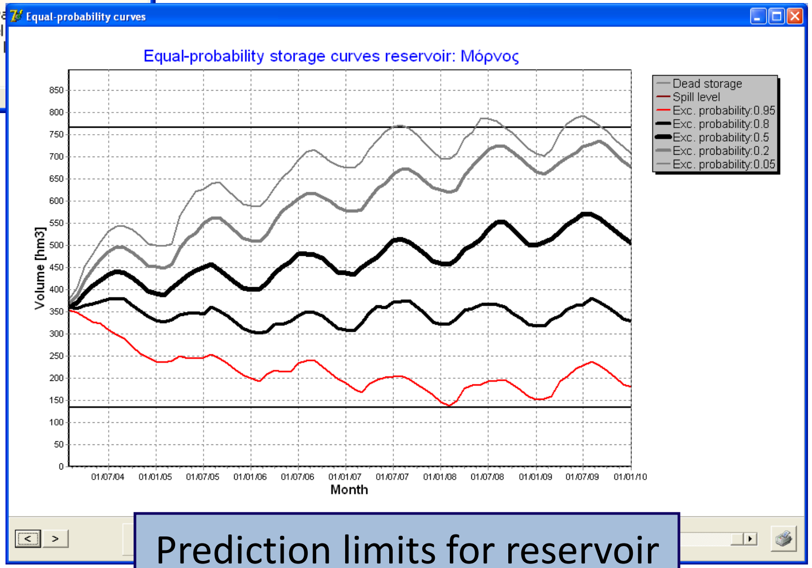
Failed time steps: 174/14400

Chart period: 72 steps

☐ Show values

Target: Μέγιστο απόθεμα Μαραθ

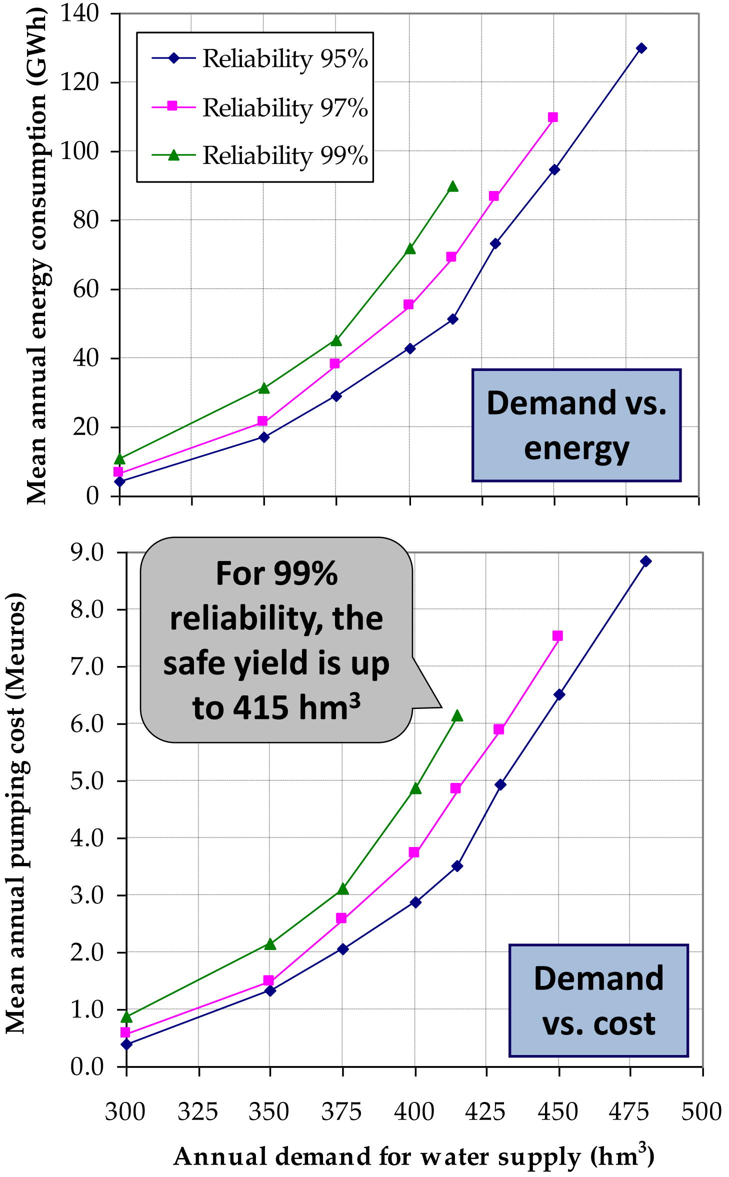
Time-distribution of failure probability (terminating simulation)



