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Session HS4.20: *Anthropogenic influence on the hydrological cycle. How can we deal with mixed natural and artificialized catchments?*

Accounting for water management issues within hydrological simulation: Alternative modelling options and a network optimization approach

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Introduction

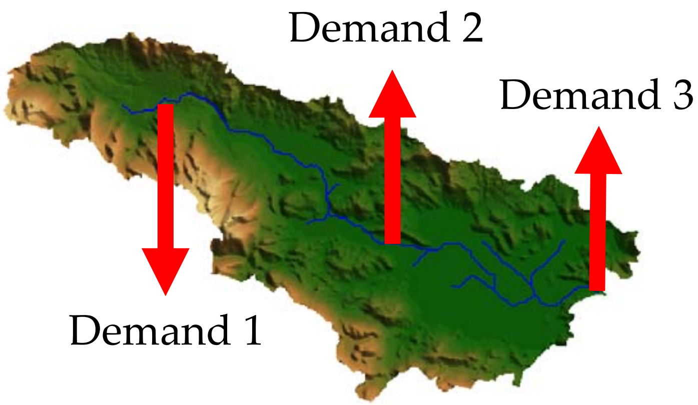
- **Which is the practical role of hydrological models in the actual technological scene?**
  - Why in most scientific publications, hydrological modelling is treated just as a calibration exercise, aiming to represent complex physical processes in purely natural areas?
  - Can we identify unmodified hydrological systems in real-world engineering studies?
- **What adaptations are necessary to support engineering and management decisions?**
  - How can we incorporate hydraulic structures, costs, operation rules, constraints and water use priorities within hydrological simulation?
  - What kind of feedbacks arise in case of combined surface and groundwater abstractions?
  - How feasible is an off-line cooperation of hydrological, hydro-geological and water management models?
  - Why is computational efficiency so essential?

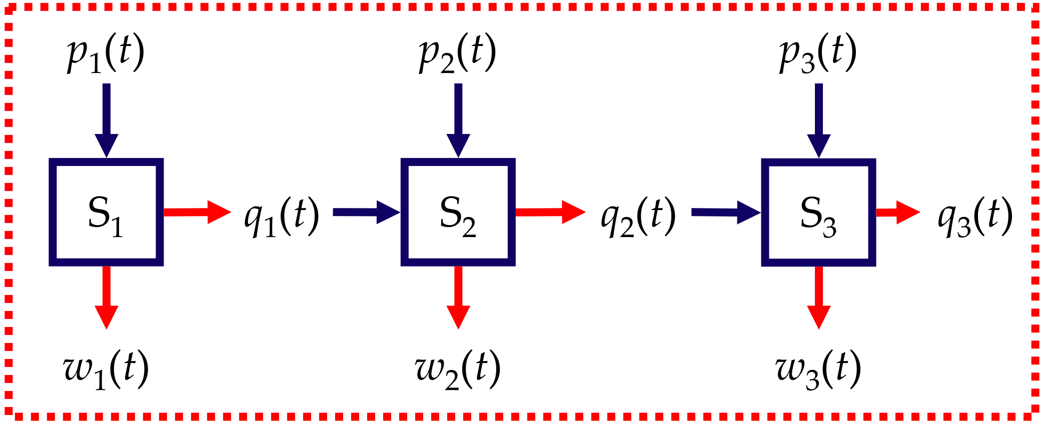
Hydrological vs. water management models

	Hydrological model (HM)	Water management model (WMM)
Reference area	river basin and/or aquifer	hydrosystem
Inputs	atmospheric forcing (precipitation)	inflows (water availability) and demand for multiple water uses
Outputs	hydrological fluxes	regulated flows, abstractions
Spatial scale	from lumped to fully-distributed	network-type schematization
Mathematical framework	from black-box to physically-based	system-based approaches
Parameters	conceptual "properties" assigned to hydrological mechanisms	control variables related to the water management policy, usually embedded within operation rules
Optimization objectives	good fitting of modelled to observed responses	decision-support, to compromise conflicting targets and criteria
Control period	past (calibration)	future (stochastic simulation)

Case 1: Simple links between HMs and WMMs

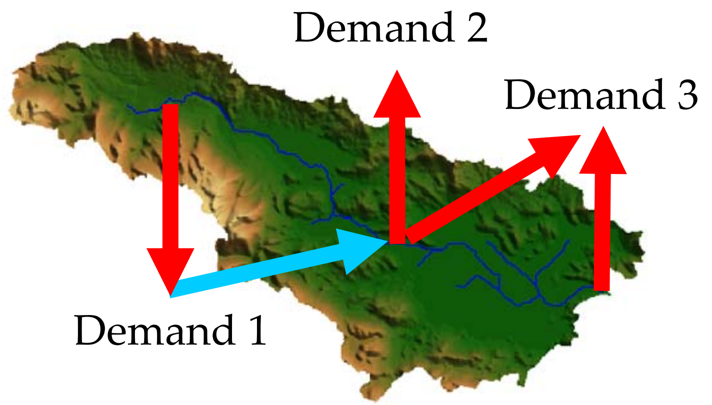
- The entire basin is separated into pure natural and artificial sub-systems, assuming a serial structure of processes (other types of interactions are omitted).
- Each natural sub-system is modelled individually and its predictions (i.e. inflows) become input to a related water management model; next, the outputs of the latter (i.e. net outflows, after withdrawals) are transferred to the downstream natural sub-system, etc.
- Each withdrawal should satisfy a unique demand (conjunctive water uses and water returns are not accepted).
- Due to the serial operation of the modelling components, a "first-come, first-served" management policy is mandatory.
- If historical withdrawals are unknown, the hydrological components should be calibrated separately.

