School for Young Scientists

"Modelling and forecasting of river flows and managing hydrological risks: towards a new generation of methods"

Moscow State University (20-23 November, 2017)

Water resources management in practice: From sophisticated simulations to simple decisions

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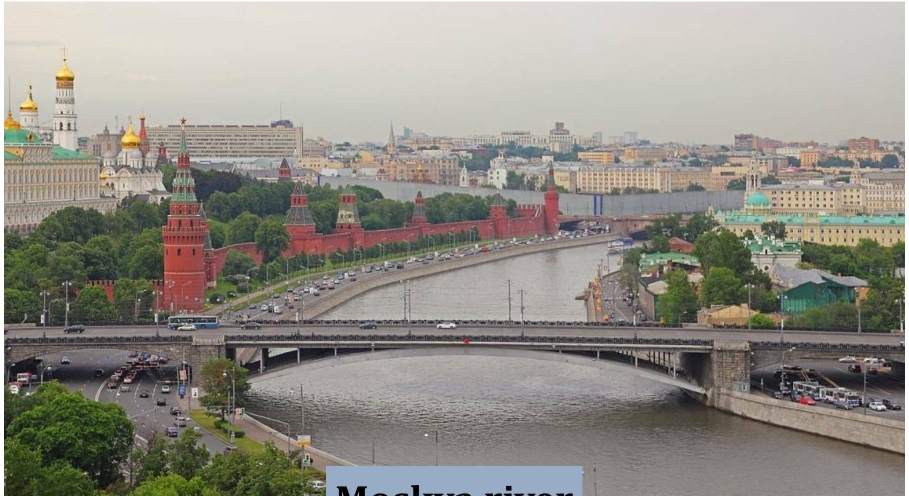
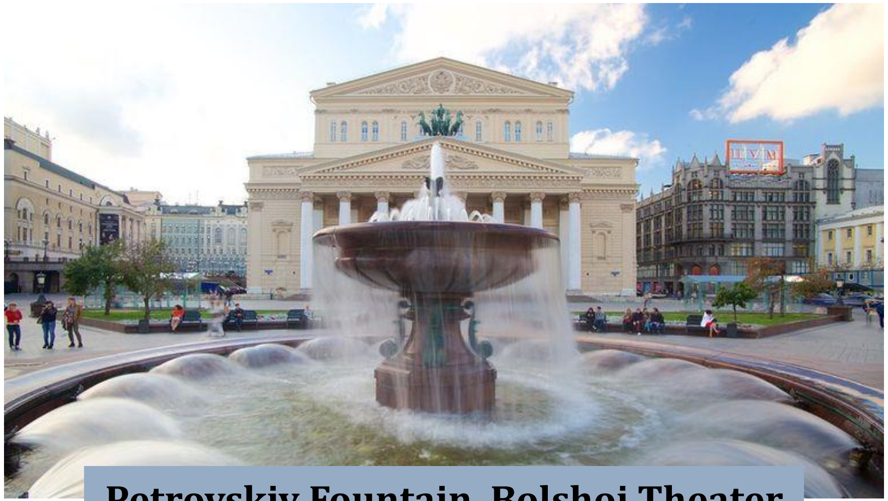
The presentation is available at: http://www.itia.ntua.gr/1755/

Water in Moscow vs. water in Athens



Moskva river



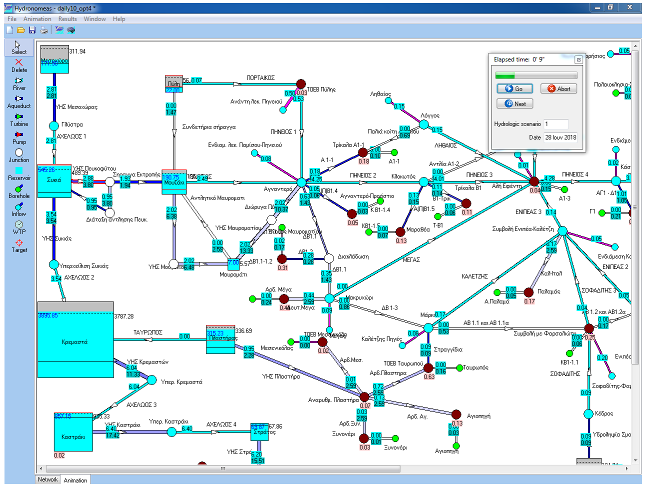
Petrovskiy Fountain, Bolshoi Theater

Kephisos river

Fountain, Constitution (Syntagma) Square

Different water regimes, similar water problems

- Operate drinking water systems to ensure the derisible quantity and quality with minimal risk.
- Be aware that your financial resources are limited.
- Take advantage of existing works, since the construction of new large-scale water infrastructures is very expensive.
- Account for additional environmental constraints.
- Make decisions, under multiple uncertainties and changing conditions.
- Ensure sustainability.
- **Explain all these to politicians, managers and stakeholders**.