Prediction limits for reservoir storage and level (terminating simulation)

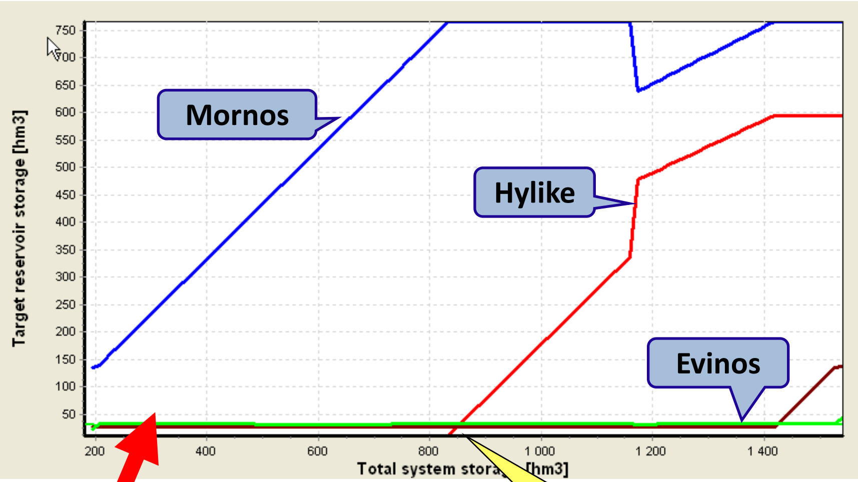
Question 1: Appraisal of energy cost against demand and reliability

- **Problem statement**: Estimation of the mean annual energy consumption and the related cost, for a given annual demand and a given reliability level.
- Control variables were the six parameters of the operation rules for Mornos, Evinos and Hylike, while the borehole thresholds were manually specified.
- Formulated as a non-linear (global) optimization problem of two criteria, i.e. minimization of energy and preservation of the desirable reliability level.
- The two criteria were evaluated through steady-state simulation, using 2000 years of synthetic hydrological data.
- **Practical interest**: Assessing the full (i.e. financial and environmental) cost of water.