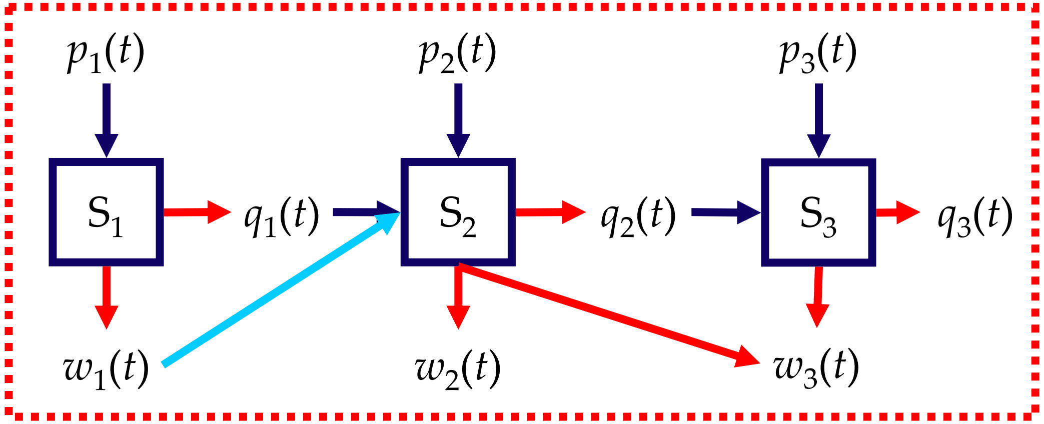




Case 2: Complex links between HMs and WMMs

- Complex (non-serial) links arise when:
  - multiple uses are satisfied by multiple sources;
  - withdrawals can be conveyed via multiple paths (i.e. through a network), each one having different discharge capacity and transportation cost;
  - part of the consumed water returns downstream through drainage systems.
- An overall water management scheme is required to allocate the hydrological fluxes, tanking into account operation rules, constraints and water use priorities.
- To obtain a feasible allocation of flows and withdrawals, the multi-stage modelling scheme should run within an iterative procedure.
- If historical withdrawals are unknown, the hydrological components cannot be calibrated.



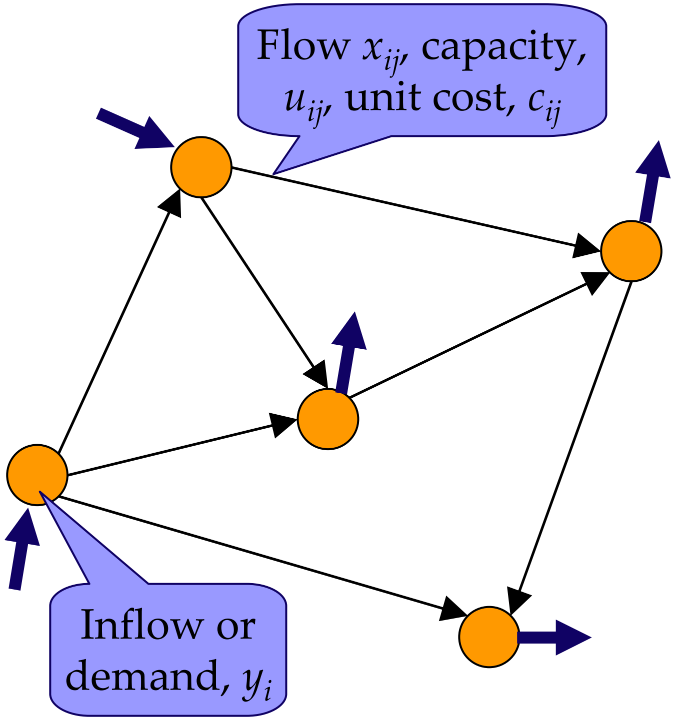


Case 3: “Vertical” links with groundwater

- In case of conjunctive water uses, a combined modelling of surface- and groundwater processes is essential.
- Integrating groundwater modelling (GM) within HM and WMM introduces further complexity, since “vertical” interactions exist between:
  - the river basin and the aquifer (percolation);
  - the aquifer and the river network (infiltration, groundwater runoff);
  - the water management system and the aquifer (pumping, recharge);
- While surface abstractions affect only the downstream water availability (discharge reduction), the groundwater ones have multiple and “non-visible” impacts to the entire system (e.g. decrease of piezometric levels, reduction of baseflow), which in turn involves the overall water management policy.
- A staged procedure, based on an off-line coupling of the various modelling components, is infeasible, due to:
  - unknown boundary conditions;
  - unknown allocation of abstractions;
  - different requirements in time and space resolutions.

Network linear programming (NLP) approaches in water resources management

- Models based on NLP (transshipment problem) have been used in a variety of water resources planning and management applications (Graham *et al.*, 1986; Kuczera, 1989; Labadie *et al.*, 1995; Fredericks *et al.*, 1998; Israel and Lund 1999; Dai and Labadie, 2001; Koutsoyiannis *et al.*, 2003; Efstratiadis *et al.*, 2004).
- For given inflows and demands, these implement one- or multi-step simulation, by minimizing the allocation of costs through hydrosystems of network format.
- The optimization is based either on real economic criteria or on artificial costs, which are assigned to preserve water rights and water use priorities.
- The specific mathematical structure of the problem allows accurate and exceptionally fast solvers, e.g. the network simplex (Smith, 1982).



Problem formulation:

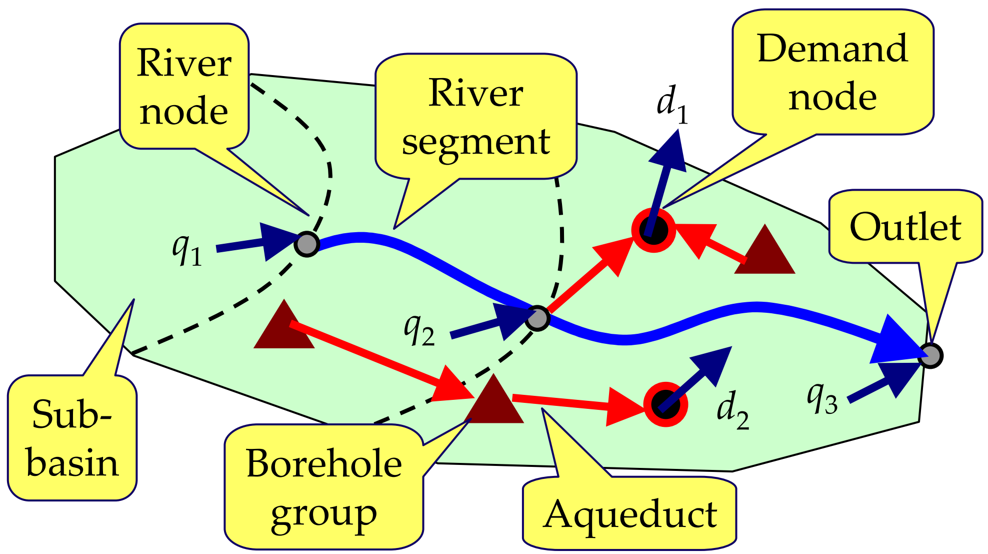
minimize $f(\mathbf{x}) = \mathbf{c}^T\mathbf{x}$

