Flood modelling in complex hydrologic systems with sparsely resolved data

EGU General Assembly 2009, Vienna, Austria, 19 – 24 April 2009

Session HS5.3: *Hydrological modelling. Adapting model complexity to the available data: approaches to model parsimony*

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1. Introduction

The **European Directive on Assessment and Management of Flood Risks** emphasises establishing tools suitable for simulating the relevant hydrologic processes in areas of high flood risk. Because **flood modelling** requires relatively **detailed spatial and temporal resolutions**, model selection is dictated by the distributed hydrologic information. The value of, mainly, stage/discharge data is indisputable, since the **quality of calibration,** and thus a model's predictive capacity, depends on the availability of reliable observations at multiple sites. On the other hand, **data scarcity** is a global hydrologic engineering problem that is getting increasingly severe as the monitoring infrastructure is shrinking and degraded. It is therefore crucial to **build reliable and parsimonious models**.

In this vein, we have adapted the **HYDROGEIOS** model (Efstratiadis *et al.*, 2008[*]), initially developed as a conjunctive surface-groundwater simulation and management tool at the monthly time scale, to run in daily time steps. In typical flood simulation packages, inputs are time series of precipitation, which are resolved in hourly or finer increments, and detailed hydro-morphologic properties of the stream network. In contrast, the enhanced version of HYDROGEIOS only uses **daily rainfall depths** and a **limited number of parameters** that are estimated or calibrated on the basis of **once-a-day discharge data**. As a conjunctive model, HYDROGEIOS enables to represent simultaneously the interactions among the **surface and sub-surface processes** and the **human interventions**, and to route the runoff across the stream network. Lacking finely resolved rainfall data and for the purpose of **flood routing**, we have applied a **disaggregation technique** to analyse the simulated daily hydrographs in hourly time steps. Flood routing is implemented via either a **kinematic-wave** or a **Muskingum diffusive-wave** scheme, using stream reaches a few km long.

The new version of HYDROGEIOS is being tested on the Boeotikos Kephisos River Basin for **flood forecasting in real-time**, using as input precipitation forecasts from numerical weather prediction simulations (EC FP6 project FLASH). The basin is **heavily modified**, with strong heterogeneities, involving multiple peculiarities such as significant **karst springs**, which rapidly contribute to the streamflow, thus reflecting a strong interaction between surface and ground water processes, and a drainage canal and network in the lower basin with **extremely small slopes**.

(*) 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 Systems Sciences*, 12, 989-1006, 2008.

2. Flood modelling under data scarcity: A realistic perspective?

The problem that we faced is summarised as follows:

1) We realised that the model predictions at the daily scale required including wave propagation for the main stem of the stream network.
2) Given the area of the basin, the response times of its sub-basins and the propagation time of the flood waves through the sub-reaches, flood routing would yield meaningful results only if a sufficiently fine time increment were used, say, of the order of one hour.
3) On the other hand, discharge observations were available as once-a-day measurements, at a few cross-sections of the main stream.

To satisfy the computational flood routing requirements, which are in conflict with the scarce data at hand, we decided to resolve the streamflow hydrographs at the hourly time scale though a data disaggregation method, which we outline in Section 5 herein.