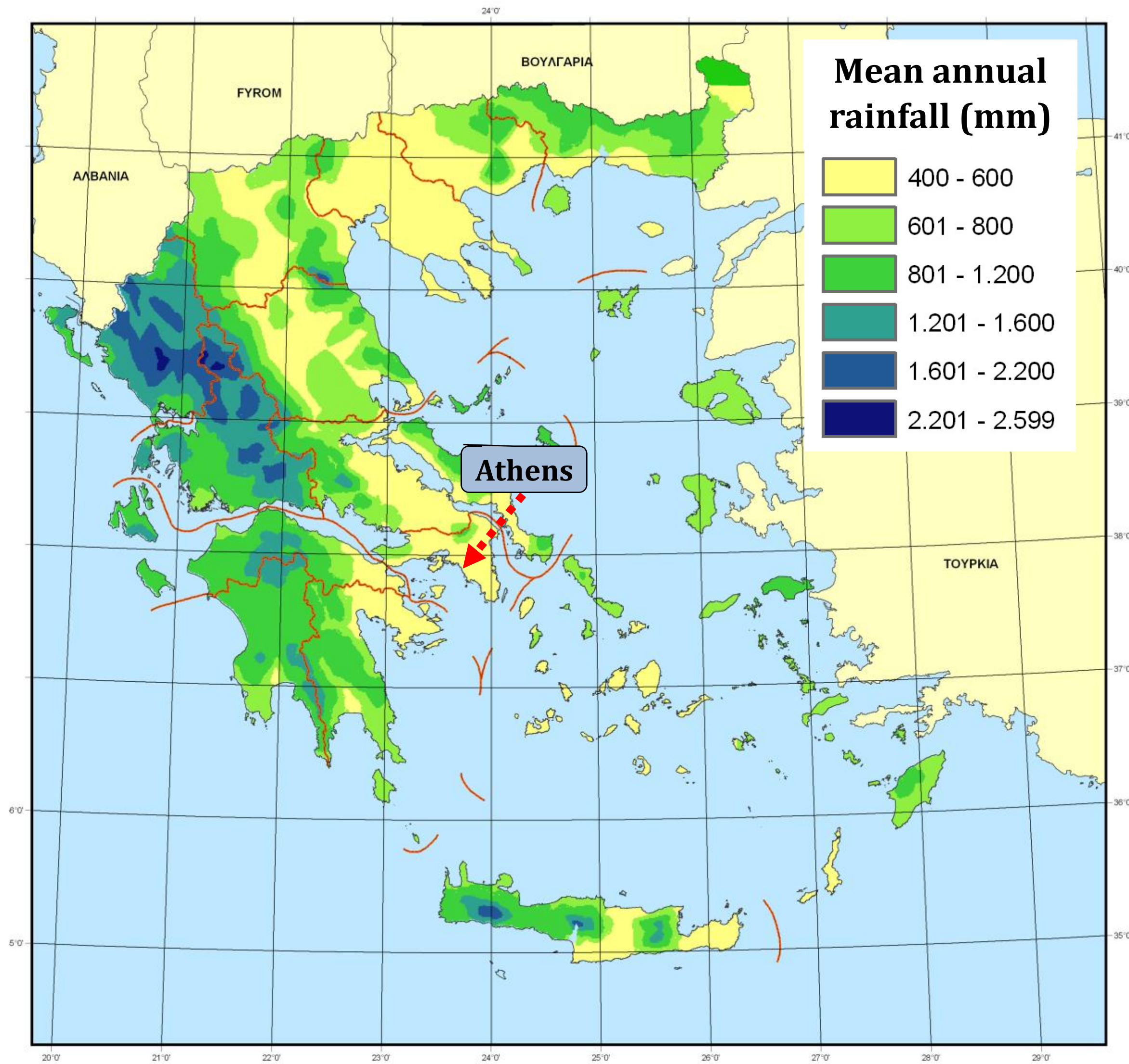


Sophisticated models

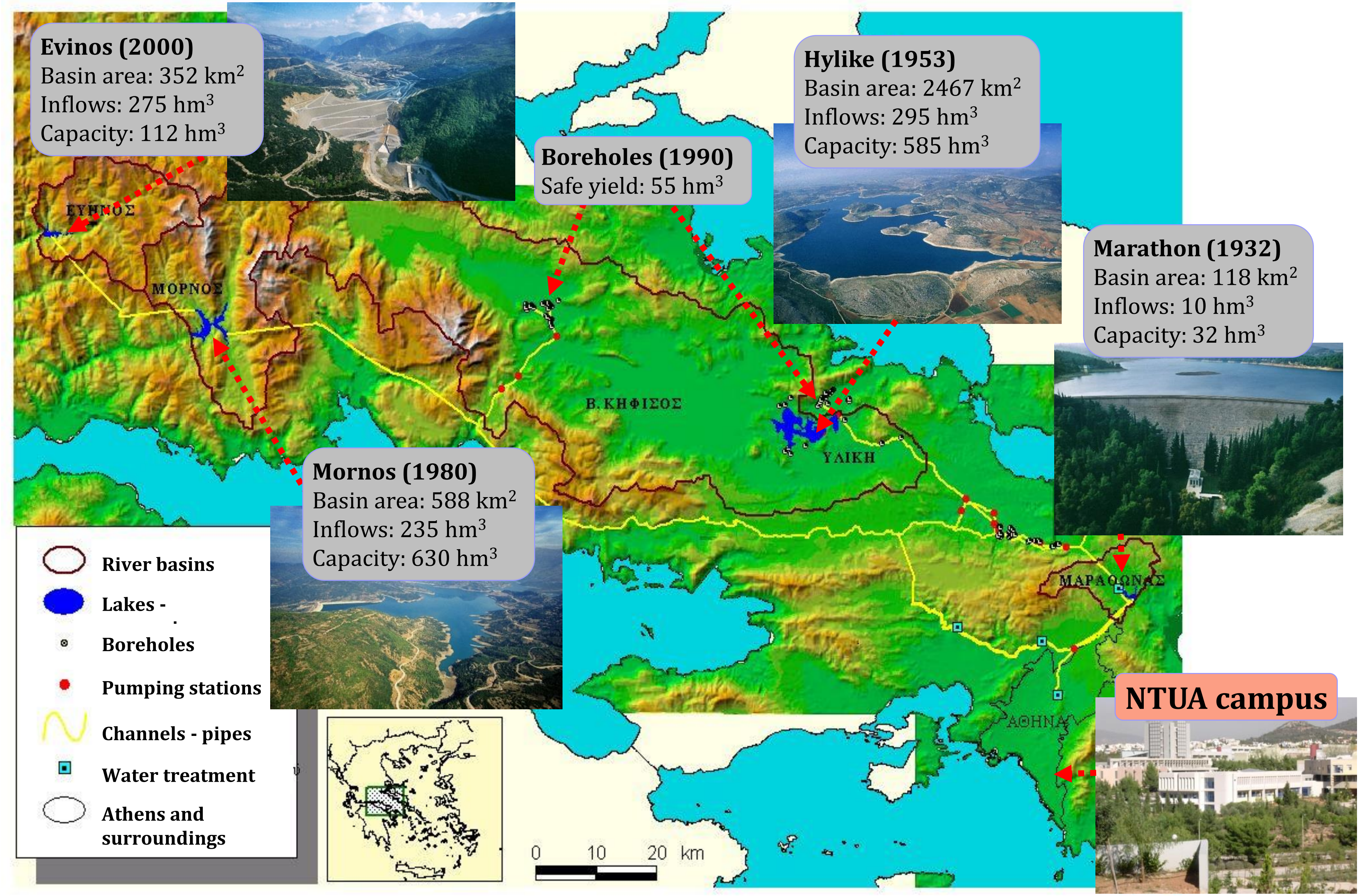
Simple decisions

The hydrological "paradox" of Greece

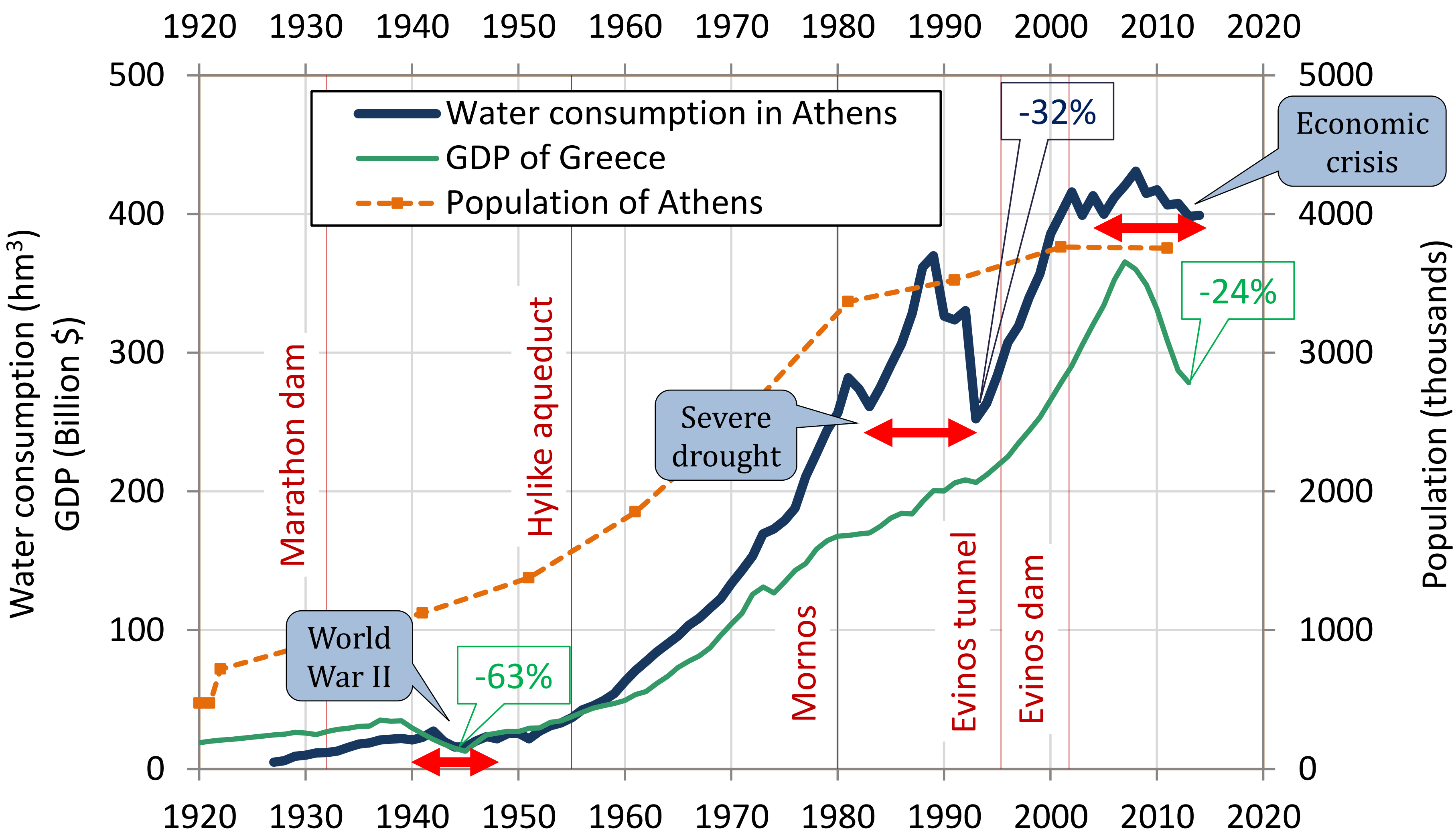
- Western Greece is very prosperous in water recourses (wet climate, mountainous topography), yet it is poorly developed.
- Eastern Greece attracts most of the population (~40% in Athens) and economic activities, but it is poor in water, due to its semi-arid hydroclimatic regime and unfavourable topography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



The water supply system of Athens (~4000 km²)



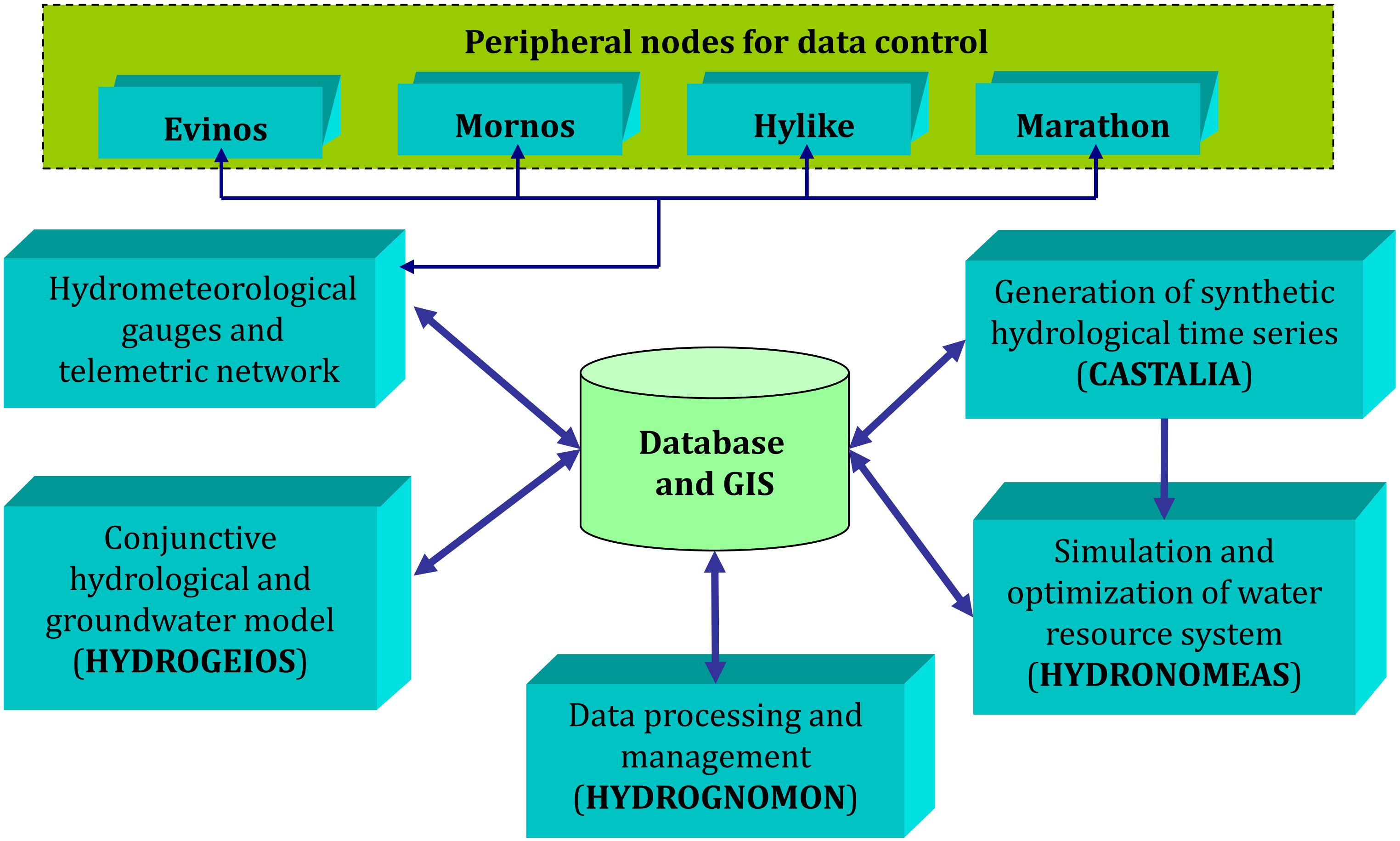
Providing drinking water to Athens: Evolution of annual demand, population, GDP and water resources



Management challenges and complexity issues

- **Conflicting objectives**
  - Water cost, mainly due to pumping (to be minimized)
  - Long-term reliability (at least 99%, on annual basis)
- **Multiple hydrosystem operation options**
  - 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 paths, some of them through pumping
  - Four water treatment plants, multiple water distribution alternatives
- **Multiple water uses**
  - Drinking water to Athens (450 hm^3, also considering leakages)
  - Local water uses across the water conveyance network (50 hm^3)
  - Environmental flows through Evinos dam (30 hm^3)
  - 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)

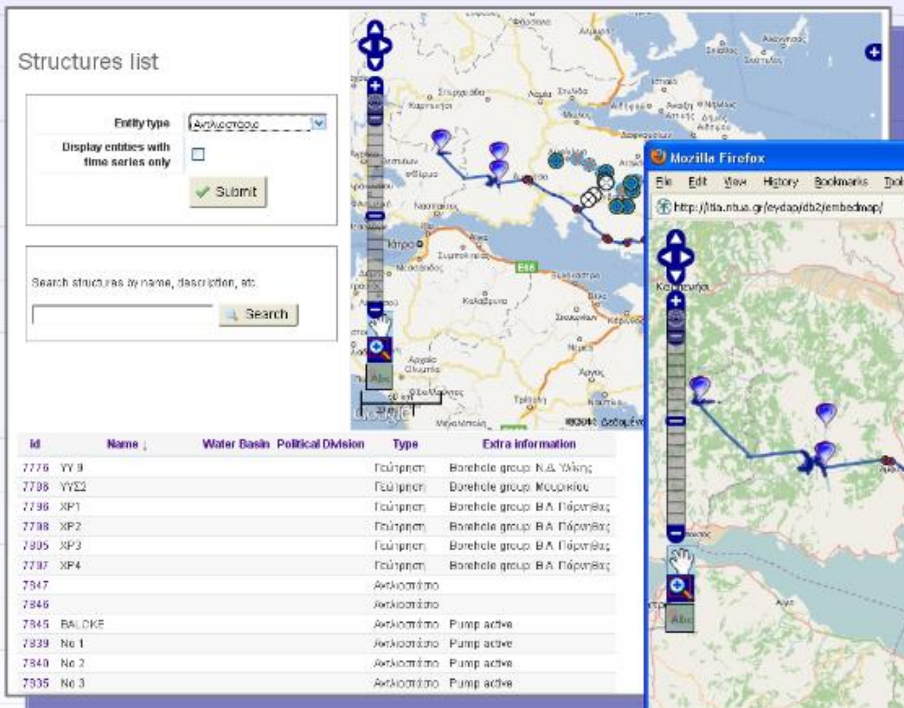
Architecture of the decision support system (DSS) for the management of Athens water supply

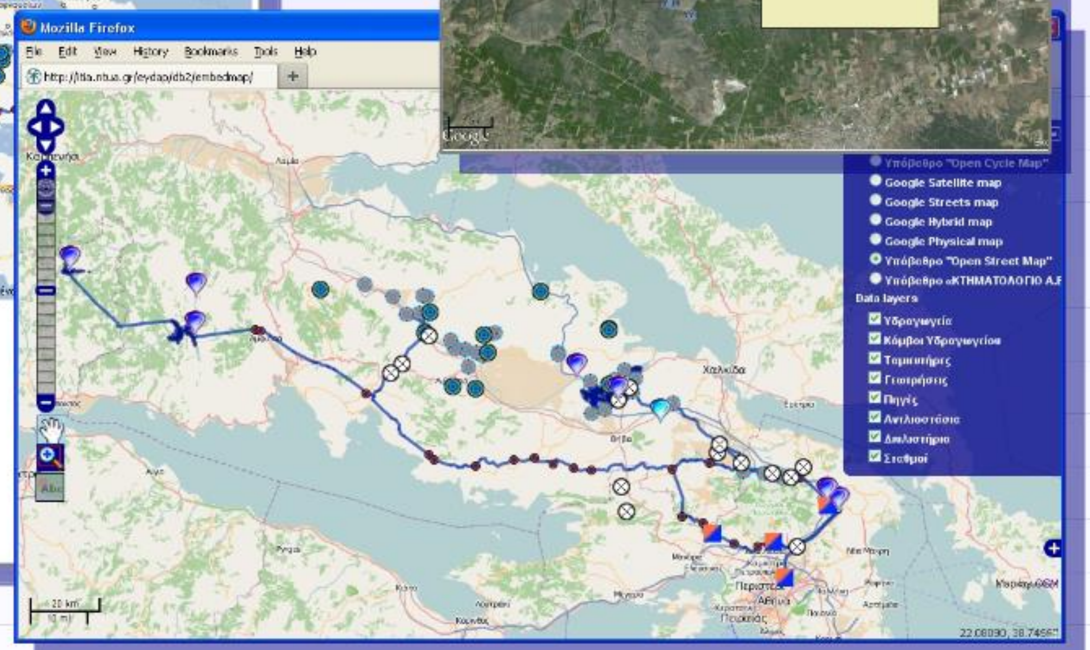


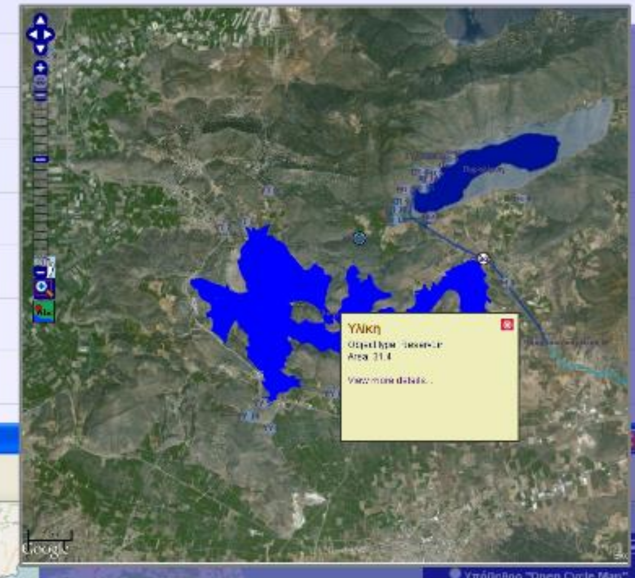
The DSS was developed from ITIA research team during 1999-2003 and upgraded during 2008-2010 (Koutsoyiannis *et al.*, 2003)