s.t. $\mathbf{A}\ \mathbf{x} = \mathbf{y}$

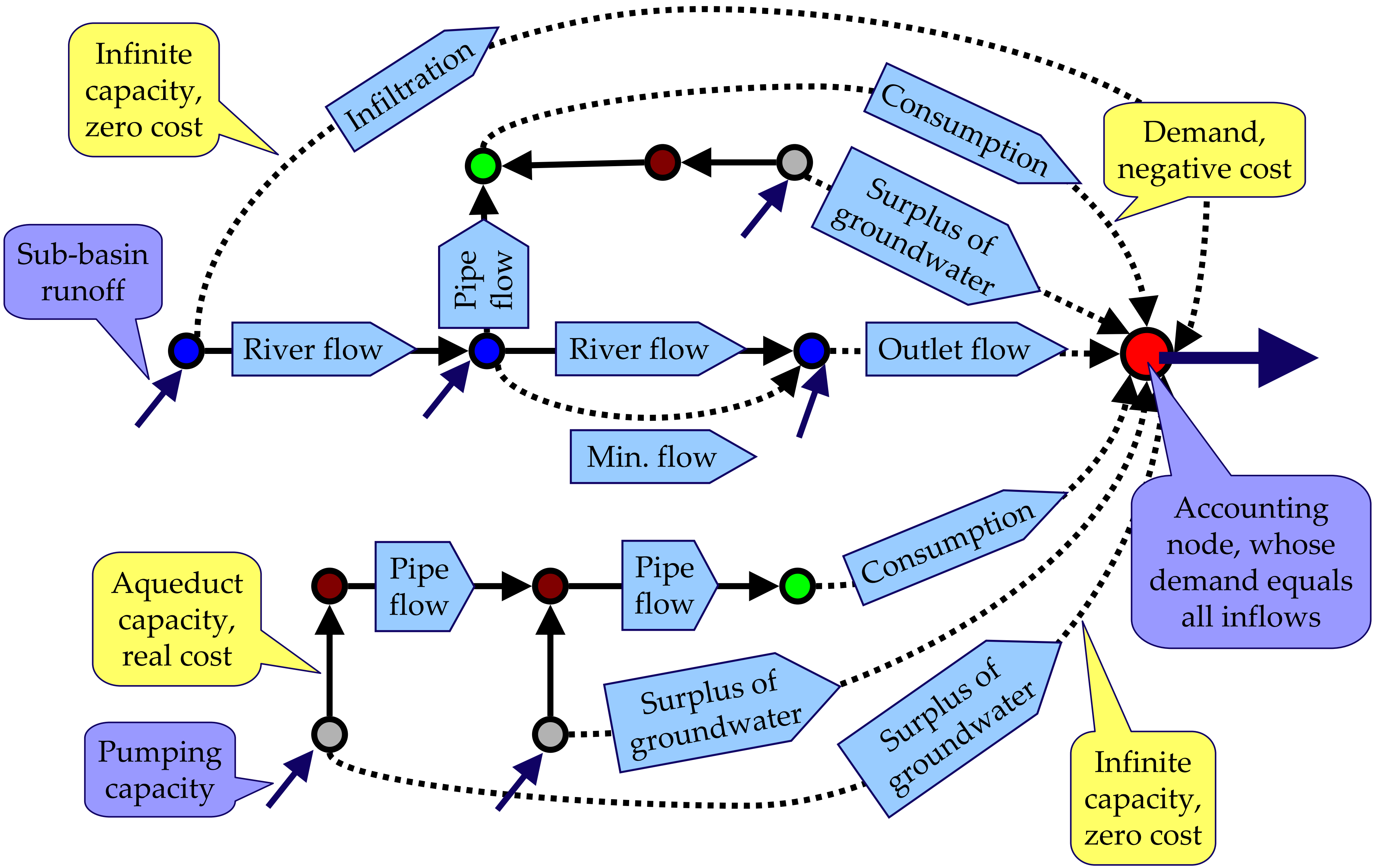
$\mathbf{0} \leq \mathbf{x} \leq \mathbf{u}$

Embedding water management issues within hydrological simulation: main assumptions

- Generalized framework, applicable for models of semi-distributed structure.
- The surface and groundwater (spring) runoff through each sub-basin is directly transferred to the corresponding river node.
- The entire upstream runoff within a specific time step is available to the downstream users (lag effects due to flow routing are not taken into account).
- Groundwater abstractions are assigned to borehole groups (representing clusters of real-world wells) and physically restricted by their pumping capacity.
- Infiltration and leakage through each river segment or aqueduct, respectively, are modelled as constant ratio of the actual flow.
- Water returns through drainage systems are modelled as constant ratio of the actual consumption.
- To account for conflicts, a priority level is assigned to all water uses and operational constraints (e.g. minimum flow requirements).



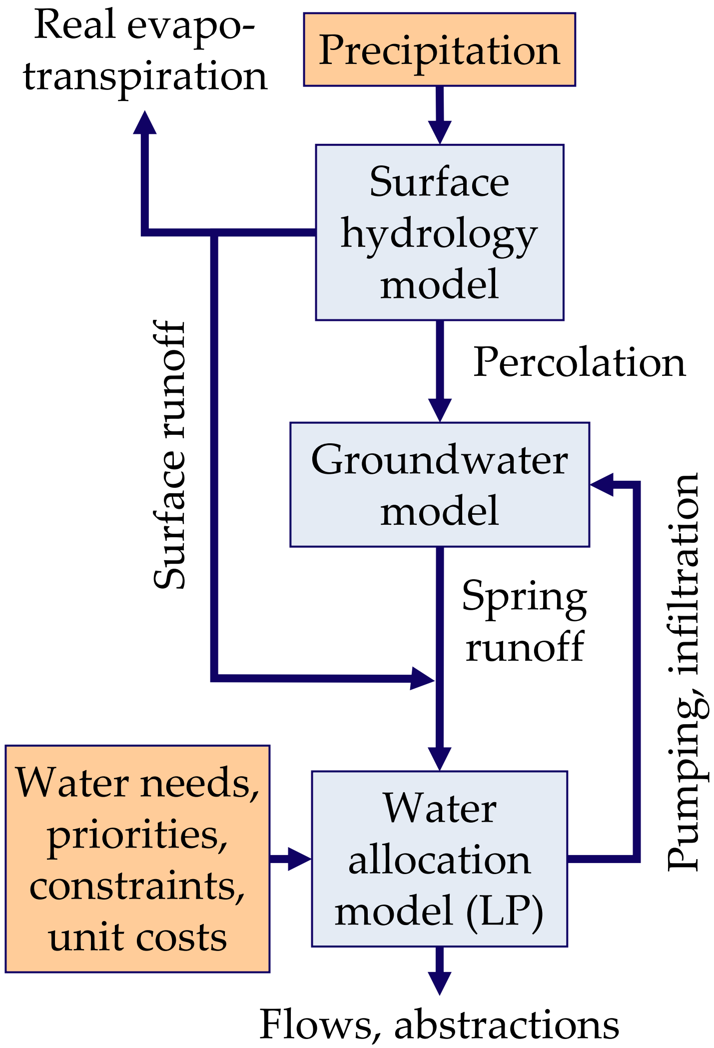
From the real system to a digraph representation