3. The HYDROGEIOS modelling system (monthly simulation version)

Surface hydrology module

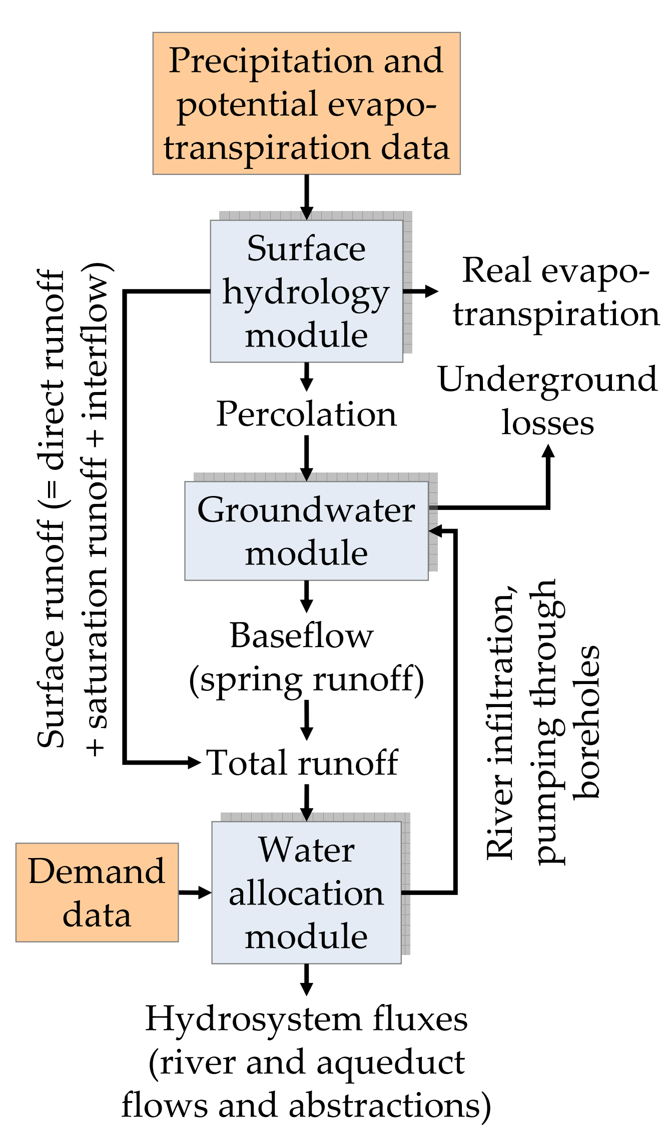
- Semi-distributed schematization, i.e. formulation of the river network and delineation of sub-basins;
- Parsimonious parameterization, using a of small number of hydrological response units (HRUs);
- Application of a soil moisture accounting model, based on monthly precipitation and potential precipitation time series (varying per sub-basin) and six parameters per HRU.

Groundwater module

- Finite-volume approach, aquifer discretization to a limited number of polygonal cells of flexible shape;
- Darcian representation of flow field;
- Stress data (percolation, infiltration, pumping) are computed via a looping scheme (not given externally).

Water allocation module

- Representation of water uses and main hydraulic structures (aqueducts, boreholes, diversion projects);
- Surface runoff and baseflow are right away available to the physical and artificial network, to fulfil downstream water uses.
- Step-by-step estimation of unknown flows and abstractions through a linear optimization approach, where artificial capacities and unit costs are imposed to preserve constraints and water use priorities.



4. Model adaptation for flood simulation using daily-resolved data

Assumptions on data availability

- Hydrological data: daily precipitation time series and discharge records (systematic or sparse), derived from once-a-day observations;
- River geometry data: insufficient to take advantage of hydraulic routing approaches.

Key modelling difficulties

- Due to the linkages between the groundwater and water allocation modules interchanging inputs and outputs, an iterative procedure is required within each time step, which is inconsistent with the condition of successive time periods assumed in numerical routing schemes;
- The coarse temporal resolution of precipitation time series is inconsistent with the fine resolution required by routing procedures;
- There is no full correspondence between the simulated discharge series (averaged over the day) and the observed (instantaneous) ones used within calibration, especially in flood events.

