A hydrometeorological forecasting approach for basins with complex flow regime (1)

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1. Abstract

The **combined use of weather forecasting and hydrological models** in flood risk estimations is an established technique, with many successful applications worldwide. However, most known flood forecasting systems have been established in large rivers with perpetual flow. Experience from small basins, which are often affected by flash floods, is limited. In this work we investigate the perspectives of hydrometeorological forecasting by emphasizing two issues: (a) which modelling approach can credibly represent the complex dynamics of **basins with highly variable runoff**; and (b) which **transformation of point-precipitation forecasts** provides the most reliable estimations of spatially aggregated data, to be used as inputs to semi-distributed hydrological models. Using as case studies the **Sarantapotamos** river basin, in Attica (145 km^2), and the **Nedontas** one, in SW Peloponnese (120 km^2), we demonstrate the advantages of continuous simulation through the **HYDROGEIOS model**. This employs conjunctive modelling of surface and groundwater flows and their interactions (percolation, infiltration, underground losses), which are key processes in river basins with significant variability of runoff. The model was calibrated against hourly flow data by the hydrometric stations of the basins for a 3-year period (2011-2014). Next the **most intense flood events** of that period are reproduced, by substituting observed rainfall by forecast scenarios. In this respect, we used consecutive 6-hour point forecasts, provided by the **numerical weather prediction model WRF**, dynamically downscaled from ~18 km, to ~6 km and finally at grid resolution of 2x2 km^2. We examined alternative spatial integration approaches, using as reference the rainfall stations of the basins. By combining consecutive rainfall forecasts (kind of ensemble prediction), we run the model to generate trajectories of flow predictions and associated uncertainty bounds.

2. Motivation: mitigating flood damage

Structural flood control is not sufficient →
- Possible underestimation in design return periods
- False impression of security

↓ importance of

Precautionary measures → Reduce the exposure of assets may be affected by floods

↓ success depends on

Early flood warning → Main type of floods in Greece: **Flash Floods**
- The striking relief patterns and the long coastline lead to the formation of numerous small-sized steep basins;
- Caused by high intensity rainfalls mainly in ephemeral streams and have immediate ("flash") response.

↓ result of

Flood forecasting →

Early flood warning becomes even more crucial in Greece for the mitigation of flood effects

↓ implemented with

Combined use of:
(a) Numerical Weather Prediction Models (NWPMs) for rainfall forecasts
(b) Hydrological Models for flood simulation using rainfall forecasts from NWPMs; apparently, models should be first calibrated against observed hydrological data.

3. Numerical weather prediction model WRF

- The WRF numerical weather prediction model has been used for a wide range of applications, from research to operational forecasting.
- We used the ARW version 3.4 of WRF (Skamarock *et al.*, 2008), running in three domains with 18, 6 and 2 km spatial resolution and 35 vertical levels, with the one-way nesting option.
- The outer domain had 184 grid points in the x-dimension and 129 grid points in the y-dimension, the second domain 174×147 and the innermost domain, in the case of Nedontas 120×108 and in that of Sarantapotamos 75×66 grid points.
- Multiple predictions were developed by applying an ensemble forecasting methodology that used slightly different, plausible initial conditions.
- In our case the initial conditions differed in terms of time; thus, for the same event, we performed a number of simulations with different initialization time (every 6 hours) but with the same end time, which also means different durations.
- The resulting hourly precipitation forecasts were then used as inputs in the hydrological model.

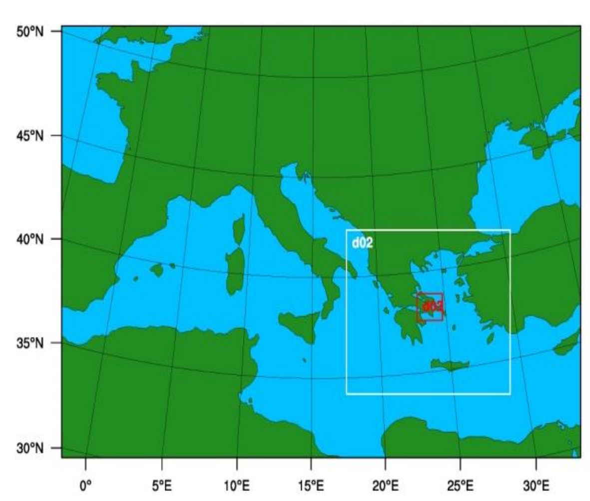


Figure: Layout of three model domains.