HYDROGEIOS: Linking hydrological, hydrogeological and water management models

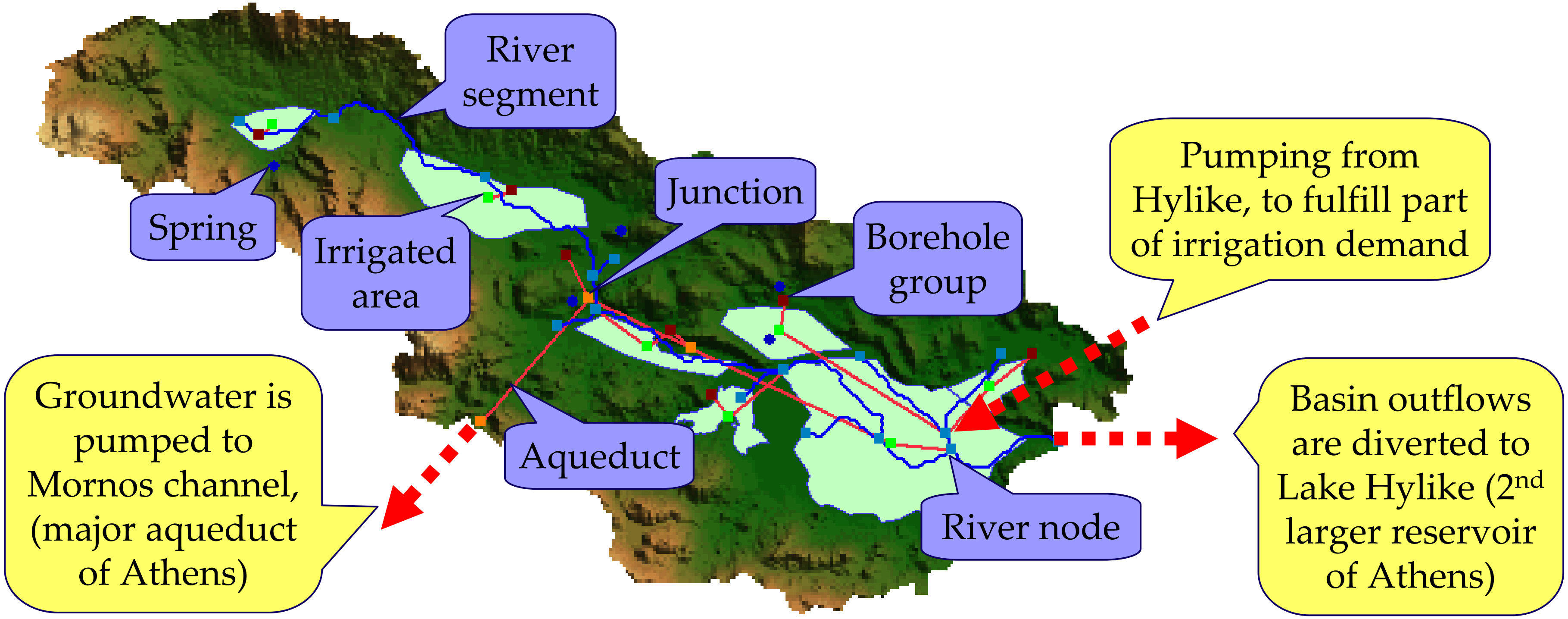
- **Initialization**: Calculation of constant data for the graph model (topology, real capacities, unit costs)
- **Step-by-step simulation**:
  1. Calculation of surface water balance (real evapotranspiration, percolation, runoff)
  2. Update of variable data for the graph model (inflows, dummy capacities)
  3. Optimal allocation of actual flows and abstractions (NLP or LP problem)
  4. Assignment of actual stresses to groundwater cells (percolation, infiltration, pumping)
  5. Calculation of baseflow (spring runoff)
  6. Exit or return to step (2), on the basis of the baseflow error (convergence criterion)

In **daily simulations**, the above procedure provides an estimation of nodal inflows and outflows; next, a hydrological routing scheme runs from the upstream to the downstream segments, to faithfully represent the temporal and spatial allocation of river flows.