Main assumptions

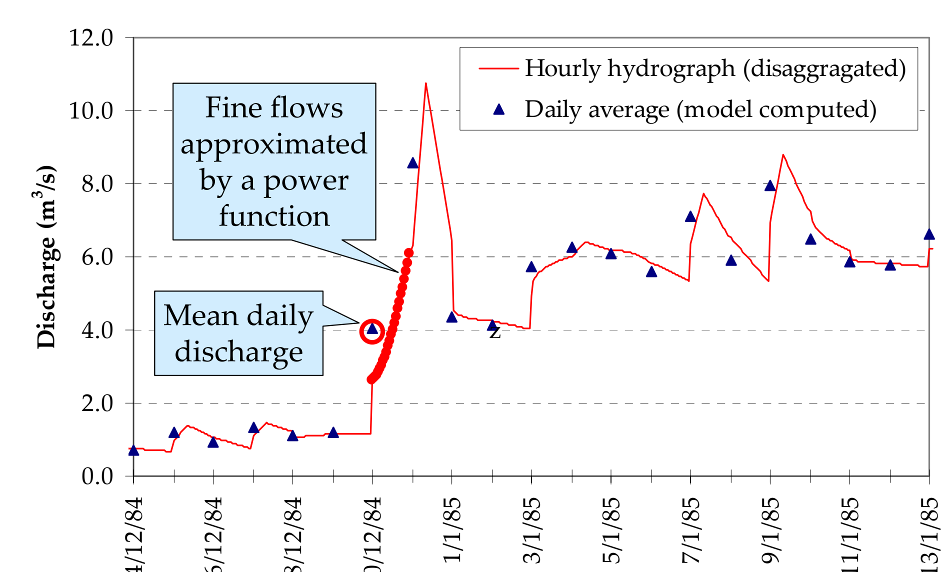
- Due to the lack of detailed hydraulic data, it is necessary to adopt parsimonious hydrological approaches, to route the simulated hydrographs through the river network;
- Since the time interval of routing models is finer than the daily simulation step, it is necessary to provide realistic representations of the in-day (typically hourly) distribution of hydrographs;
- The model follows a two-stage approach, i.e. it runs to provide initial estimates of the unknown abstractions, which are used to reconstruct the water balance across the river network and to calculate the inflow hydrograph upstream of each river segment, and next employs the routing;
- The instantaneous discharge observations are assumed representative of the average daily ones.

5. A disaggregation approach to construct finely-resolved hydrographs

Let V_t be the simulated runoff within day t, generated by a specific sub-basin by adding the flood and spring runoff. We seek to construct a consistent (and realistic) fine hydrograph within the time interval [0, n] approximated by a continuous function $q_t(k)$, such as $\int q_t(k)\,\mathrm{d}k = V_t$ (**preservation of daily volume**) and $q_t(0) = q_{t-1}(n)$ (**continuity between successive days**). To disaggregate the daily hydrograph (i.e. model output) to a finely-resolved one, we make the following assumptions:

- The first and last value of the finely-resolved hydrograph during day t are estimated by $q_t(0) = (Q_{t-1} + Q_t)/2$ and $q_t(n) = (Q_t + Q_{t+1})/2$, respectively, where Q_t is the mean discharge within day t;
- If $q_t(0)$ and $q_t(n)$ envelop Q_t, we approximate the ascending (or descending) branch of the fine hydrograph through a **power function** $q_t(k) = q_t(0) + a\,k^b$, where a, b are parameters straightforwardly estimated based on the mass preservation constraint.
- If Q_t exceeds both $q_t(0)$ and $q_t(n)$, the hydrograph has a peak value in that daily interval and is approximated by a **triangular function**, assuming that the time to peak equals $n/4$.
- If Q_t is less than both $q_t(0)$ and $q_t(n)$, the hydrograph has a minimum value in that daily interval and is approximated by an **inverse triangular function** that ensures non-negative discharges.

The finely resolved flows from each sub-basin are directly transferred to the corresponding downstream node of the river network, as point inflows.



6. Runoff routing across modified river networks: Combining accuracy and parsimony

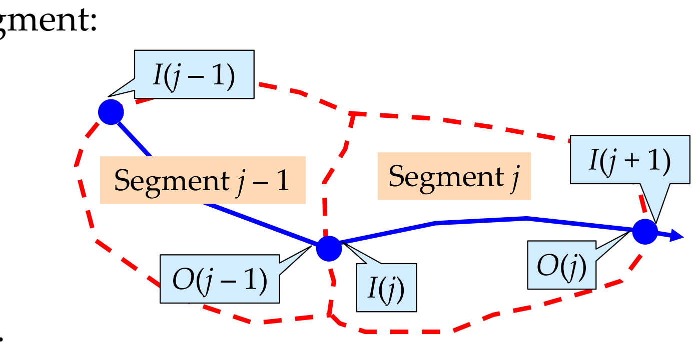
Let $I(j)$ and $O(j)$ be the fine inflow and outflow time series along a river segment j, where j also represents the routing order (since the segments are sorted from upstream to downstream).