Question 2: Potential of existing resources

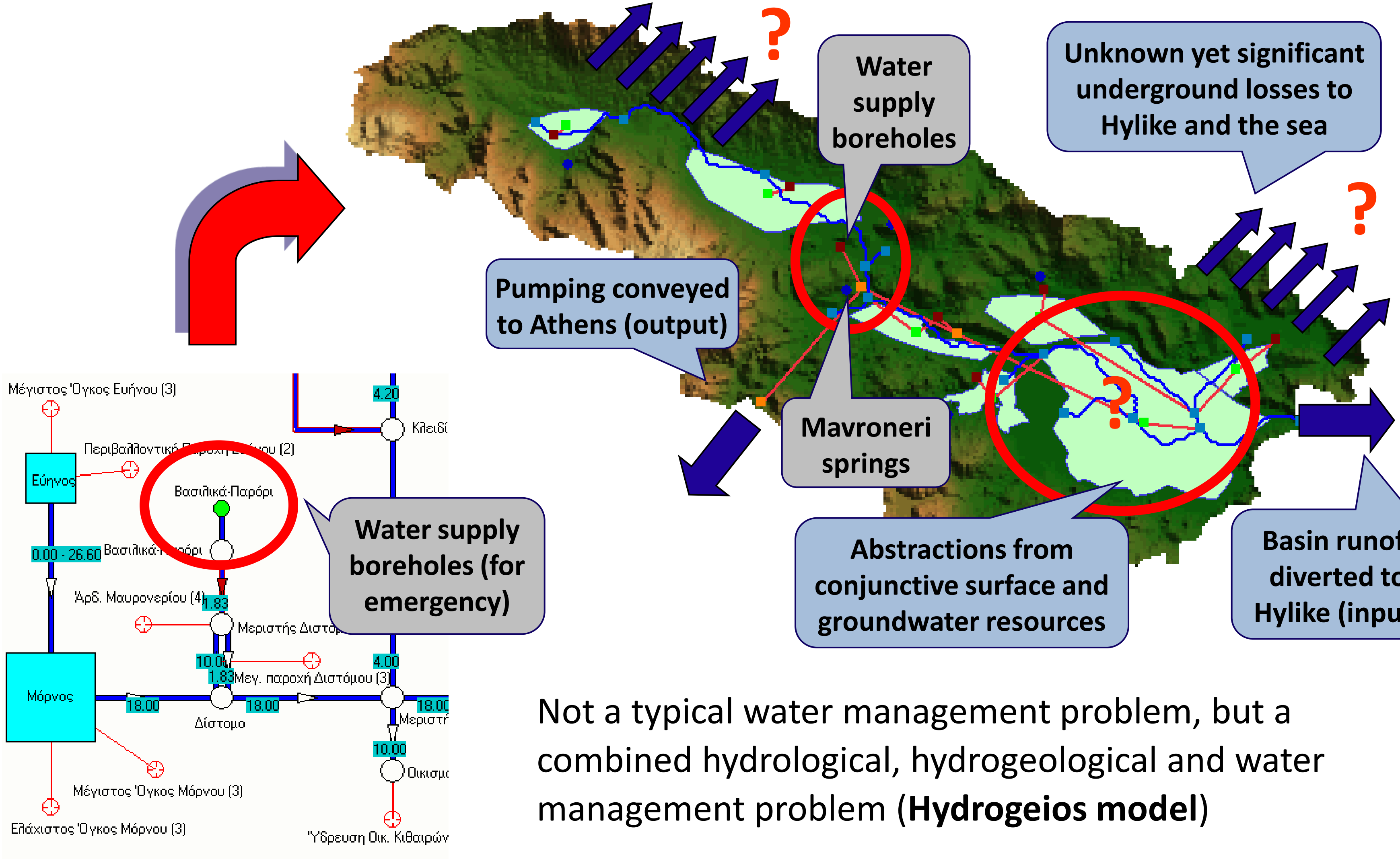
- **Problem statement**: Estimation of theoretical safe abstraction from water resources for 99% reliability, assigning unlimited flow capacity to the network, for various borehole operation policies.
- **Practical interest**: assessing the limits of the actual resources, for the long-term planning of new projects.



Below this limit, Hylike should be used by priority

Borehole operation policy	Intensive	Normal	Limited	No pumping
Upper usage threshold (%)	80	40	20	0
Lower usage threshold (%)	50	25	10	0
Safe abstraction for water supply (hm³)	610.0	560.0	510.0	430.0
Average abstraction from Mornos (hm³)	330.4	400.9	378.1	340.1
Average abstraction from Hylike (hm³)	183.6	140.6	128.8	93.5
Average abstraction from boreholes (hm³)	101.0	23.5	8.0	0.0
Average losses due to leakage (hm³)	82.7	113.8	125.4	143.9
Safe inflow to Athens (hm³)	530.7	487.2	443.7	374.1
Average energy consumption (GWh)	220.7	120.1	98.9	66.1

Question 3: Assessment of impacts from groundwater abstractions from Boeoticos Kephisos boreholes



Water supply boreholes

Unknown yet significant underground losses to Hylike and the sea

Pumping conveyed to Athens (output)

Mavroneri springs

Water supply boreholes (for emergency)

Abstractions from conjunctive surface and groundwater resources

Basin runoff diverted to Hylike (input)