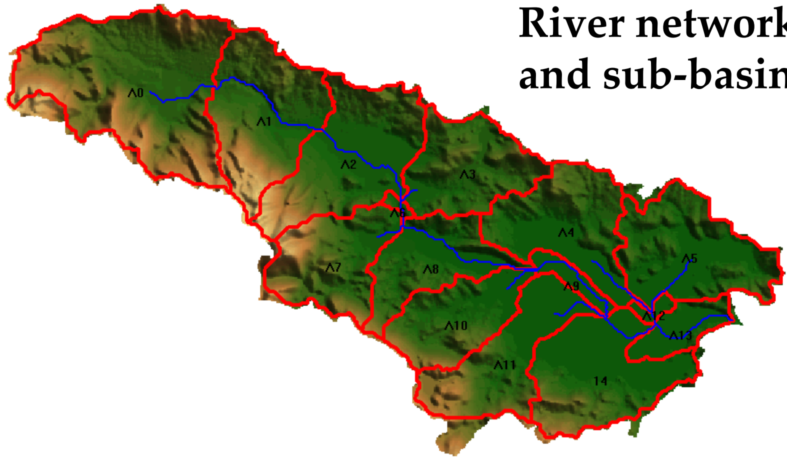


The Boeoticos Kephissos hydrosystem

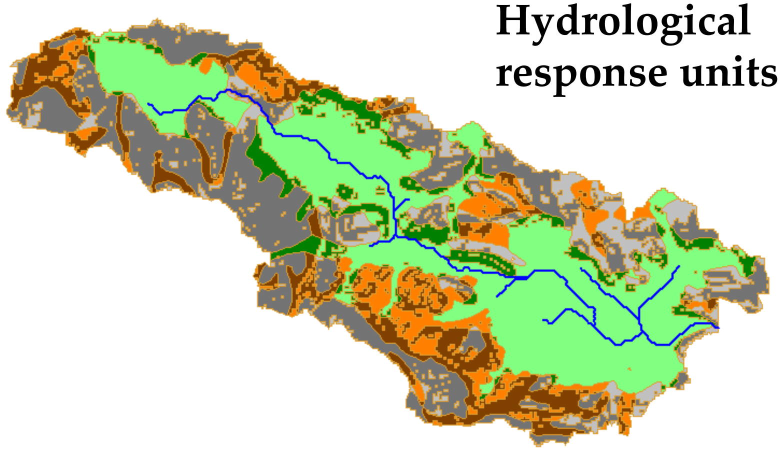
- 7 irrigated areas, represented as demand nodes (total annual demand ~220 hm^3)
- 7 borehole groups, comprising hundreds of water supply and irrigation wells, of total pumping capacity ~10 m^3/s
- 16 aqueducts (some of them real, the rest one represent virtual water transfers from the borehole groups to the corresponding irrigated areas)
- Conjunctive abstractions from surface and groundwater resources, to fulfil multiple demands, and multiple links with the Athens water supply system.



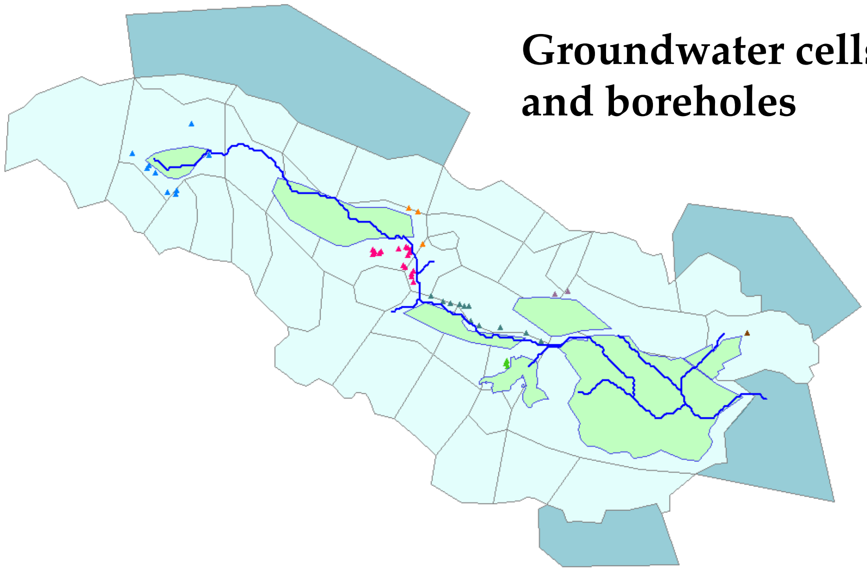
Other modelling components of HYDROGEIOS