Geodata base

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

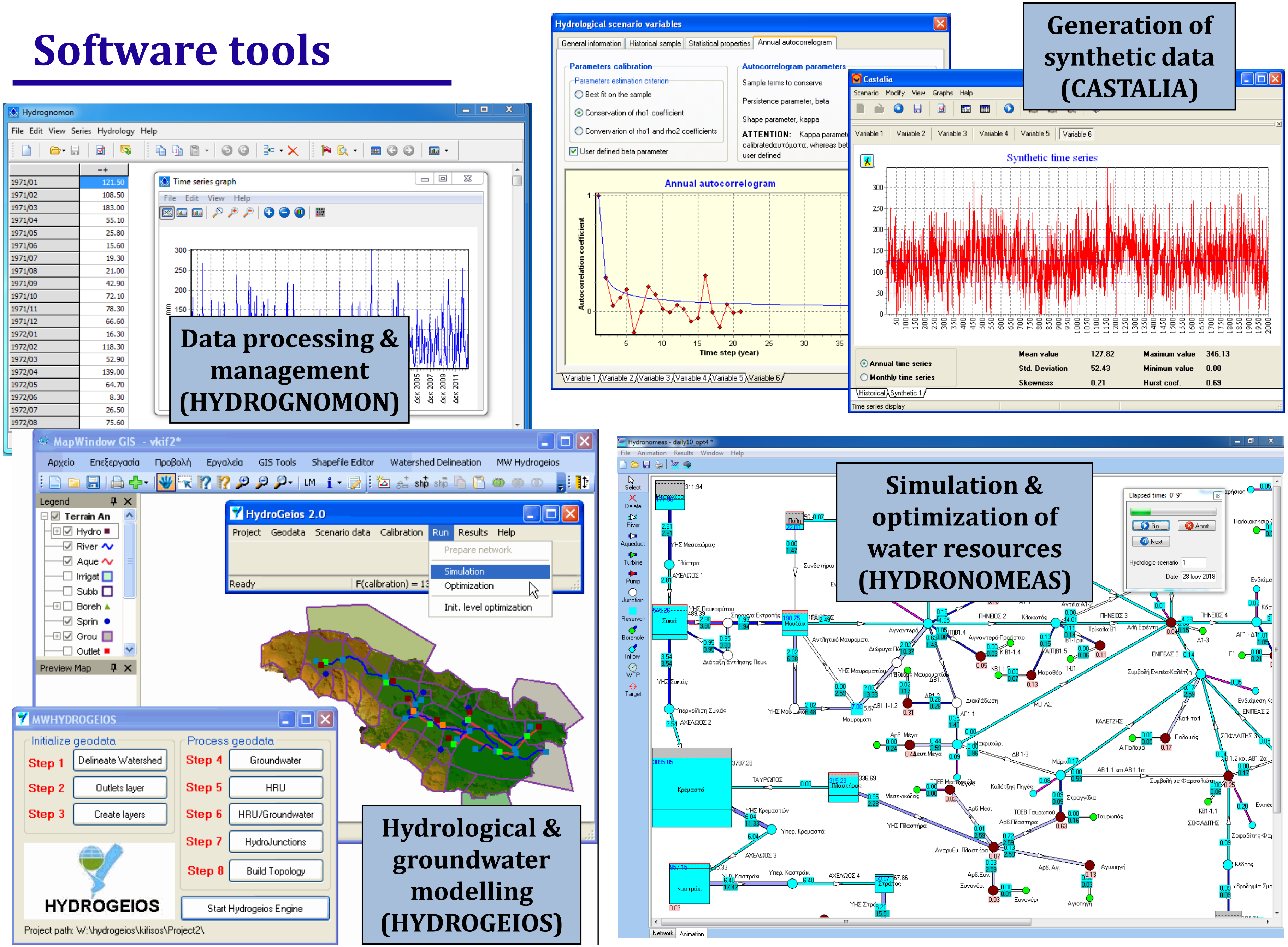




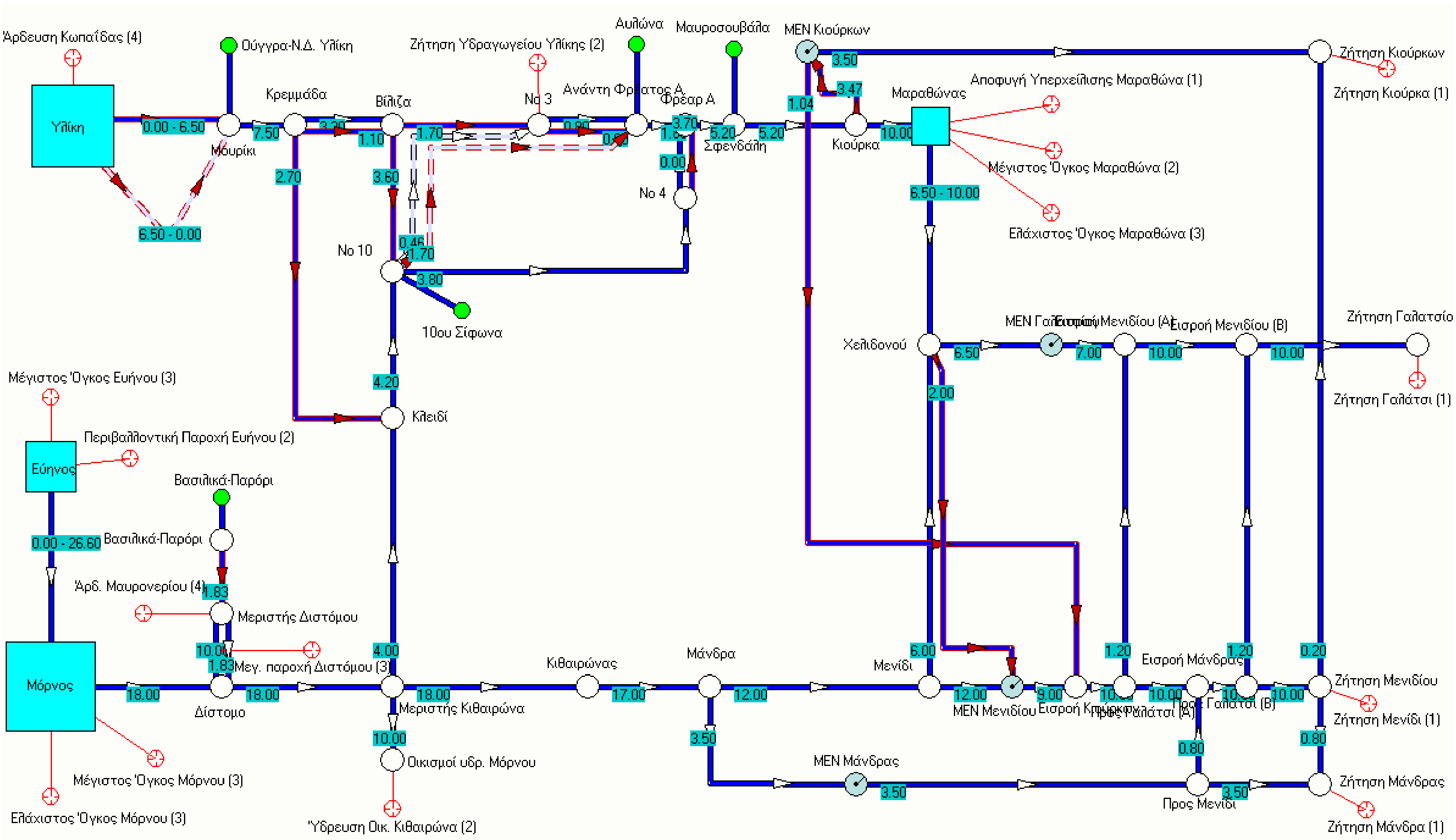


Open software for data supervision and management: Christofides *et al.*, 2011; Kozanis *et al.*, 2012