Not a typical water management problem, but a combined hydrological, hydrogeological and water management problem (**Hydrogeios model**)

The HYDROGEIOS modelling framework

Surface hydrology module

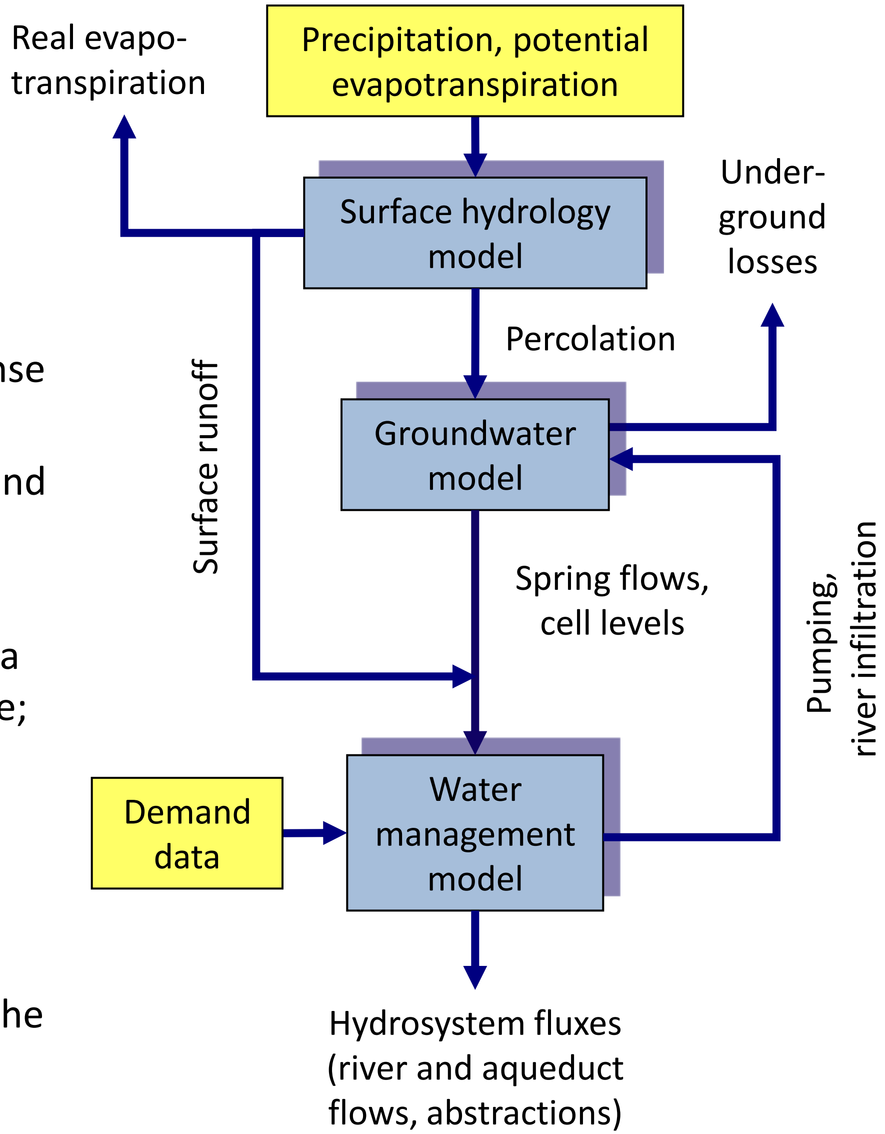
- Semi-distributed schematization;
- Conceptualization through two interconnected tanks, representing the surface processes;
- Model inputs: daily precipitation and potential precipitation (PET) data, varying per sub-basin;
- Parameterization through the hydrological response unit (HRU) concept;
- Model outputs: evapotranspiration, percolation and runoff, transferred to the sub-basin outlet.

Groundwater module

- Finite-volume approach, aquifer discretization to a limited number of polygonal cells of flexible shape;
- Darcian representation of the flow field;
- Stress data: percolation, infiltration, pumping;
- Model outputs: cell levels, spring runoff;

Water allocation module

- Extension of the NLP approach, to also embrace the river network components.