River network and sub-basins



Hydrological response units

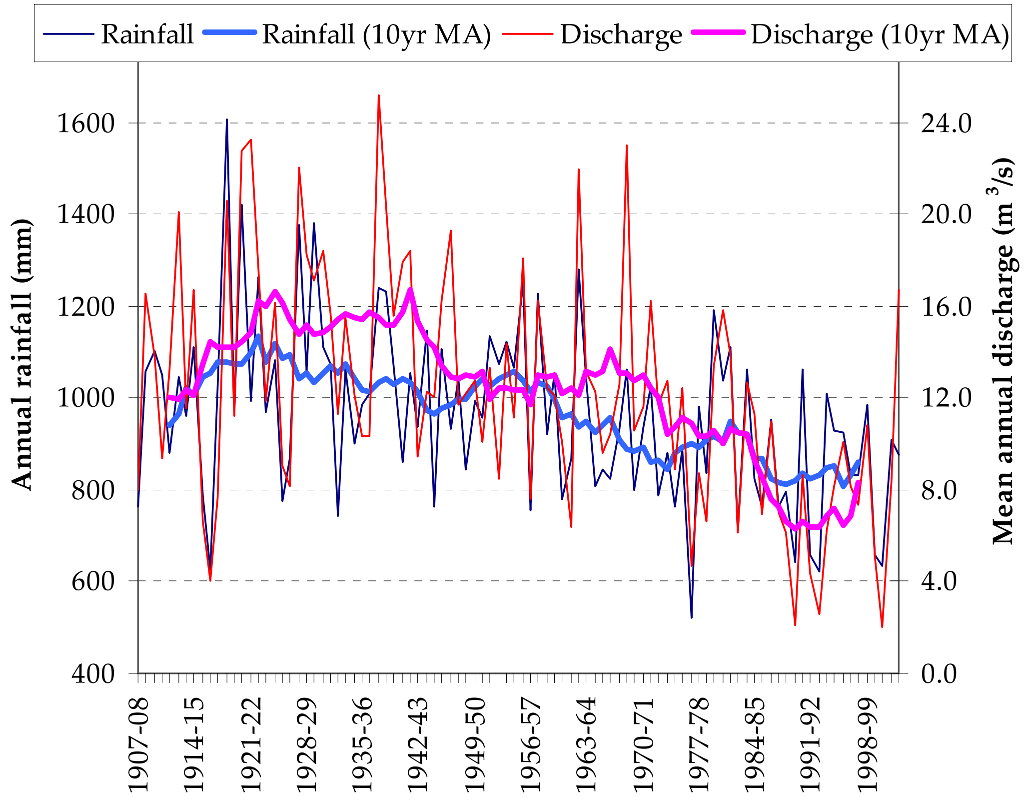


Groundwater cells and boreholes

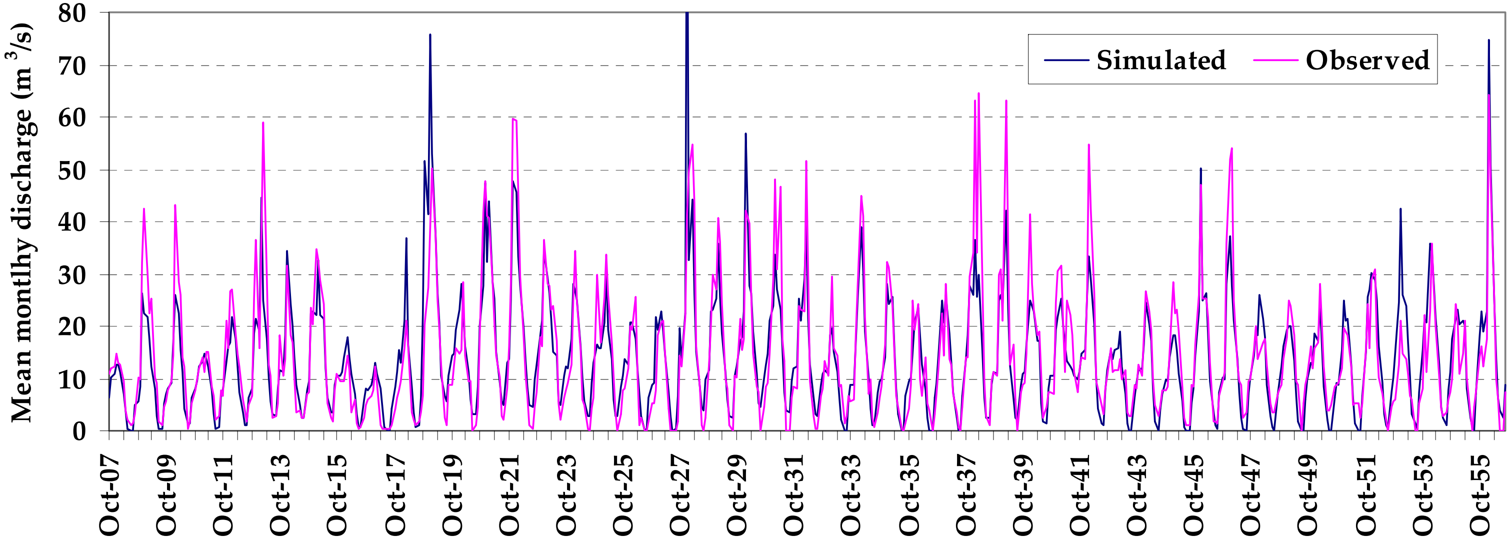
- **Surface system**: 15 sub-basins, 15 river segments, 16 river nodes, 6 hydrological response units;
- **Groundwater system**: 42 cells (the four virtual, to account for groundwater losses), 6 springs, 53 boreholes (grouped in 7 clusters);
- **Model parameters (~60)**: Estimated via hybrid multicriteria calibration, for the period 1984-1994 (Efstratiadis *et al.*, 2008).

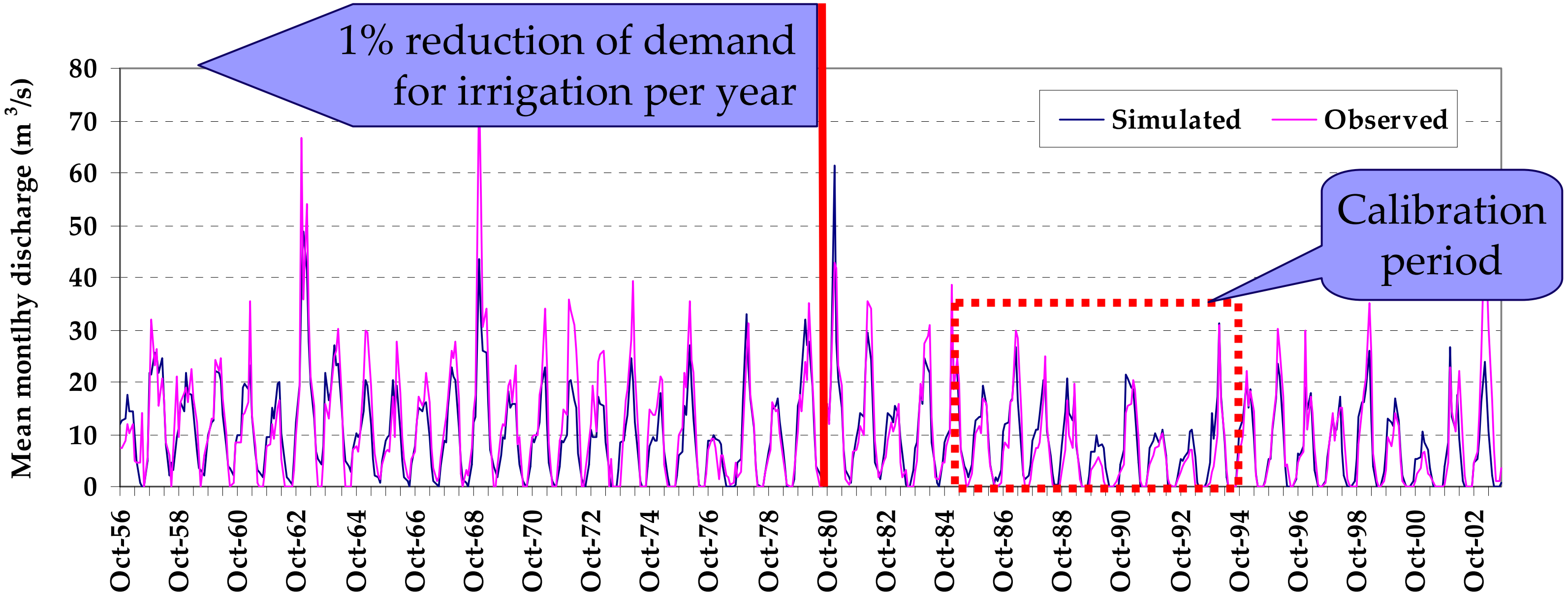
Problem 1: Can we reproduce the long-term variability of runoff during the last century?

- The observed annual runoff at the basin outlet during the last century (1907-2003) exhibits significant variability, which is partially only explained by the variability (i.e. the Hurst-Kolmogorov behaviour) of the areal precipitation.
- The hydrological regime of the basin is evidently affected by both the natural forcing and the man-made interventions, i.e. hydraulic works for river abstractions and pumping.
- For a realistic representation of the hydrosystem operation, we assumed the actual demands for irrigation after 1980 and a 1% annual reduction for the preceding years, which is consistent with the rates of agricultural development during the 20th century.