Software tools

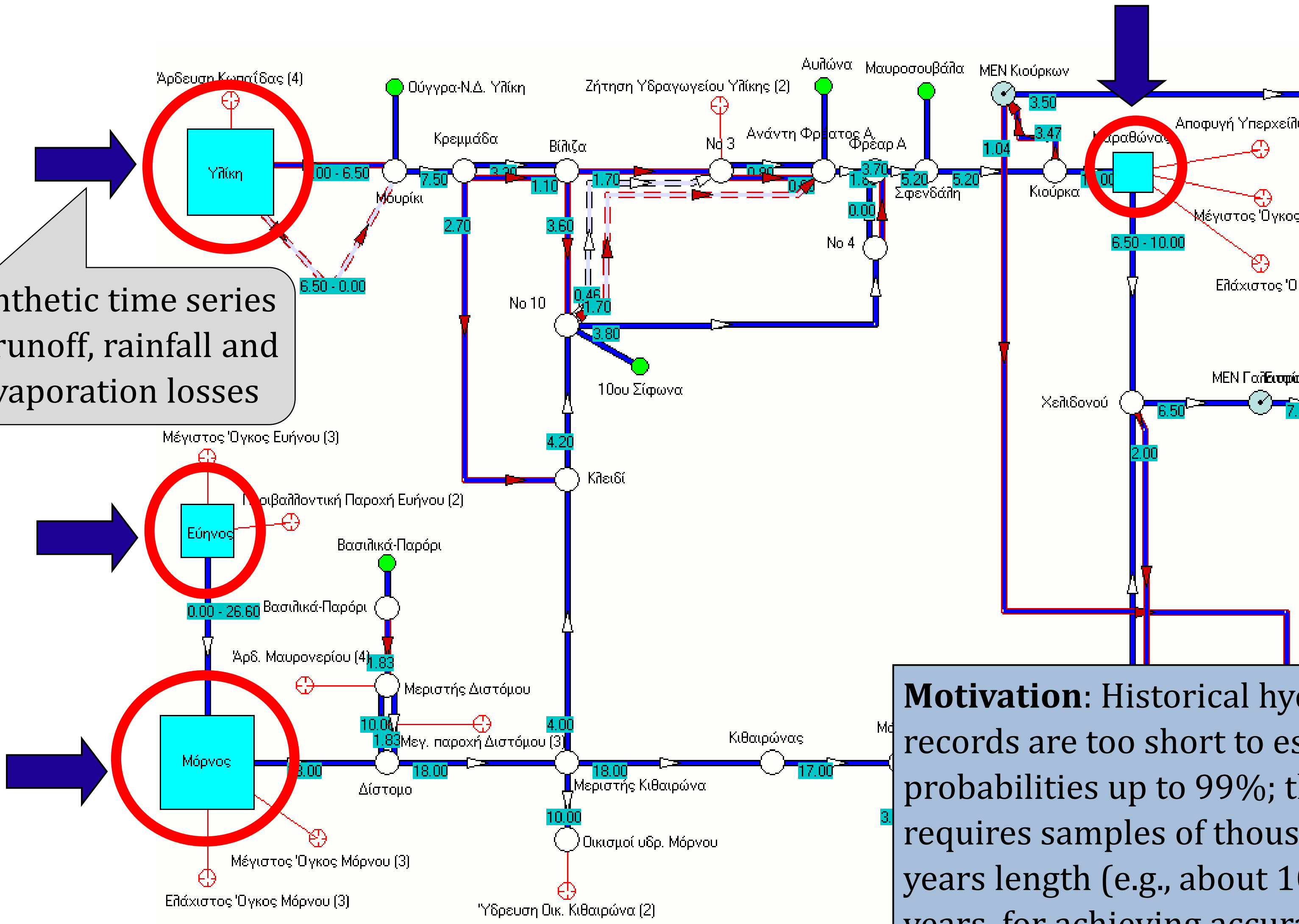


Modelling task 1: Schematization of the hydrosystem



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

Modelling task 2: Generation of hydrological inputs

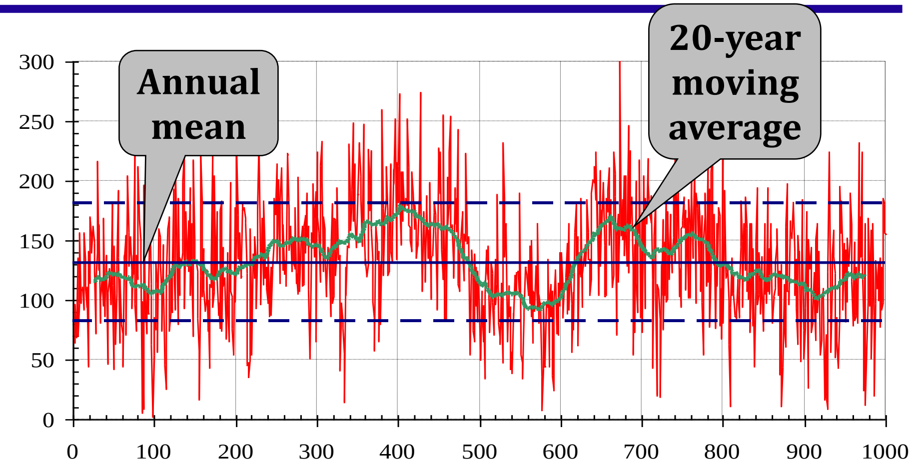


Synthetic time series of runoff, rainfall and evaporation losses

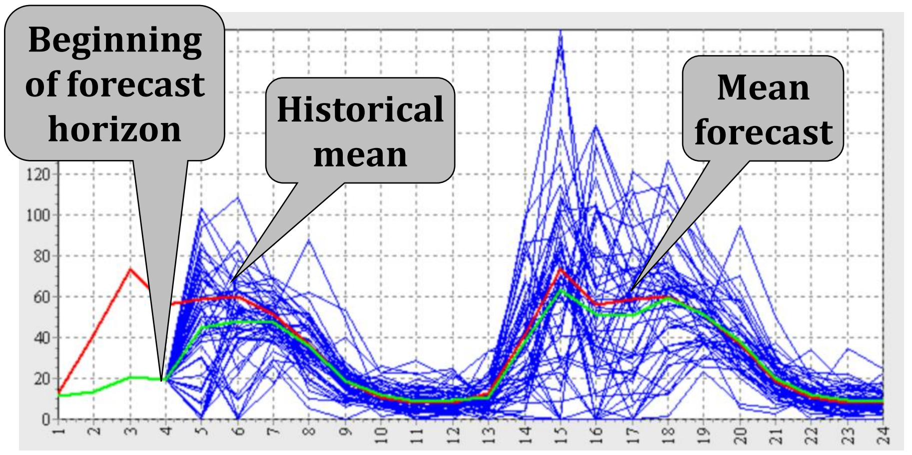
Motivation: Historical hydrological records are too short to estimate probabilities up to 99%; this requires samples of thousands of years length (e.g., about 10 000 years, for achieving accuracy of 1%)

The stochastic model Castalia

- **Multivariate stochastic model**, to represent correlated processes;
- Preservation of essential statistics:
  - **Marginal statistics** up to third order (mean , variance, skewness);
  - **Temporal and spatial correlations**;
  - **Long-term persistence** (Hurst phenomenon; annual and over-annual time scales);
  - **Periodicity** (monthly time scale);
- Operation in two modes:
  - **Steady-state simulation** mode (synthetic data of long horizon);
  - **Stochastic forecast** mode, by means of "ensemble" time series, representing multiple inflow scenarios for relatively small horizons, conditioned to past data.



Annual time series for steady-state simulation

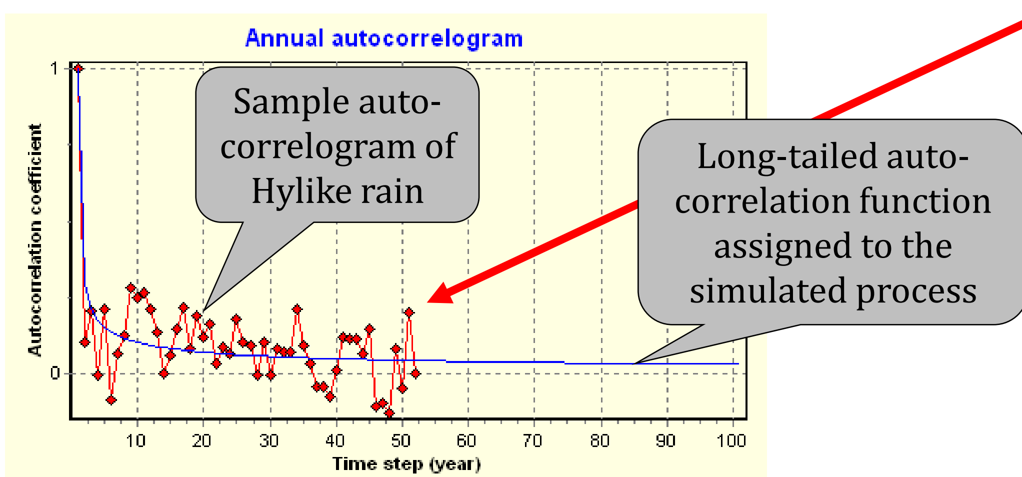


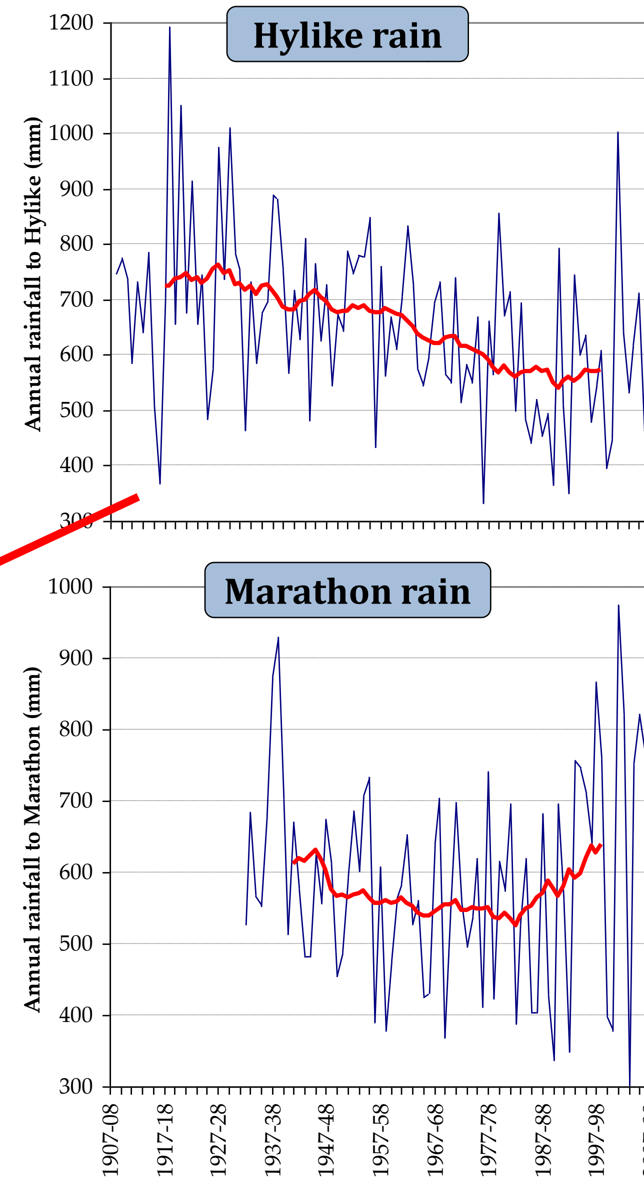
Monthly time series for terminating simulation

Stochastic simulation framework and its modelling implementation: Koutsoyiannis and Manetas, 1996; Koutsoyiannis, 1999, 2000; 2001; Efstratiadis *et al.*, 2014

Representing the Hurst-Kolmogorov behaviour

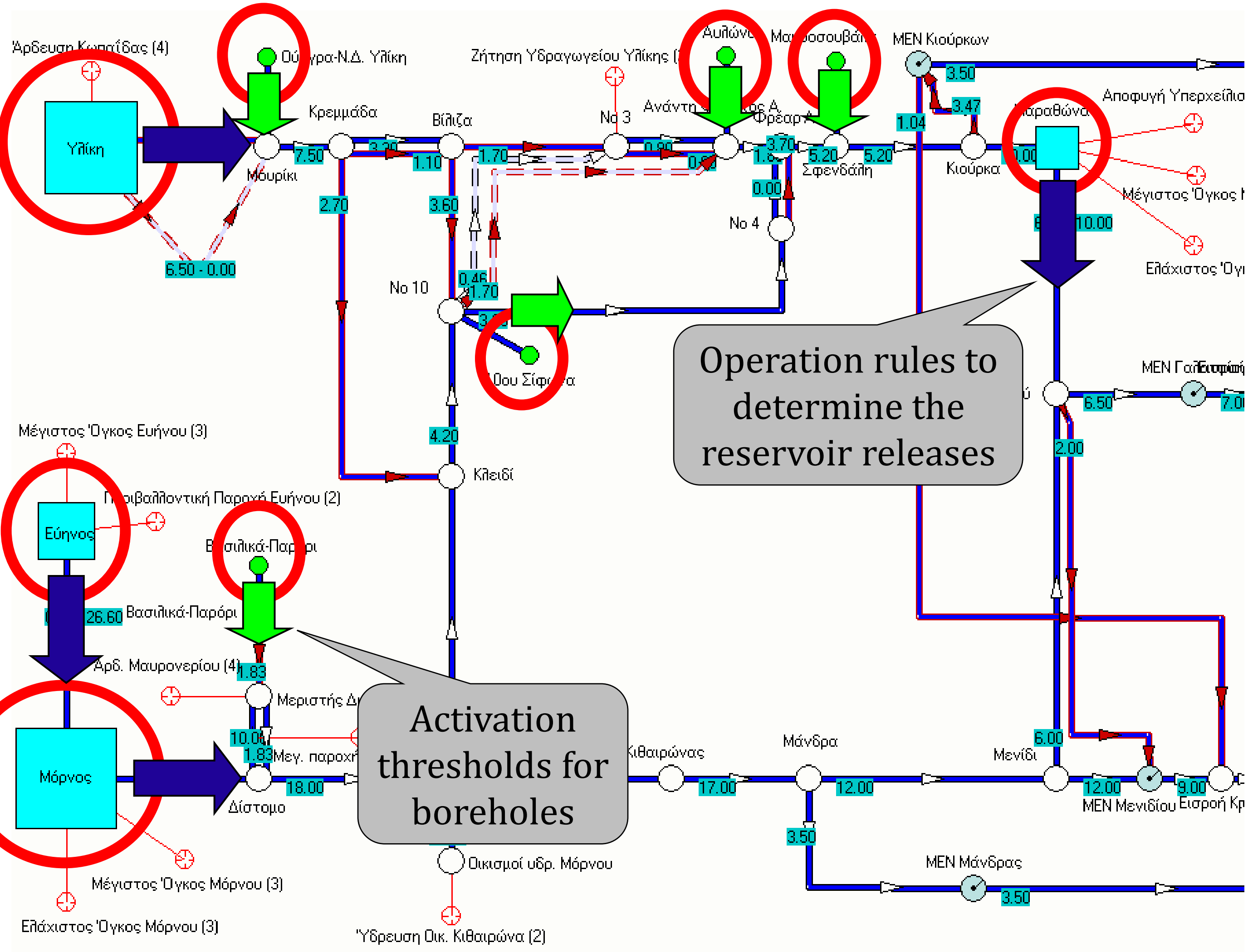
- Historical data exhibit multiscale fluctuations and trends that cannot be represented through **short-memory** schemes, such as ARMA-type models.
- **Persistent droughts** and **changing climate** are typical aspects of this behaviour, which is crucial to be represented in water management models.
- The **Hurst-Kolmogorov dynamics** is easily implemented in terms of **long-term autocorrelation** of the stochastic process.





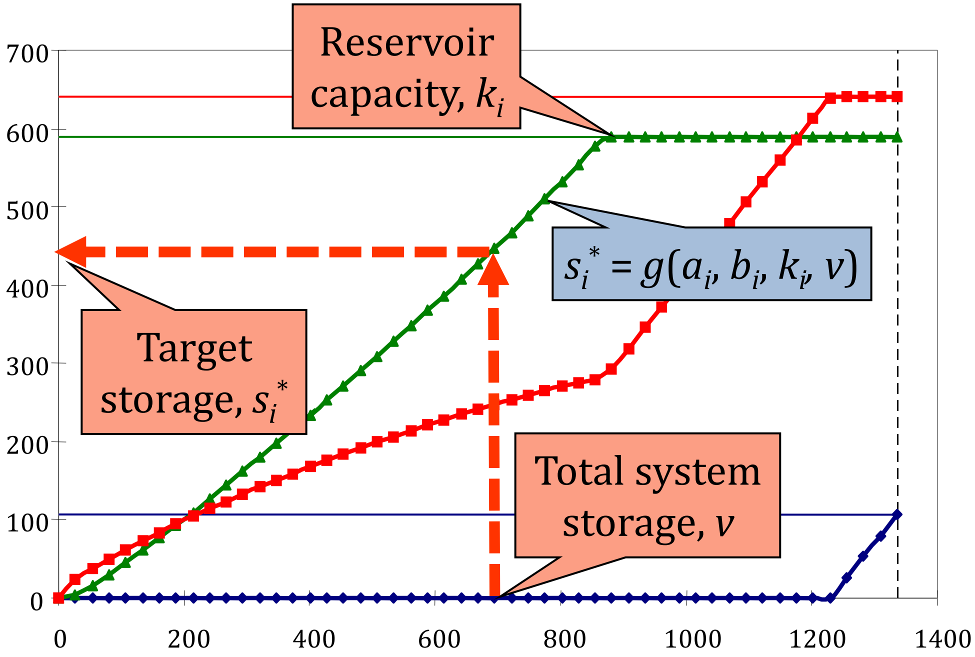
Long-term persistence in stochastic modelling and HK dynamics in geophysical processes: Koutsoyiannis 2000, 2003, 2011

Modelling task 3: Establishment of the long-term control policy for reservoirs and boreholes



Operation rules for multi-reservoir systems

- **Graphical rules** that specify the desirable allocation of reservoir resources and their **target-releases**, as function of:
  - the estimated total storage of the system at the end of each control period (month);
  - the capacities of all reservoirs (physical constraints);
  - other storage constraints, imposed by the user.