Real evapo-transpiration

Precipitation, potential evapotranspiration

Surface hydrology model

Under-ground losses

Percolation

Surface runoff

Groundwater model

Spring flows, cell levels

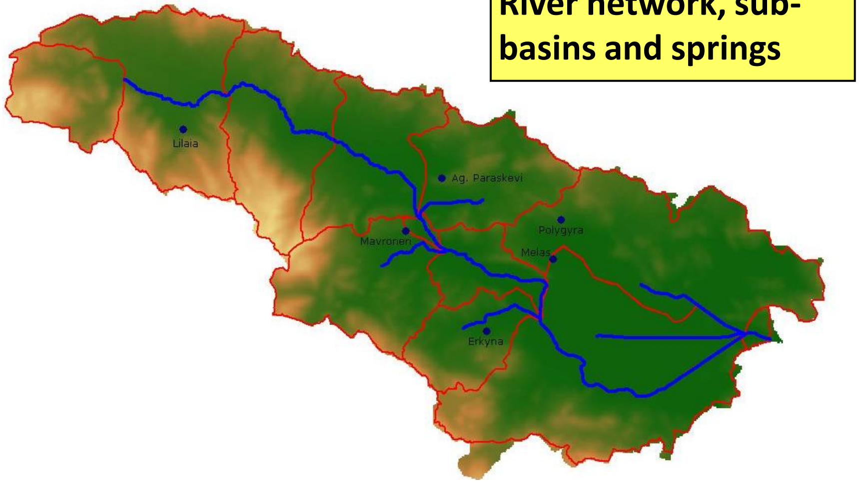
Pumping, river infiltration

Demand data

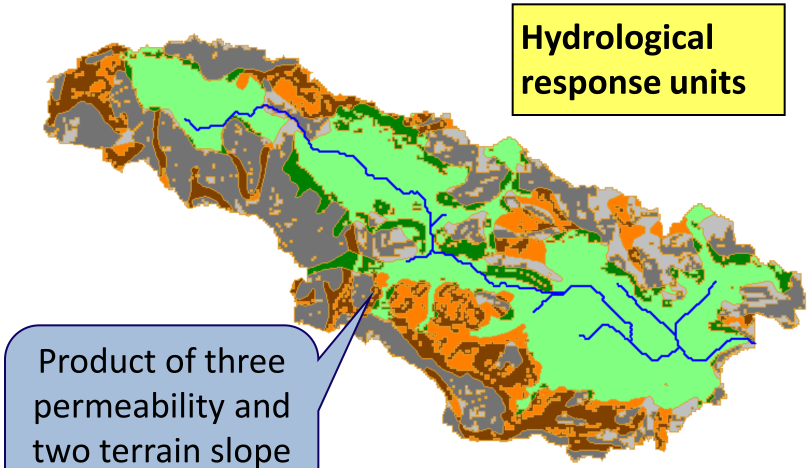
Water management model

Hydrosystem fluxes (river and aqueduct flows, abstractions)