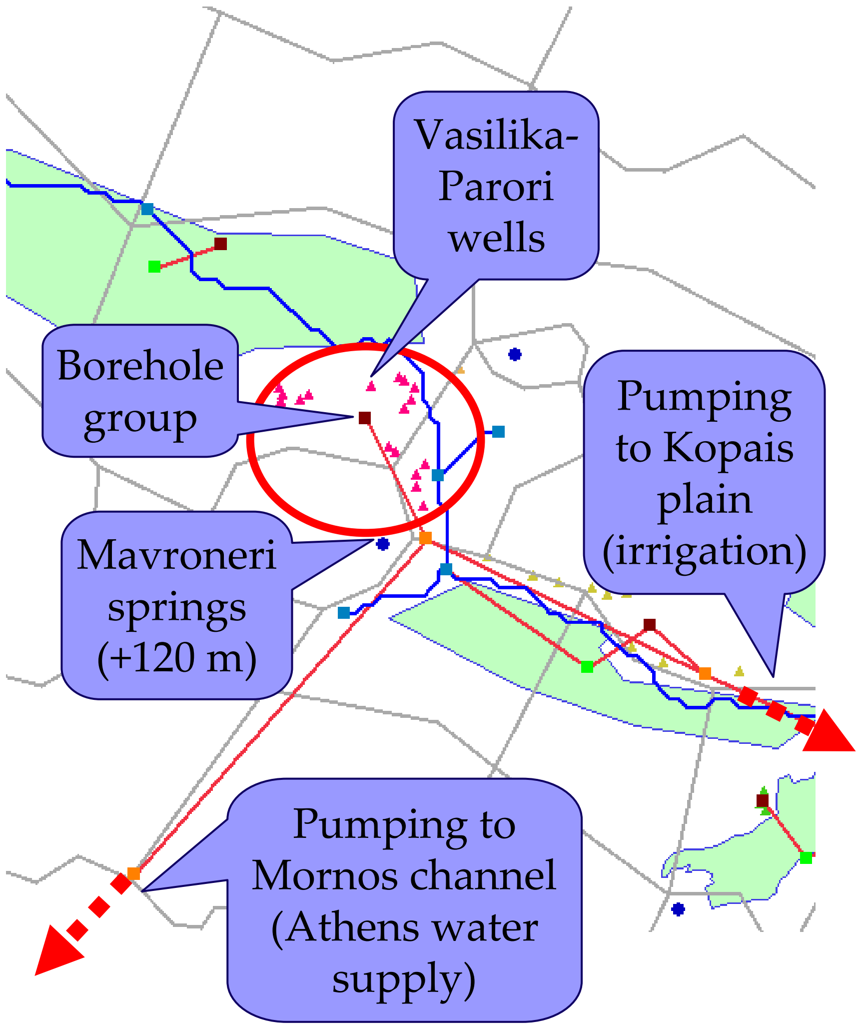
Problem 1: Simulation of basin runoff





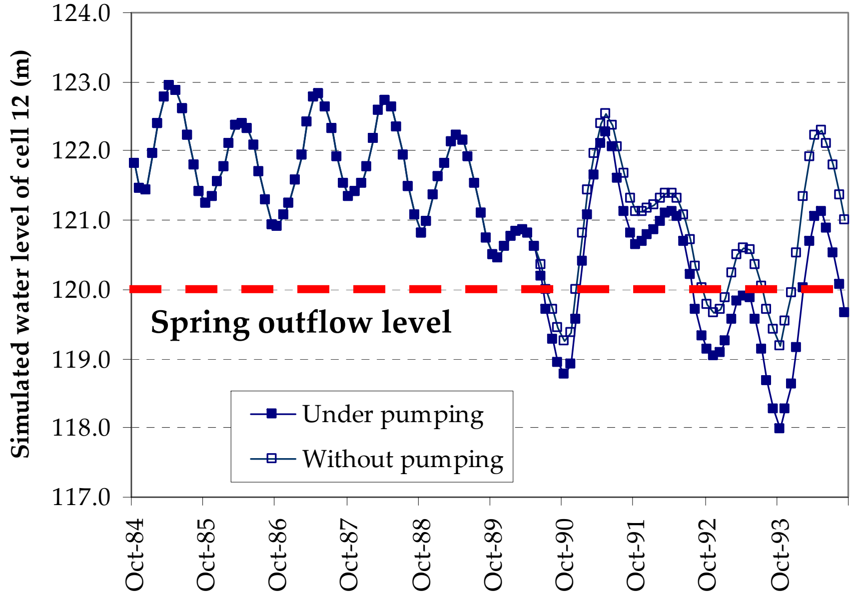
Problem 2: What are the impacts from the operation of Vassilika-Parori boreholes?

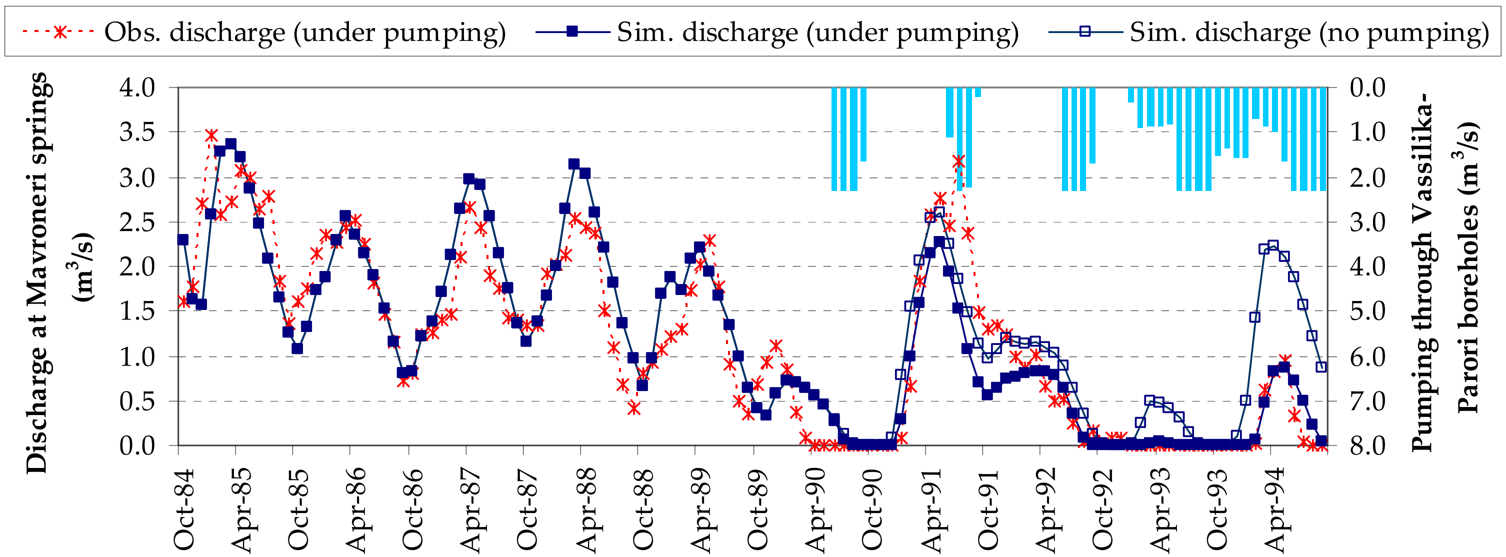
- A number of wells were drilled in 1990 in the middle course of the basin (Vassilika-Parori), to provide drinking and agricultural water for Athens and the Kopais plain, respectively.
- These were drilled within the frame of emergent measures taken during a severe drought in the period from 1989 to 1994, at the end of which almost all surface resources dried out.
- Due to the considerable reduction of precipitation and the intense pumping from the Vassilika-Parori boreholes, the discharge of Mavroneri springs was twice interrupted during 1990 and 1993, thus resulting to various social and environmental problems.