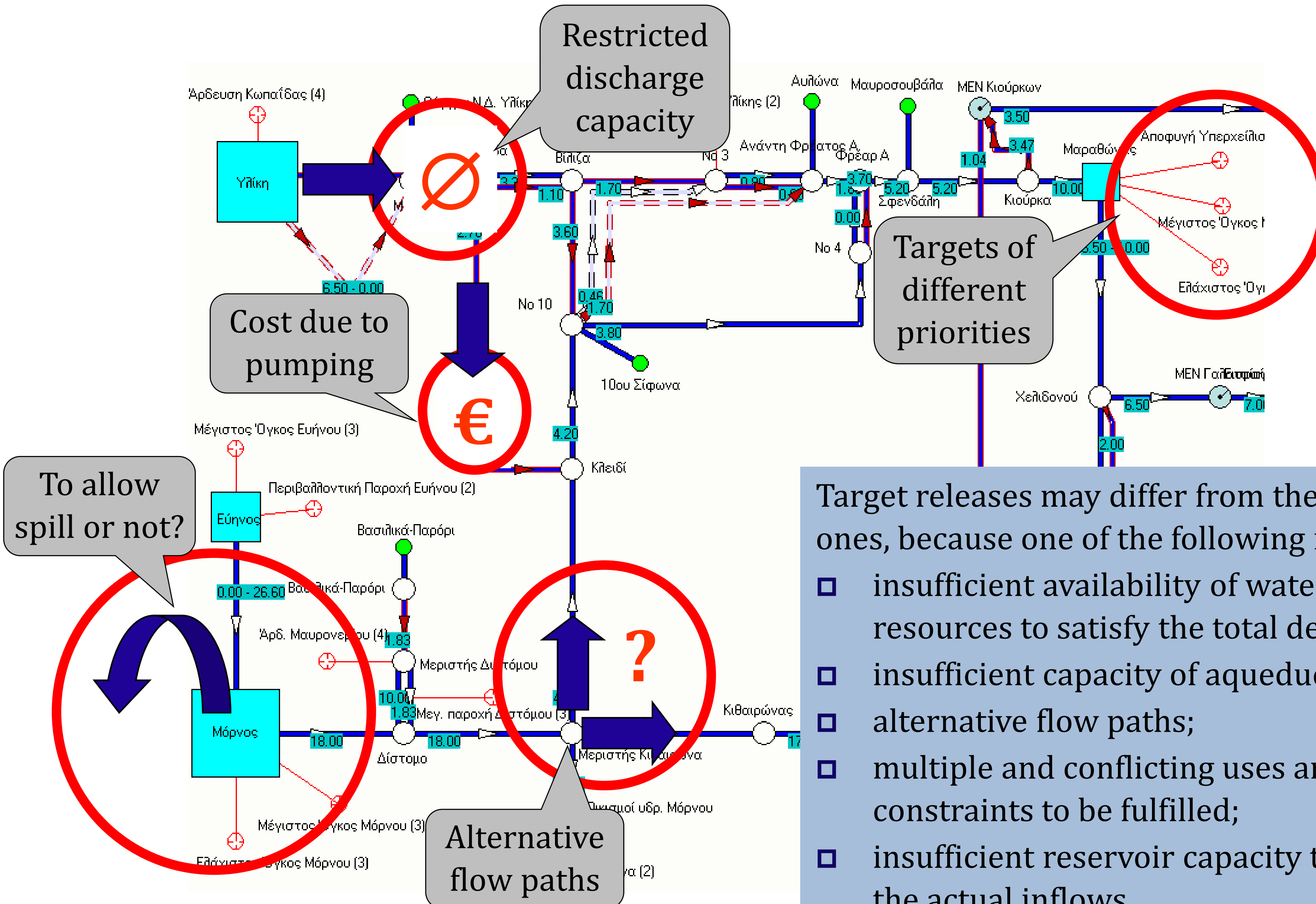
- Since inflows are projected through simulation, the target releases are easily estimated, on the basis on the actual storages and the total water demand.
- The rules are mathematically expressed using two parameters per reservoir, thus ensuring a **parsimonious parameterization** of the related optimization 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.
- At each time step, on the basis of the ratio of **total reservoir storage to total capacity** we get one of the following cases:
  - If the storage ratio exceeds the upper threshold, boreholes are not activated;
  - if the storage ratio is below the lower threshold, the borehole 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.
- The **long-term management policy** is expressed through few parameters for reservoirs and boreholes – their number does not depend on simulation length.

Operation rules for reservoir systems and the parameterization-simulation-optimization framework: Nalbantis and Koutsoyiannis, 1997; Koutsoyiannis *et al.*, 2002; Koutsoyiannis and Economou, 2003

Modelling task 4: Optimal allocation of actual fluxes



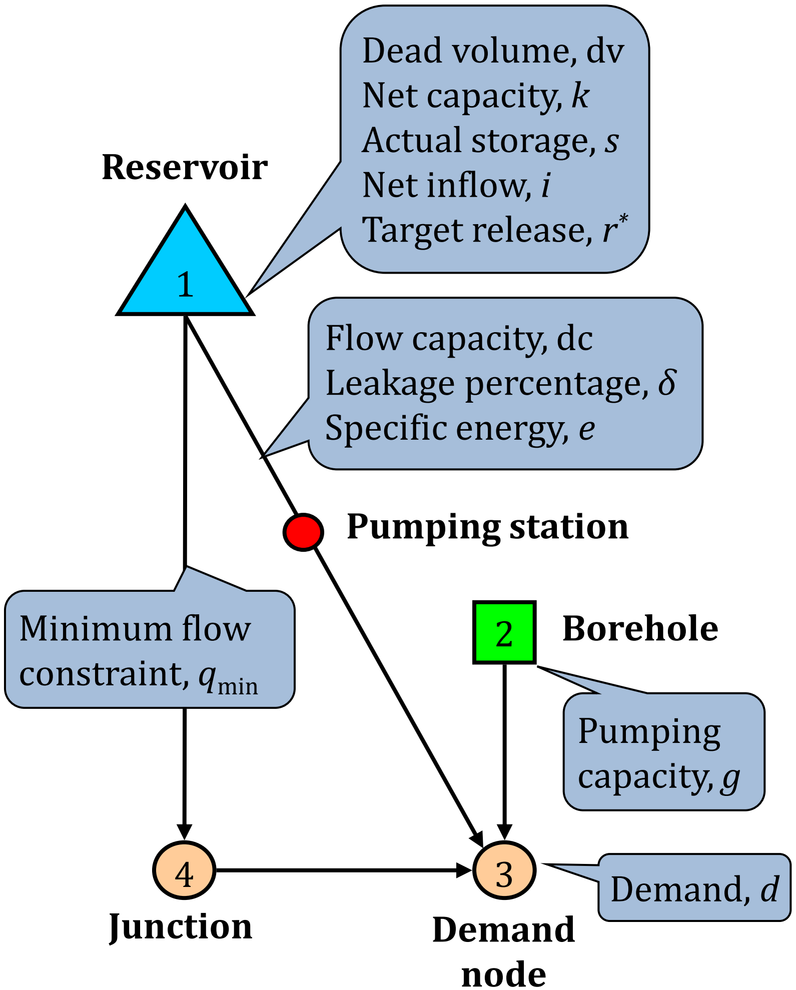
Target releases may differ from the actual ones, because one of the following reasons:

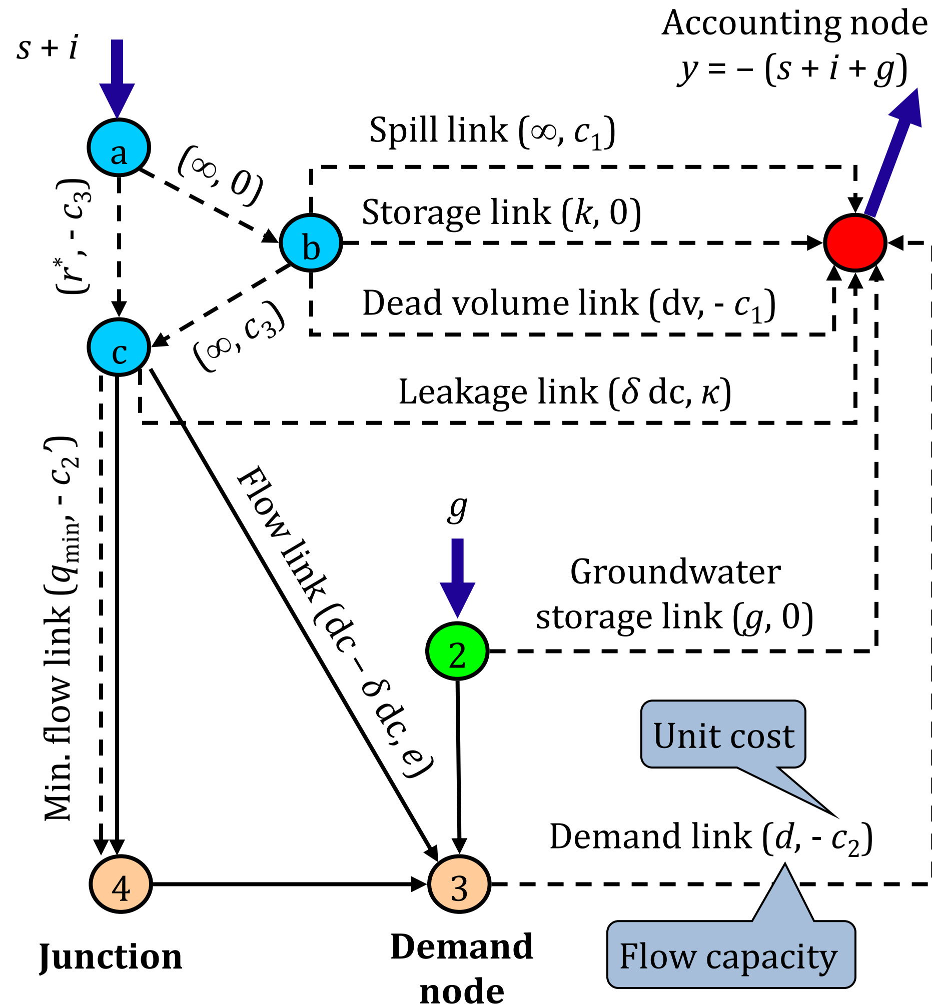
- insufficient availability of water resources to satisfy the total demand;
- insufficient capacity of aqueducts;
- alternative flow paths;
- multiple and conflicting uses and constraints to be fulfilled;
- insufficient reservoir capacity to store the actual inflows.

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.