The **inflow hydrograph** to segment j comprises the following components:

- the sum of outflow hydrographs that confluence the upstream node;
- the finely resolved hydrograph from the sub-basin crossed by the specific river segment (we assume 1:1 correspondence between sub-basins and river segments);
- the algebraic sum of water supply and abstractions (at a point basis), as well as the infiltration losses along the river segment j, which are already approximated by the water allocation module (we assume that these variables do not fluctuate during the daily interval).

The **outflow hydrograph** is calculated through one of the following parsimonious approaches, involving one or two parameters to estimate per river segment:

- a kinematic wave model, suitable for *medium river slopes*, where inflows are displaced by a time-lag K;
- a Muskingum routing scheme, suitable for *mild river slopes*, where the current outflow is the weighted sum of the current and previous inflow and the previous outflow; this requires an additional parameter x (dimensionless), accounting for wedge storage effects.



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7. Application to the Boeoticos Kephisos basin

General information

- Closed system of 1930 km² area, without physical outlet to the sea (runoff is conducted to the neighbouring Lake Hylike – the second largest storage project for the water supply of Athens – through an artificial drainage network, lying in the downstream part of the basin);
- Geology dominated by heavily karstified limestone (~ 40% or total area), mostly developed on the mountains, and alluvial deposits, lying in the plain areas;
- Heavily modified basin, with combined surface and groundwater abstractions for water supply and irrigation, affecting significantly the entire hydrological cycle.

Main difficulties with regard to hydrological and water management simulation

- Large number of karst springs, major contribution of baseflow (~ 50% of annual runoff);
- Unknown and spatially extended water losses to neighbouring basins and the sea;
- Complexity of infiltration mechanisms, since surface flows through the river network recharging the karst aquifer reappear downstream as spring outflows;
- Unknown distribution between surface withdrawals and pumping, to fulfil irrigation needs.

Additional difficulties with regard to flood modelling

- Lack of proper infrastructure to account for storms and floods, i.e. rain and discharge gauges with continuous recording, and lack of hydraulic data regarding cross-section geometry;
- Unusually quick response of the karst system to storm events;
- Negligible slope of the downstream canal, for a length of 35 km (~ 1/3 of the main stem length).

8. Modelling components and input data

River network

- Discreterization of the main river branch to 7 segments and delineation of 13 sub-basins upstream of the corresponding river nodes;
- Estimation of daily areal precipitation using 13 point records with Thiessen weights;
- Estimation of potential evapotranspiration using the Penman-Monteith method.

Hydrological response units (HRUs)

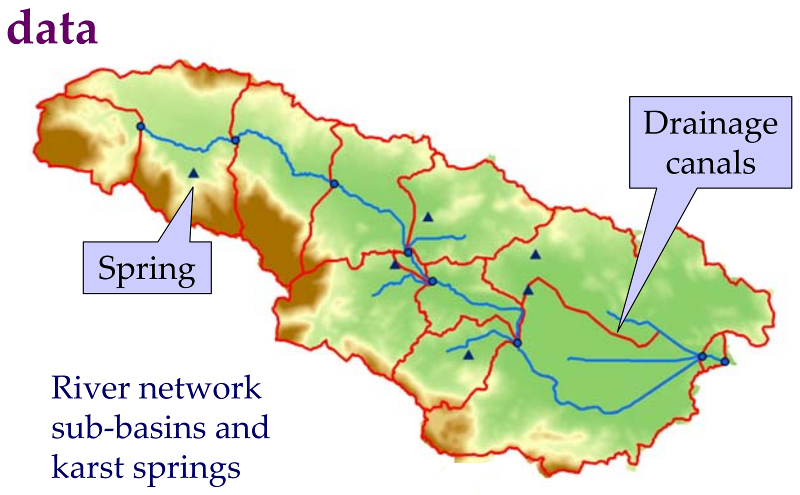
- Formulation of 6 HRUs, by combining two geographical layers representing three categories of permeability (low, medium, high), and two categories of terrain slope, with threshold 10%;