Modelling the Boeoticos Kephisos basin

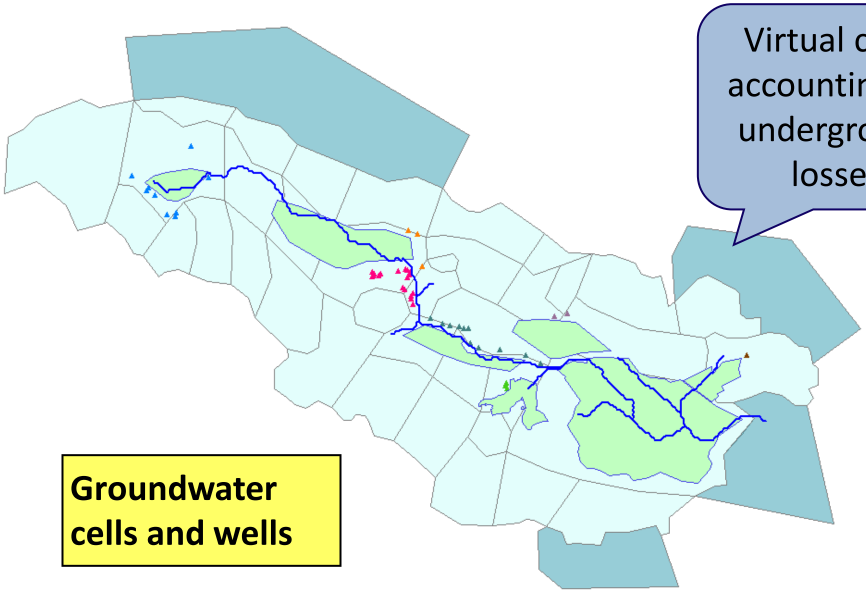


River network, sub-basins and springs



Hydrological response units

Product of three permeability and two terrain slope classes



Virtual cells, accounting for underground losses

Groundwater cells and wells

Basin area: 1956 km^2

Mean altitude: 481 m

Main course length: 102 km

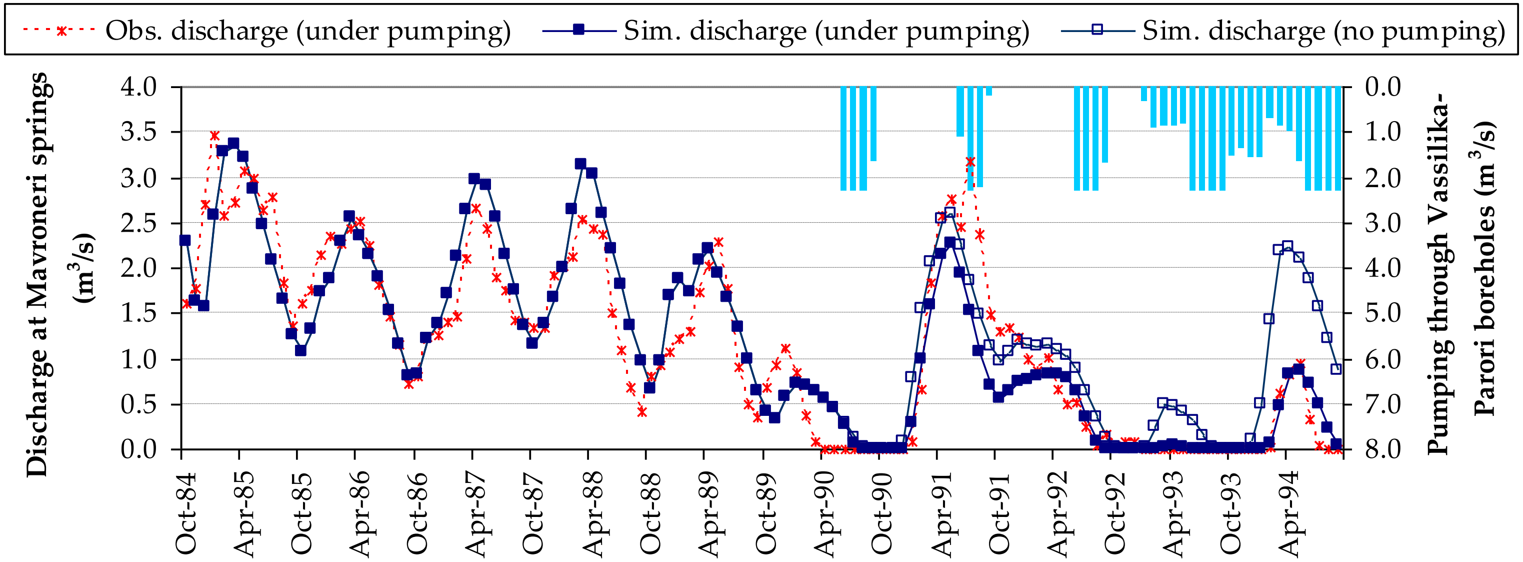
Mean annual rainfall: 875 mm

Mean annual runoff: 146 mm (after abstractions; 50% is the baseflow)