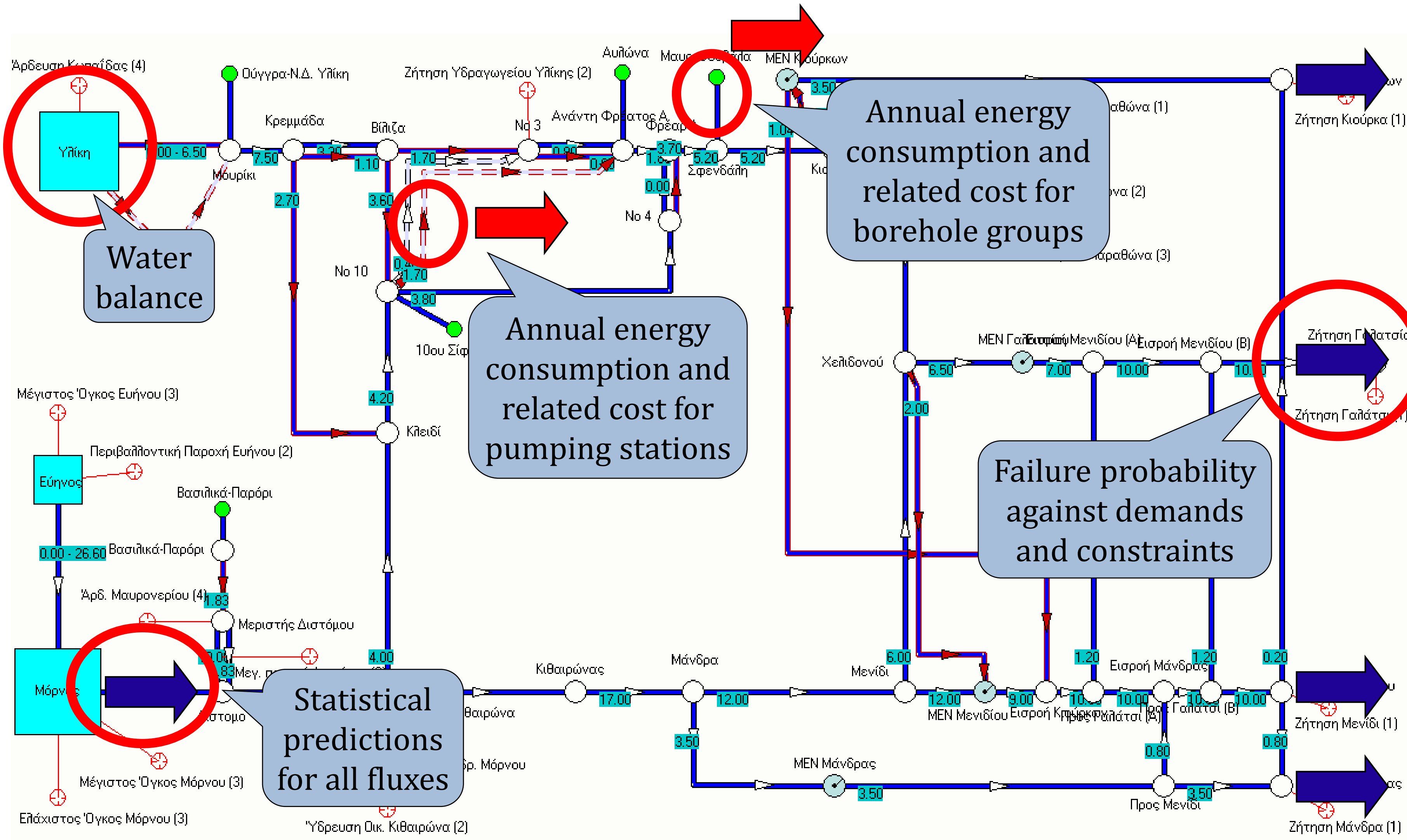
Example of optimizing the running flow allocation policy across a water recourses system through NLP



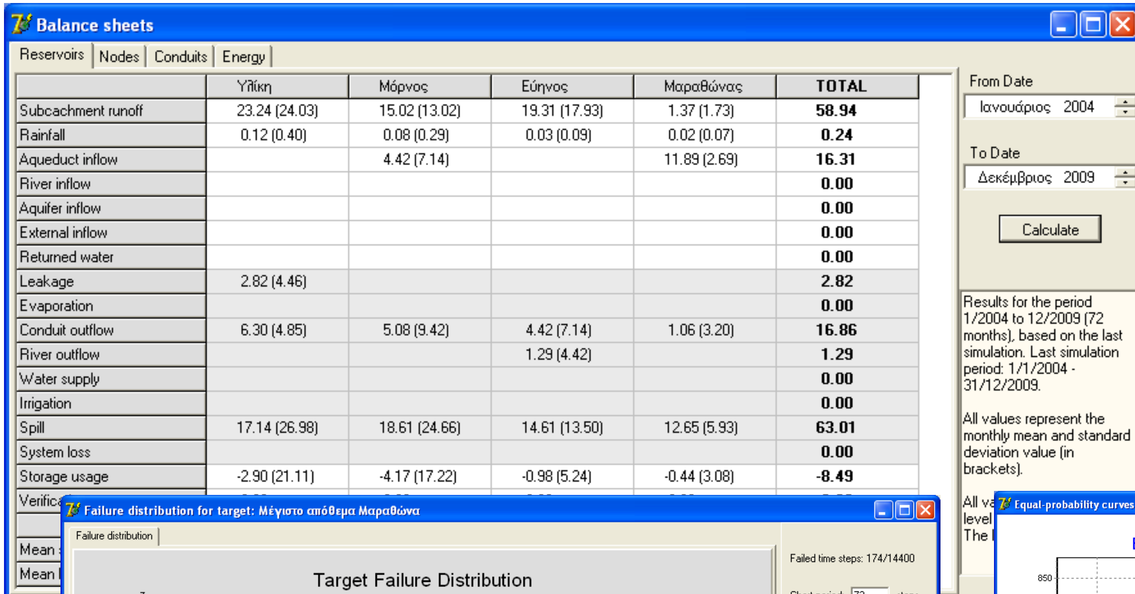


The use of NLP within water resources modelling: Efstratiadis *et al.*, 2004; Efstratiadis *et al.*, 2008

Modelling task 5: Evaluation and optimization of the hydrosystem operation policy

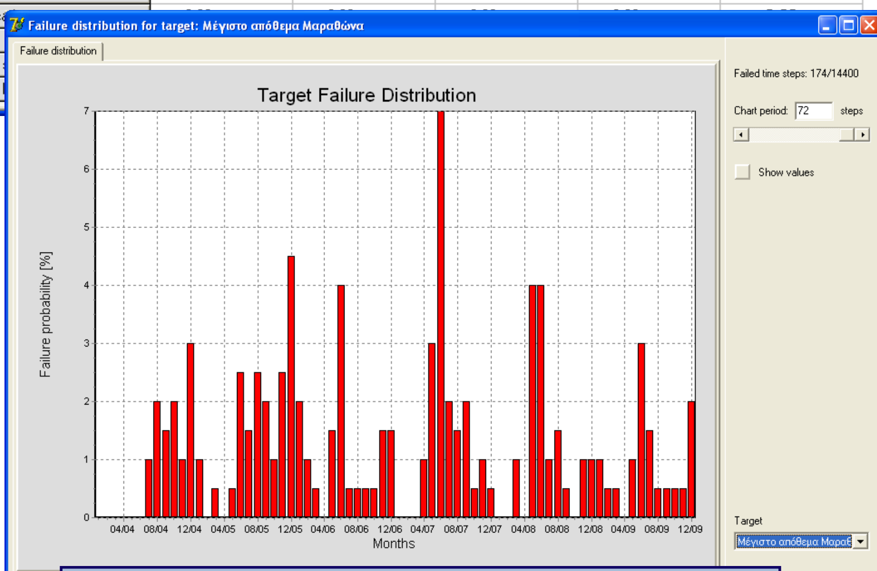


Simulation results

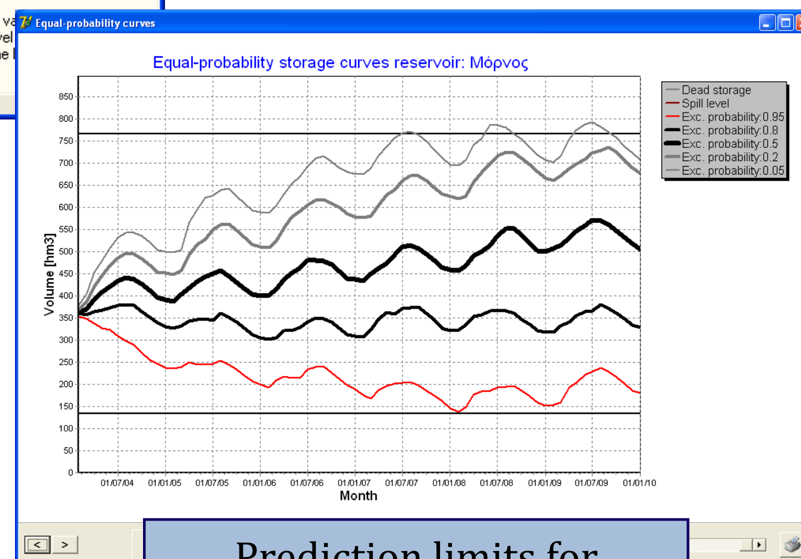


	Υλίκη	Μόρνος	Εύηνος	Μαραθώνας	TOTAL
Subcachment runoff	23.24 (24.03)	15.02 (13.02)	19.31 (17.93)	1.37 (1.73)	58.94
Rainfall	0.12 (0.40)	0.08 (0.29)	0.03 (0.09)	0.02 (0.07)	0.24
Aqueduct inflow		4.42 (7.14)		11.89 (2.69)	16.31
River inflow					0.00
Aquifer inflow					0.00
External inflow					0.00
Returned 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

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

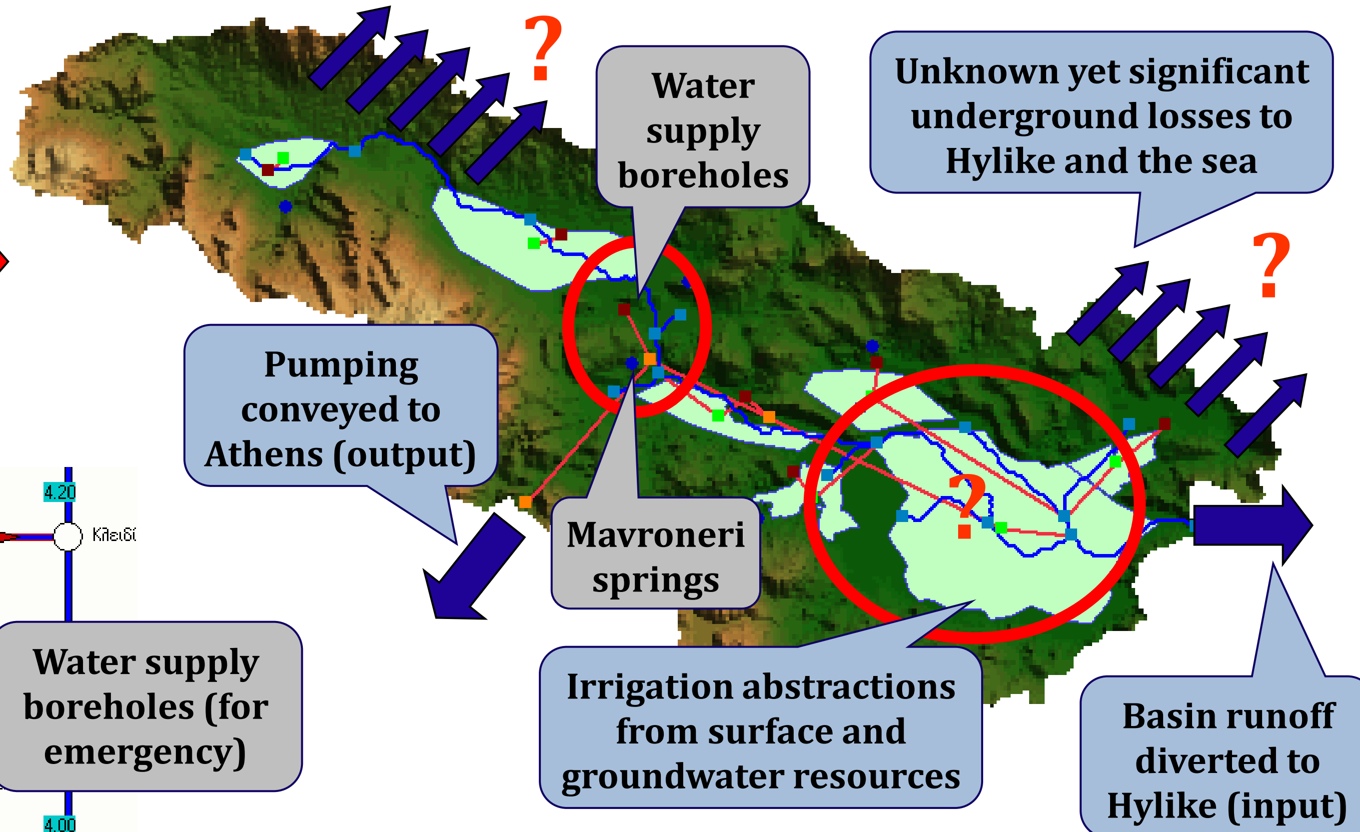


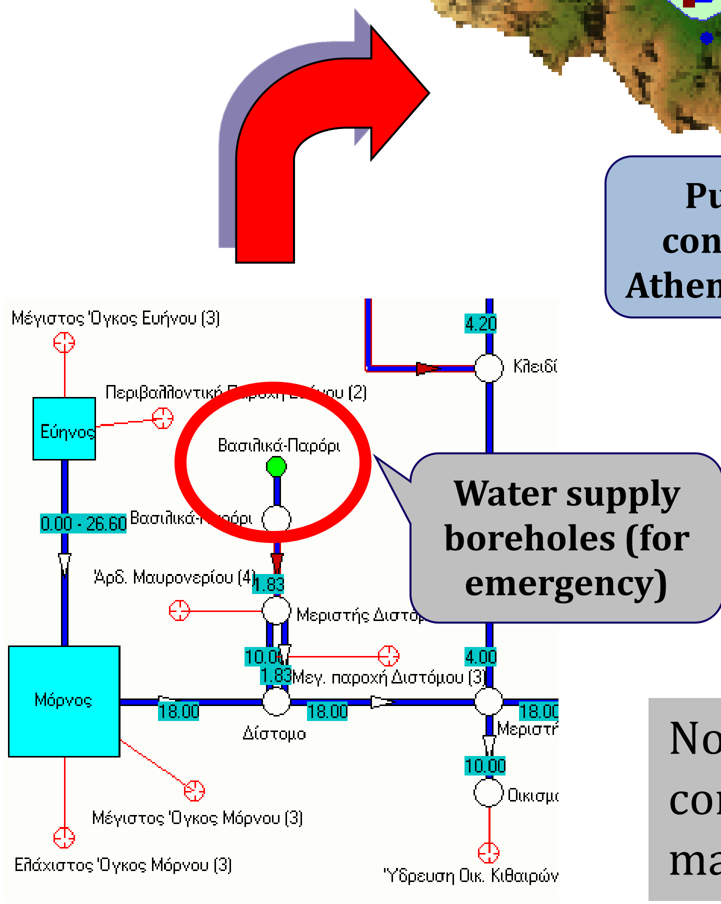
Stochastic forecast of failure probability (terminating simulation)



Prediction limits for reservoir storage and level (terminating simulation)

Modelling task 6: Assessment of impacts of groundwater abstractions from Boeoticos Kephisos boreholes





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

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.