Table: Details of the NWPM parameterization used in the simulations.

Model version	WRF-ARW version 3.4
Domains	3
Vertical Levels	35
Microphysical scheme	WSM3, WRF Single Momentum 3
Radiation scheme	RRTM / Dudhia scheme
Cumulus parameterization	Kain-Fritsch
Surface layer option	Monin-Obukhov Scheme
Land surface scheme	Unified Noah Land Surface Model
Planetary boundary layer option	Mellor-Yamada-Janjic TKE (ETA) scheme

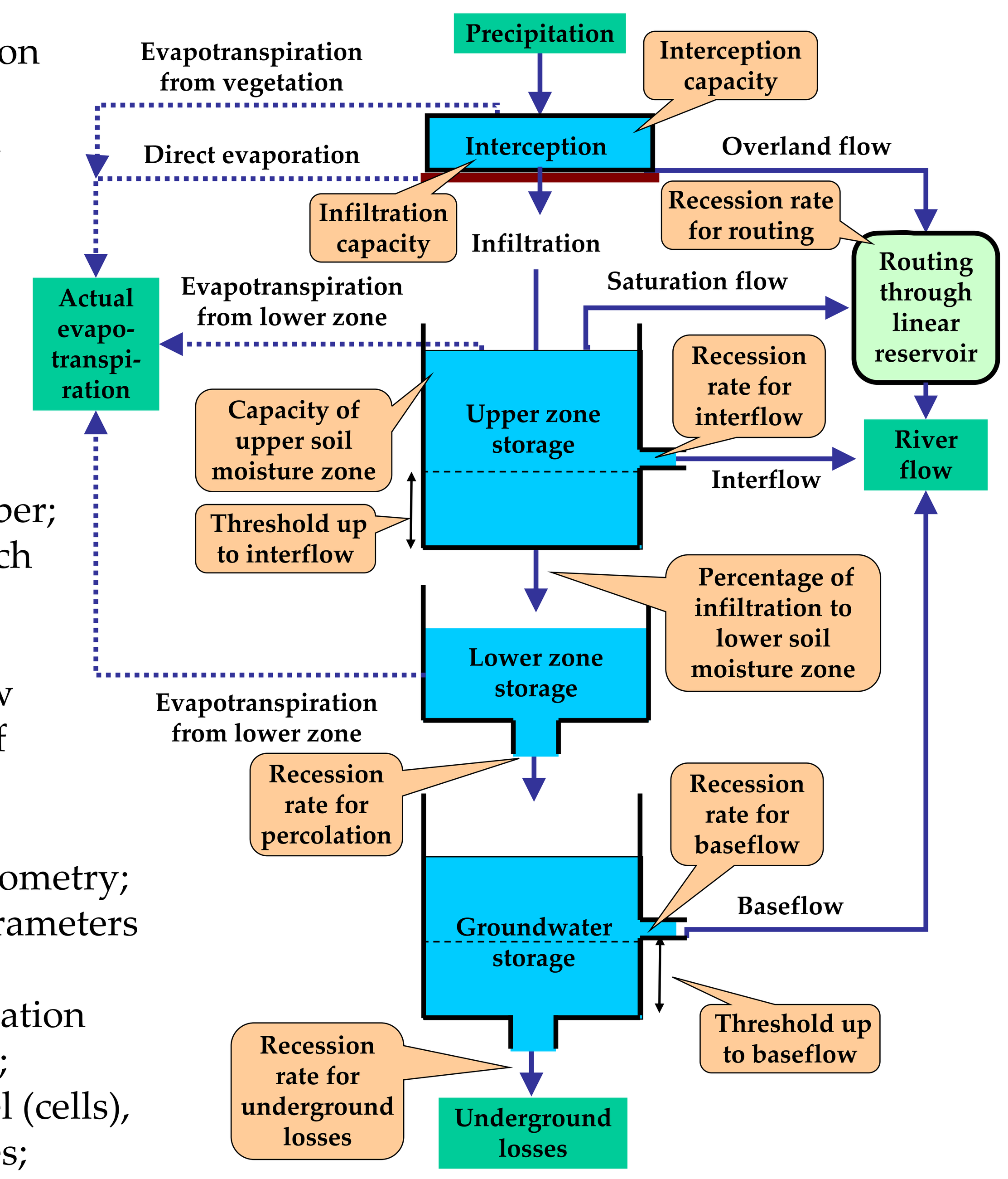
4. Hydrological model HYDROGEIOS

Surface hydrology model

- Consists of four components: i) retention reservoir (due to vegetation), ii) soil surface (surface flow after infiltration), iii) upper unsaturated zone (saturated and hypodermic flow), iv) lower unsaturated zone (percolation);