Groundwater system

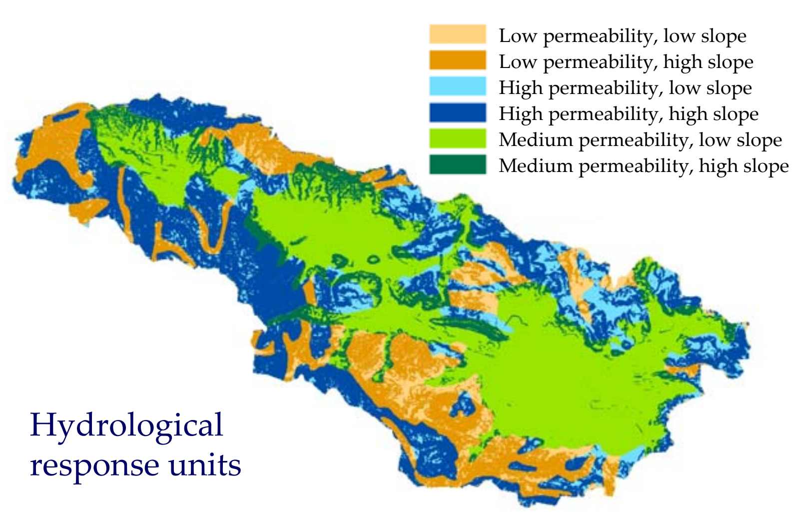
- Formulation of 40 non-rectangular cells following geological and topographical criteria; 6 of them represent karst springs and 4 the draining of underground leakages;
- System parameterization on the basis of three permeability and porosity categories;
- Estimation of initial levels and boundary conditions (i.e. impermeable edges) using piezometric information and geological criteria (e.g. faults), respectively.

Water management system

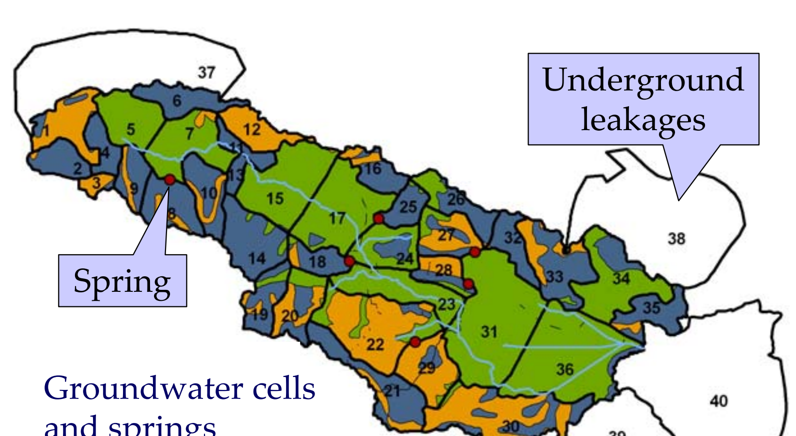
- Representation of six major agricultural areas as irrigation demand nodes;
- Annual irrigation demand = 6500 m³/ha.
- Hydraulic projects include 56 boreholes and 5 diversion aqueducts across the river network.



River network sub-basins and karst springs



Hydrological response units



Groundwater cells and springs

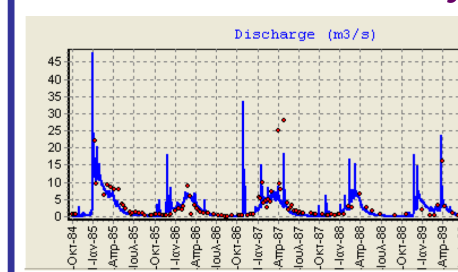
9. Model calibration and validation

HYDROGEIOS is now being tested for real-time flood forecasting, within the EC FP6 project “FLASH”. The study period starts from 2000, while two discharge gauges are used for flood control, lying at the basin outlet (Karditsa) and the middle course of Boeoticos Kephissos (Anthohori).

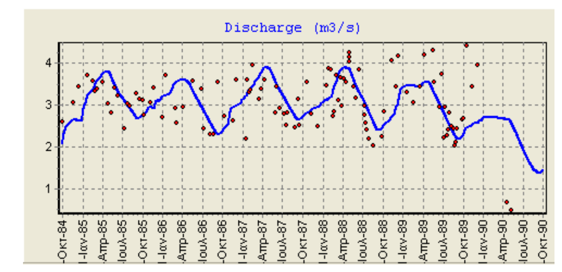
Yet, the amount of historical data is inadequate to estimate the about 60 parameters of the model, especially those of the groundwater module. Thus, we attempted an initial calibration for the 1984-1990 period, taking advantage of the daily discharge sample at the basin outlet (continuous) and the sparse albeit systematic (i.e. two per month) flow measurements downstream of the six springs and through the river network (11 control responses, in total). The calibration objectives included statistical (e.g. Nash-Sutcliffe efficiency) and empirical criteria, to ensure satisfactory fitting to the distributed observations, as well as realistic representation of model outputs that cannot be controlled by measurements (e.g. groundwater levels).