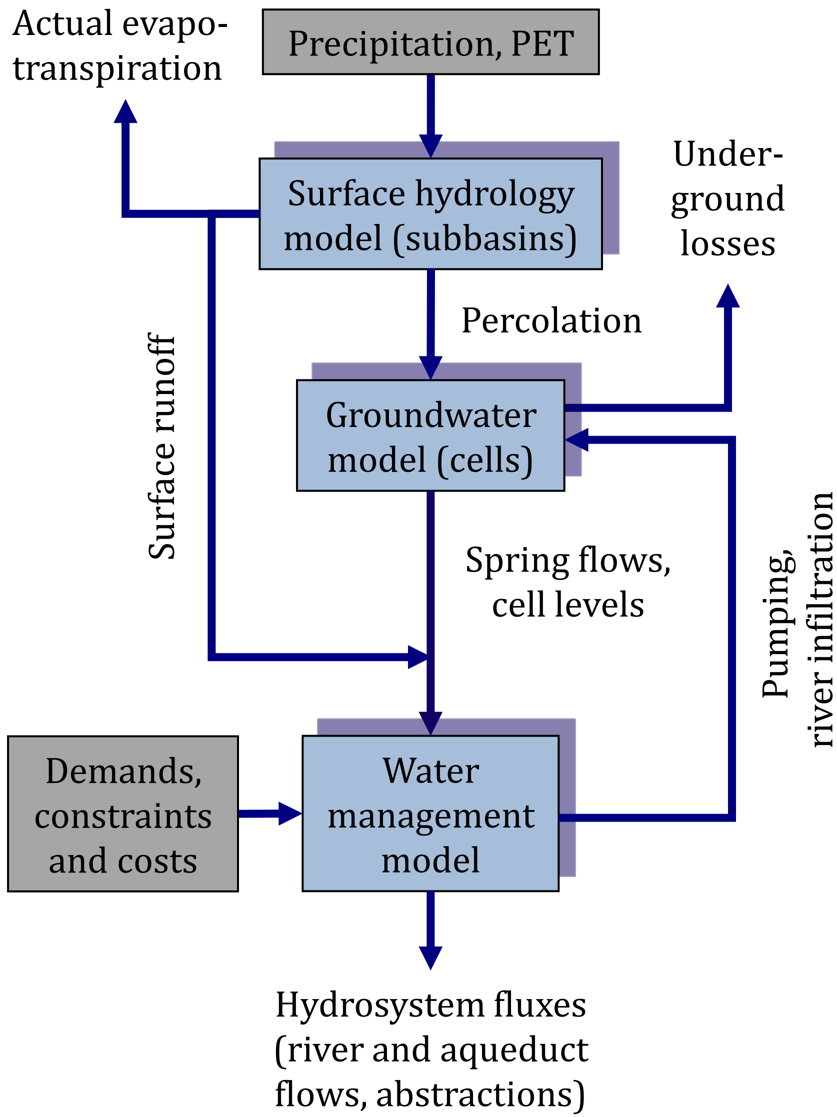
Groundwater module

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

Water allocation module

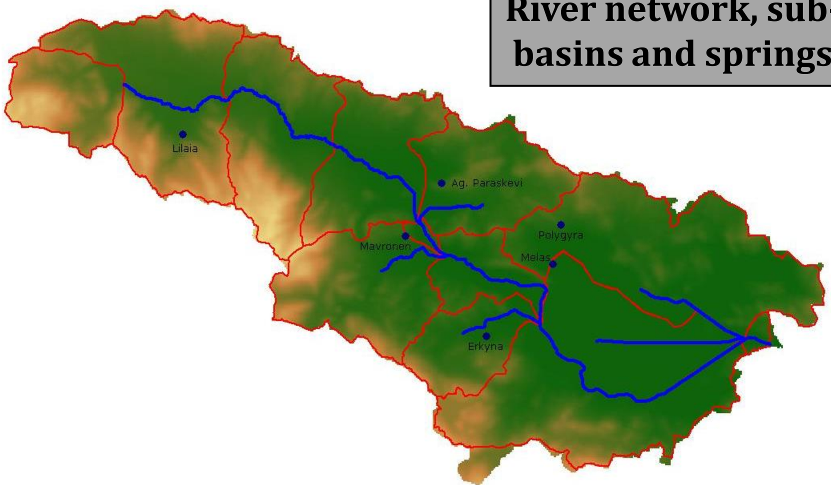
- Extension of the NLP approach, to also embrace the river network components.

Modelling of human-modified basins: Rozos *et al.*, 2004; Efstratiadis *et al.*, 2008; Nalbantis *et al.*, 2011

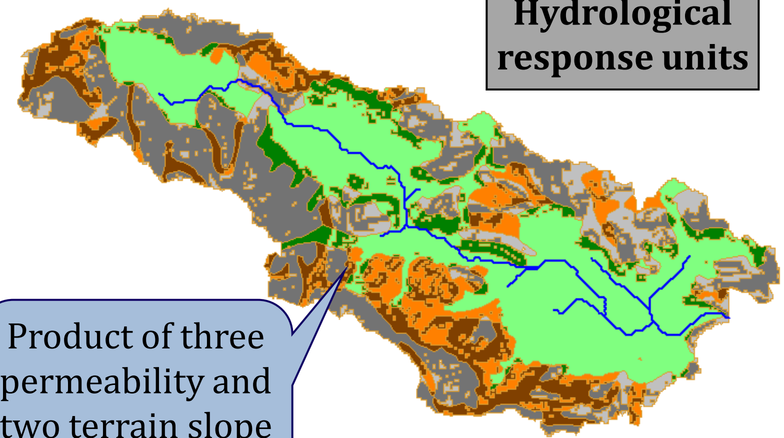


Geographical components of Boeoticos Kephisos model

River network, sub-basins and springs

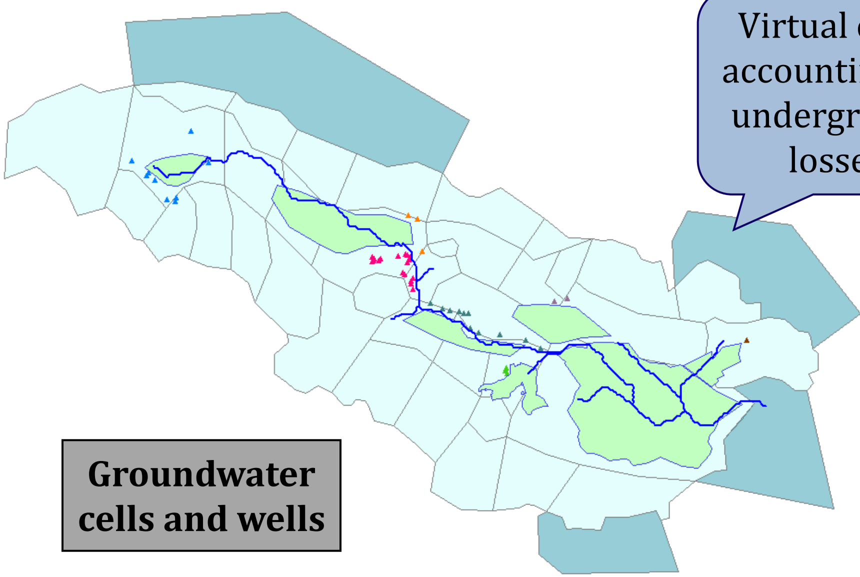


Hydrological response units



Product of three permeability and two terrain slope classes

Virtual cells, accounting for underground losses



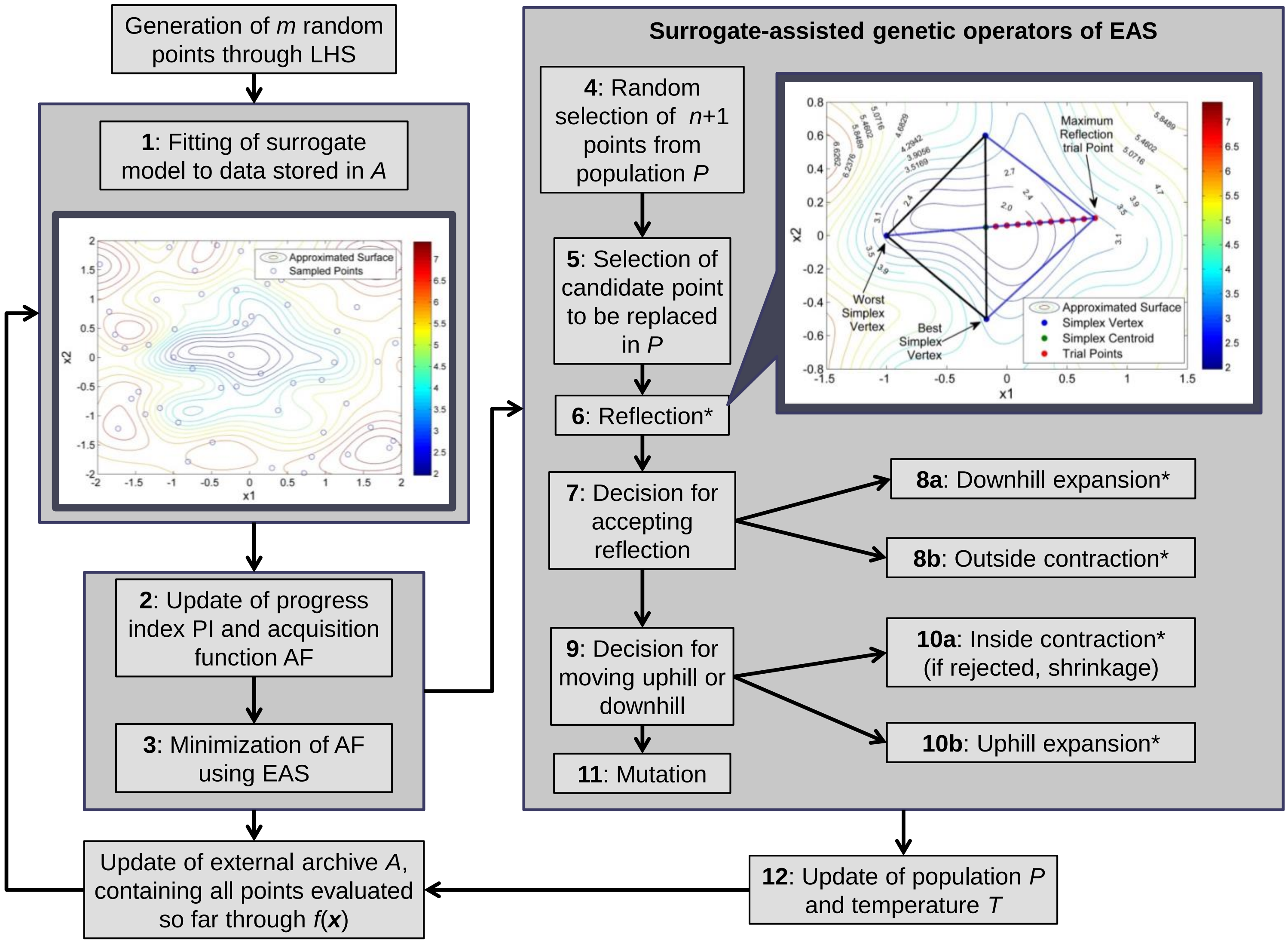
Groundwater cells and wells

Basin area: 1956 km^2
Mean altitude: 481 m
Main river 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%)

Modelling task 7: Challenging optimizations

- **HYDROGEIOS – Global optimization within calibration**
  - Inverse problem (unknown system dynamics, known responses);
  - Many parameters (six per HRU, two per groundwater cell);
  - Multiple and conflicting calibration criteria (observed flows at multiple sites, criteria for internal model consistency);
  - Highly nonlinear search space, comprising many local optima due to parameter interactions and equifinality;
  - Computational time for a single historical simulation ~1 sec (10 years of observed data);
- **HYDRONOMEAS – Global optimization for long-term management policy**
  - Direct problem (known system dynamics, unknown responses);
  - Few parameters (two per reservoir, two per borehole group);
  - Two major and conflicting performance criteria (reliability, cost);
  - Search space comprising extended smooth areas (similar performance obtained for different operation rules, since abstractions are mainly dictated from downstream water uses and constraints);
  - Computational time for a single stochastic simulation ~1 min (2000 years of synthetic data);