Major geological formation: limestone, at most karstified (40%)

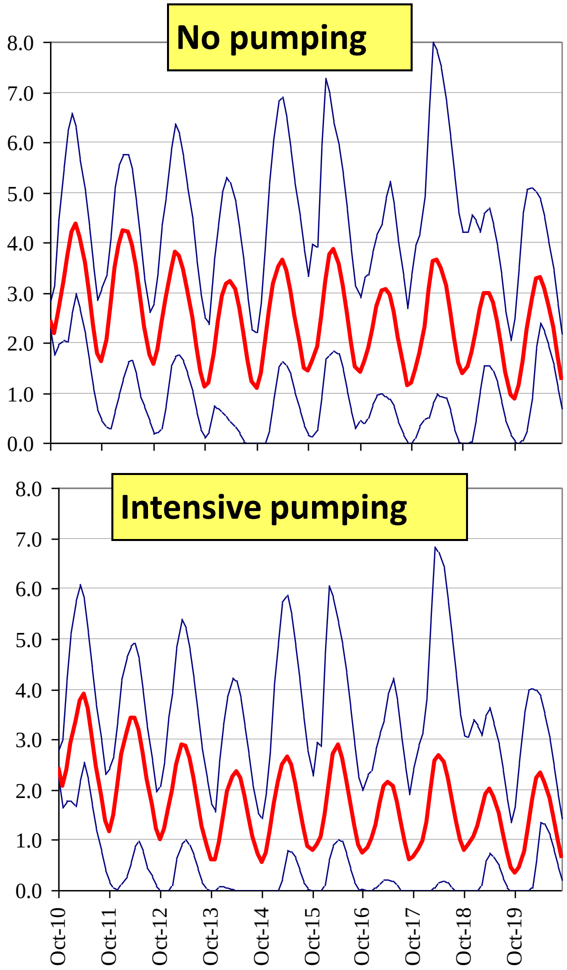
Question 3: How sustainable is the exhaustive use of boreholes?

- Most of the water supply boreholes of Athens were drilled within the frame of emergent measures taken during the persistent drought from 1988 to 1994.
- The most important were drilled in the middle course of Boeoticos Kephisos basin, close to the karst springs of Mavroneri, accounting for 15% of the basin runoff, which is turn is diverted to Hylike.
- Due to the considerable reduction of rainfall and the intense pumping, the flow of Mavroneri springs was twice interrupted during 1990 and 1993, thus resulting to severe social and environmental problems.



Stochastic simulation of the basin under alternative water supply policies

- Terminating simulation; generation of 100 synthetic rainfall scenarios, of 10-year length.
- Two extreme management scenarios are examined, with regard to the operation of the water supply boreholes at the middle course of the basin, assuming (a) zero pumping, and (b) intensive pumping, during the 10-year control period.
- Actual irrigation demands were considered across seven broader agricultural areas.
- Under the intensive abstraction policy, there is a progressive decrease of the spring outflow, which indicates that, in a long-term perspective, the intensive use of the boreholes for the water supply of Athens is not sustainable.
- **Practical interest**: evaluation of safe groundwater yield; estimation of environmental impacts and related costs, under specific pumping policies.



Simulated outflows through Mavroneri springs (mean and 80% prediction limits)

Synopsis of the modelling framework

- Model schematisation through a network-type representation of the hydrosystem components;
- Parameterisation of processes and controls on the basis of parsimonious structures, which are consistent with the available data;
- Conjunctive representation of hydrological and anthropogenic processes;
- Recognition of uncertainty and quantification of system risks through stochastic simulation;
- Representation of the Hurst-Kolmogorov behaviour in the modelled hydroclimatic processes;
- Faithful description of system dynamics;
- Use of effective and efficient optimization techniques to provide rational results, with reasonable computational effort;
- Interpretation of model results to provide pragmatic solutions in real-world problems.

Complex processes → simple models → solutions validated by common sense

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