Problem 2: Explanation of flow interruption

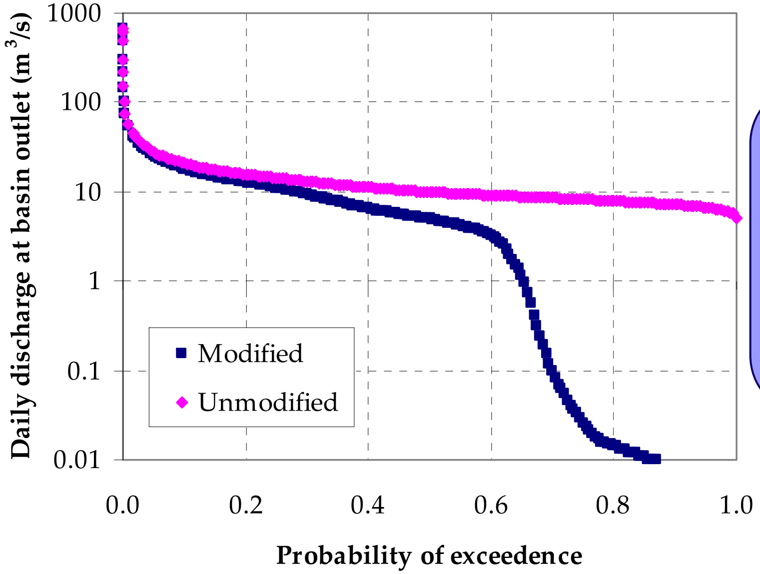
- Two scenarios, assuming (a) historical abstractions from the Vassilika-Parori boreholes, and (b) zero pumping.
- The simulations proved that the interruption of the flow through Mavroneri springs during 1990 was inevitable; on the other hand, the elimination of discharge during 1992-1994 could be partially avoided, under a more sustainable pumping policy.



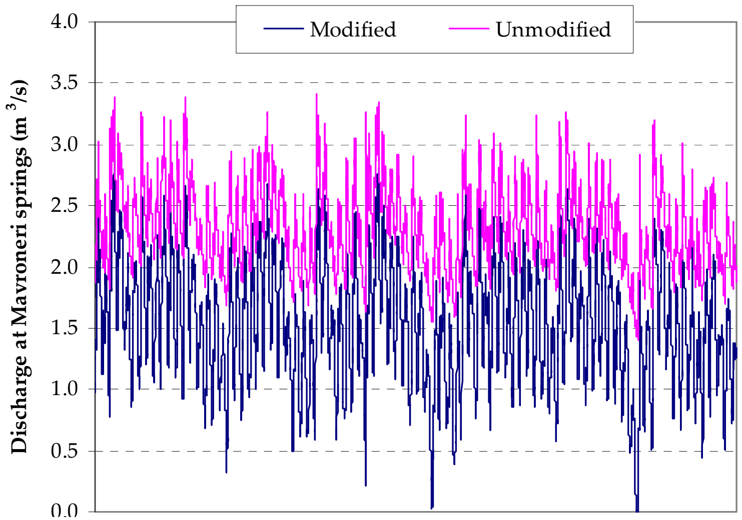


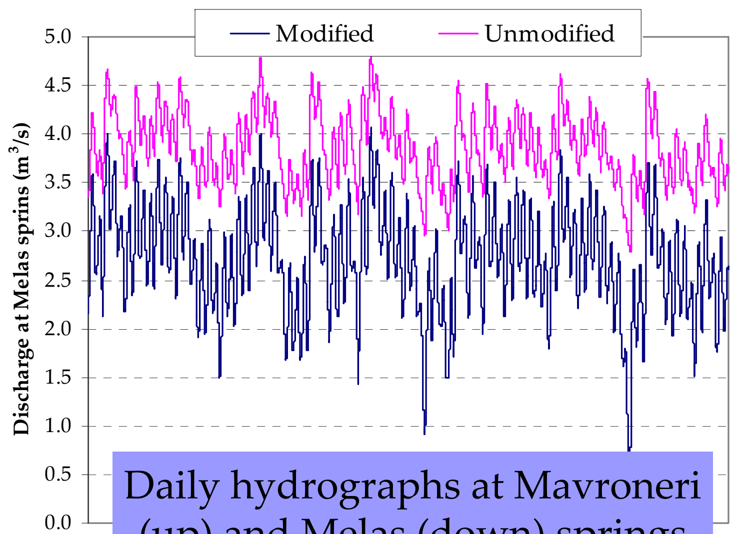
Problem 3: Comparison of modified vs. unmodified flows through stochastic simulation

- Daily simulation with 1000-year synthetic precipitation data (>365 000 time steps).
- Two scenarios were examined, assuming (a) actual agricultural uses, and (b) unmodified physical system, without water uses.
- Significant change of the distribution of surface flows, 10-40% average reduction of the discharge through the main karst springs.



Duration curves for simulated mean daily flow series (basin outlet)





Daily hydrographs at Mavroneri (up) and Melas (down) springs

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This presentation is available on-line at:

http://www.itia.ntua.gr/en/docinfo/960/

The HYDROGEIOS model is available on-line at:

http://www.hydroscope.gr/software/hydrogeios.html

Flood modelling through stochastic simulation:

Tue, 4 May, 08:00-19:30 / Hall A, A294 (poster)

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