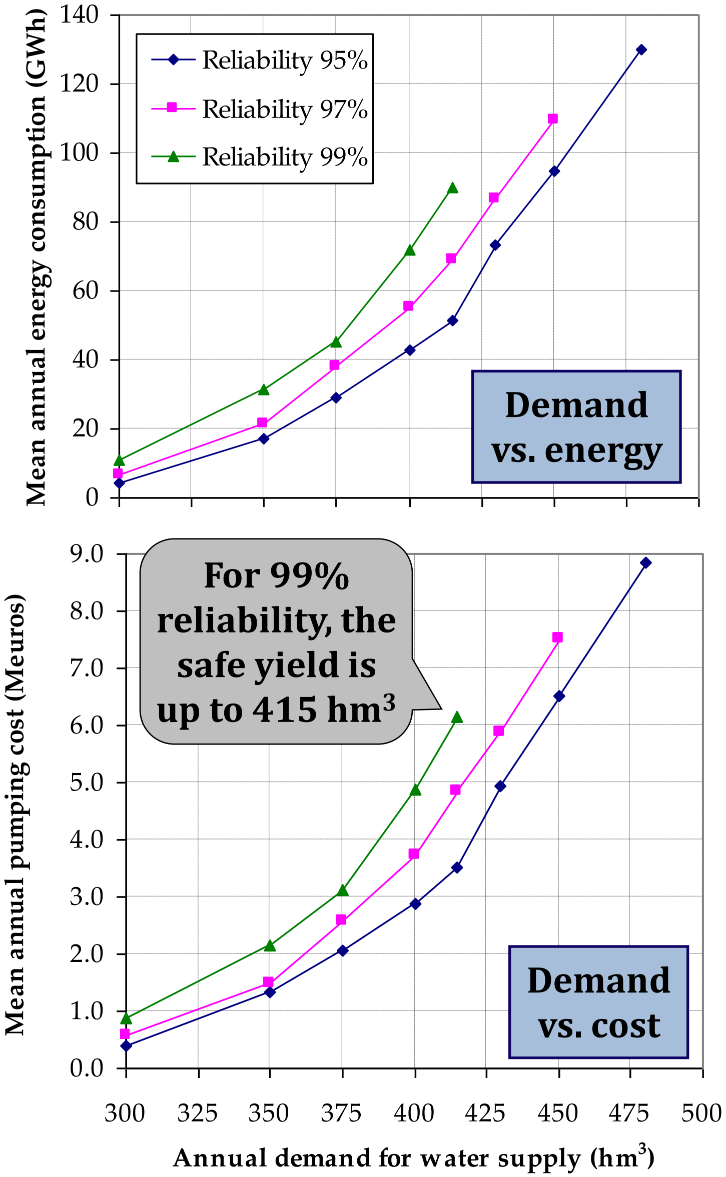
Surrogated-enchanced evolutionary annealing-simplex



Optimization algorithms: Efstratiadis and Koutsoyiannis, 2002; Rozos *et al.*, 2004; Tsoukalas *et al.*, 2016

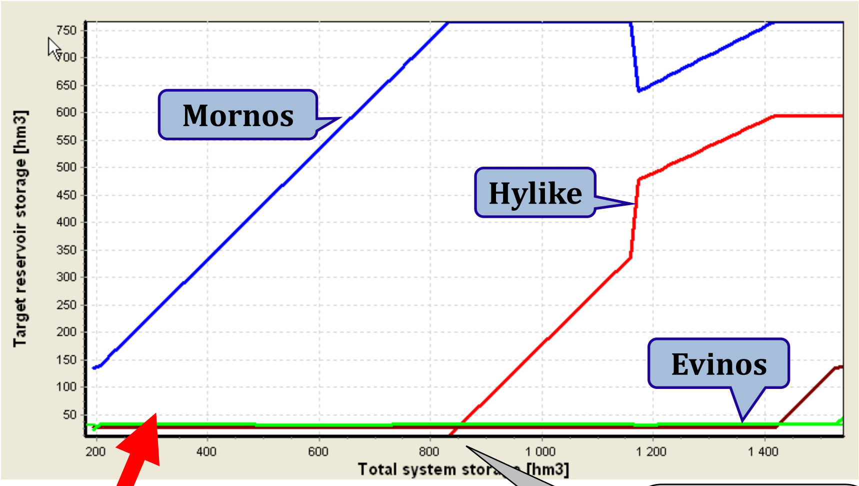
Question 1: Appraisal of water cost against multiple demand and reliability scenarios

- **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.

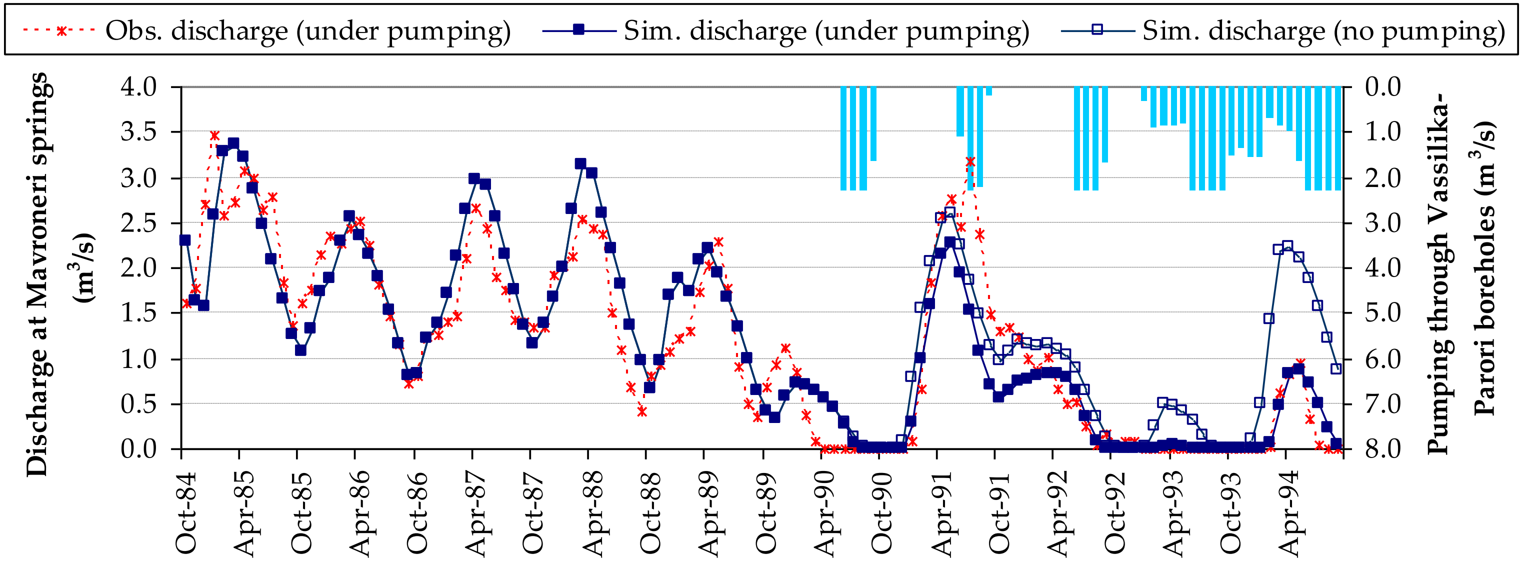


Below this limit, Hylike is activated by priority

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

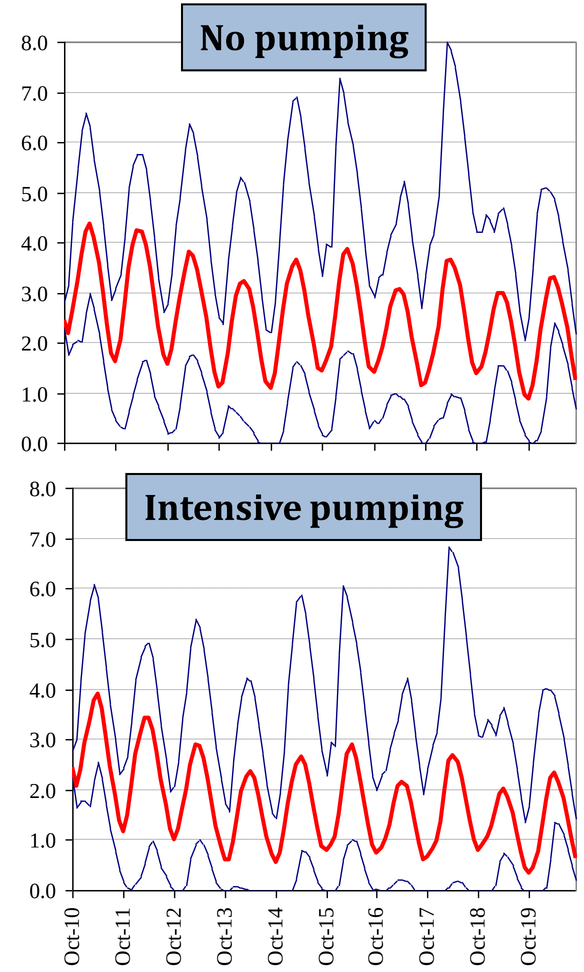
Question 3: How sustainable is the exhaustive use of emergency boreholes?

- 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 & 80% prediction limits)

Conclusions

- Model schematisation through a **network-type representation** of the hydrosystem components;
- **Parameterization** of processes and controls on the basis of parsimonious structures, which are consistent with the available data;
- Conjunctive modelling 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 yet realistic models → very simple decisions

References

- Christofides, A., S. Kozanis, G. Karavokiros, Y. Markonis, and A. Efstratiadis, Enhydris: A free database system for the storage and management of hydrological and meteorological data, *EGU General Assembly 2011, Geophysical Research Abstracts, Vol. 13*, Vienna, 8760, 2011.
- Efstratiadis, A., D. Koutsoyiannis, and D. Xenos, Minimising water cost in the water resource management of Athens, *Urban Water Journal*, 1(1), 3-15, 2004.
- Efstratiadis, A., I. Nalbantis, A. Koukouvinos, E. Rozos, and D. Koutsoyiannis, HYDROGEIOS: A semi-distributed GIS-based hydrological model for modified river basins, *Hydrology and Earth System Sciences*, 12, 989–1006, 2008.
- A. Efstratiadis, Y. Dialynas, S. Kozanis, and D. Koutsoyiannis, A multivariate stochastic model for the generation of synthetic time series at multiple time scales reproducing long-term persistence, *Environmental Modelling & Software*, 62, 139–152, 2014.
- Koutsoyiannis, D., A generalized mathematical framework for stochastic simulation and forecast of hydrologic time series, *Water Resources Research*, 36(6), 1519-1533, 2000.
- 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.
- 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.
- Koutsoyiannis, D., and A. Manetas, Simple disaggregation by accurate adjusting procedures, *Water Resources Research*, 32(7), 2105-2117, 1996.
- Koutsoyiannis, D., Climate change, the Hurst phenomenon, and hydrological statistics, *Hydrological Sciences Journal*, 48(1), 3–24, 2003.
- Koutsoyiannis, D., Coupling stochastic models of different time scales, *Water Resources Research*, 37(2), 379-392, 2001.
- Koutsoyiannis, D., Hurst-Kolmogorov dynamics and uncertainty, *Journal of the American Water Resources Association*, 47(3), 481–495, 2011.
- Koutsoyiannis, D., G. Karavokiros, A. Efstratiadis, N. Mamassis, A. Koukouvinos, and A. Christofides, A decision support system for the management of the water resource system of Athens, *Physics and Chemistry of the Earth*, 28(14-15), 599-609, 2003.
- Koutsoyiannis, D., Optimal decomposition of covariance matrices for multivariate stochastic models in hydrology, *Water Resources Research*, 35(4), 1219-1229, 1999.
- Kozanis, S., A. Christofides, A. Efstratiadis, A. Koukouvinos, G. Karavokiros, N. Mamassis, D. Koutsoyiannis, and D. Nikolopoulos, Using open source software for the supervision and management of the water resources system of Athens, *EGU General Assembly 2012, Geophysical Research Abstracts, Vol. 14*, Vienna, 7158, 2012.
- Nalbantis, I., A. Efstratiadis, E. Rozos, M. Kopsiafti, and D. Koutsoyiannis, Holistic versus monomeric strategies for hydrological modelling of modified hydrosystems, *Hydrology and Earth System Sciences*, 15, 743–758, 2011.
- Nalbantis, I., and D. Koutsoyiannis, A parametric rule for planning and management of multiple reservoir systems, *Water Resources Research*, 33(9), 2165-2177, 1997.
- Rozos, E., A. Efstratiadis, I. Nalbantis, and D. Koutsoyiannis, Calibration of a semi-distributed model for conjunctive simulation of surface and groundwater flows, *Hydrological Sciences Journal*, 49(5), 819–842, 2004.
- Tsoukalas, I., P. Kossieris, A. Efstratiadis, and C. Makropoulos, Surrogate-enhanced evolutionary annealing simplex algorithm for effective and efficient optimization of water resources problems on a budget, *Environmental Modelling & Software*, 77, 122–142, 2016.