Next, we focused in the period 2000-2006, to re-estimate some crucial parameters of the surface hydrological module against the two observed hydrographs, emphasizing on flood events.

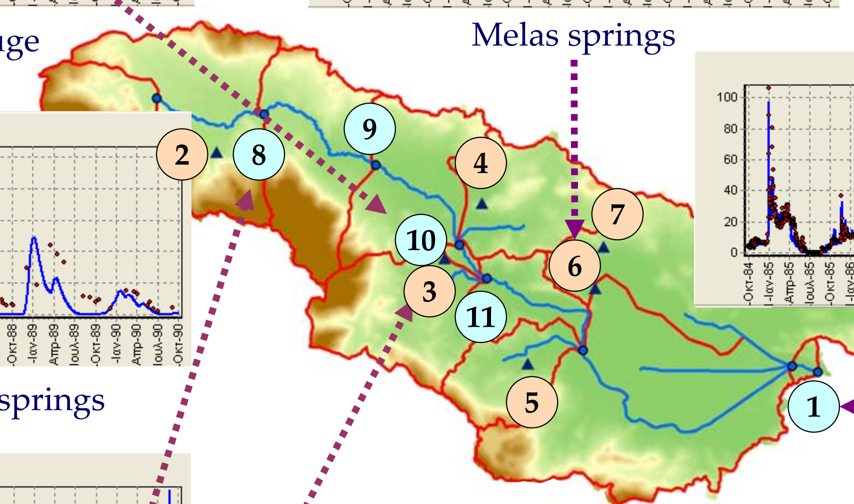
10. Model efficiency against multisite discharge data (period 1984-1990)

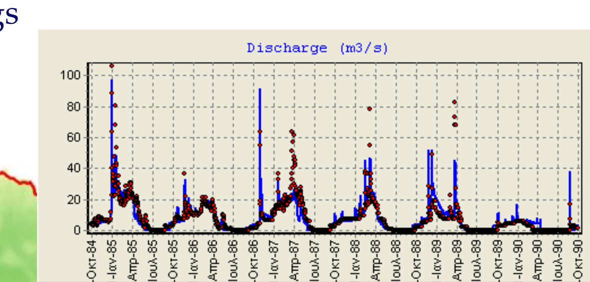


Anthohori gauge

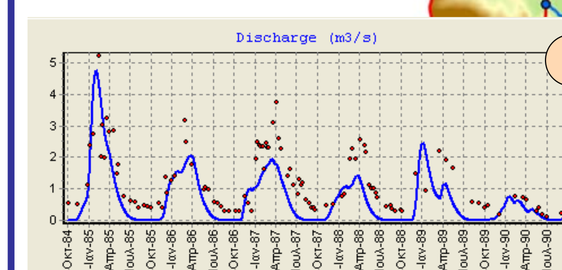


Melas springs

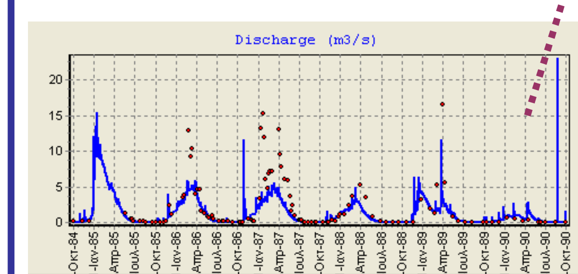




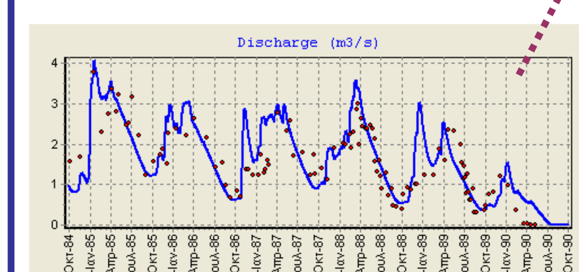
Karditsa gauge



Lilaia-Kefalovryso springs



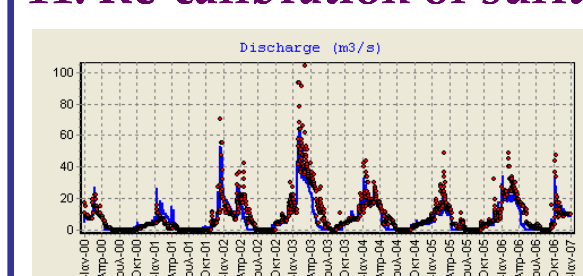
Amphicleia gauge



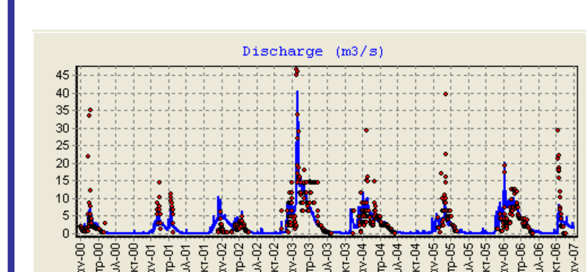
Mavroneri springs

	Calibration efficiency (1/10/1984-30/9/1987)	Validation efficiency (1/10/1987-30/9/1990)
1 Karditsa gauge	0.862	0.702
2 Lilaia springs	0.594	0.184
3 Mavroneri springs	0.580	0.428
4 Ag. Paraskevi springs	0.438	0.779
5 Erkyna gauge	0.630	0.131
6 Melas springs	-0.622	0.236
7 Polygyra springs	0.011	-0.705
8 Amphicleia gauge	0.622	0.359
9 Tithorea gauge	0.681	0.512
10 Anthohori gauge	0.761	0.489
11 Agios Vlasios gauge	0.714	0.680

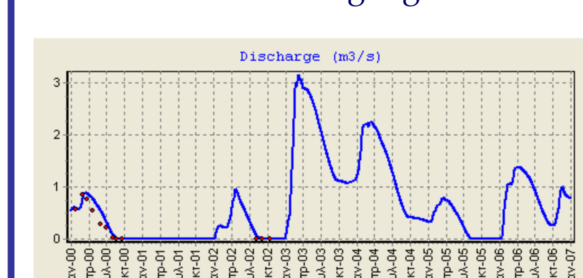
11. Re-calibration of surface runoff parameters based on 2000-2006 data



Karditsa gauge



Anthohori gauge



Mavroneri springs

We only optimized the parameters affecting the surface runoff generation mechanisms, and assumed the rest of them known through the 1984-1990 calibration scenario.

The reproduction of the daily hydrograph at the basin outlet (Karditsa gauge) is significantly good, since all but one (i.e. 26-30 January 2003) high flow events are well approximated.

The flood events at Anthohori gauge, where about half of the basin drains, are approximated with quite satisfactory accuracy. Oddly, in some cases, the observed discharges are greater than the ones measured at the basin outlet, thus introducing major conflict in calibration.

The simulated hydrograph of Mavroneri springs (the second largest of the hydrosystem) fits very well to the few discharge measurements made at the beginning of the calibration period. Moreover, it verifies the flow interruption during October 2000 to December 2001 and during the autumn of 2002.

	Calibration efficiency (1/1/2000-30/6/2003)	Validation efficiency (1/7/2003-31/12/2006)
1 Karditsa gauge	0.743	0.762
3 Mavroneri springs	0.844	-
10 Anthohori gauge	0.490	0.258

12. Remarks on routing modelling

The routing parameters were not calibrated but estimated from experience. We employed the kinematic wave approach for the streams upstream of Anthohori, and the Muskingum model for the downstream ones. The time-lag parameter K was estimated assuming a reasonable travel time, on the basis of the stream length and slope, while the parameter x (used in the Muskingum method) was gradually reduced from 0.20 to zero, to account for the negligible slopes of the drainage network downstream.

This approach improved the efficiency values by 3-5%, also allowing for smoothing the peak flows.