- Discretization into sub-basins through delineation of the DEM with different parameters for each HRU;
- HRUs are defined on the basis of distributed maps of runoff curve number;
- Rooting using kinematic wave approach
- Inputs: precipitation and potential evapotranspiration for each sub-basin;
- Outputs: evapotranspiration, total flow and percolation for all combinations of sub-catchments with HRUs.

Groundwater model

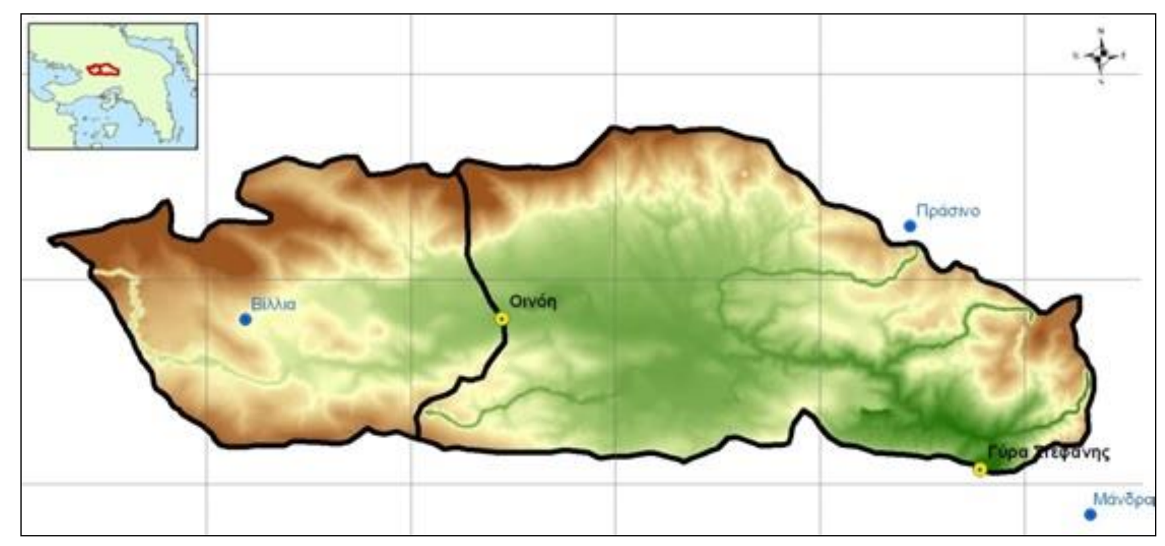
- Discretization into cells of irregular geometry;
- Use of Darcy's equation and only 2 parameters (hydraulic conductivity and porosity);
- Input: percolation (from HRUs), infiltration (water losses across the river network);
- Output: groundwater storage and level (cells), baseflow (springs), underground losses;

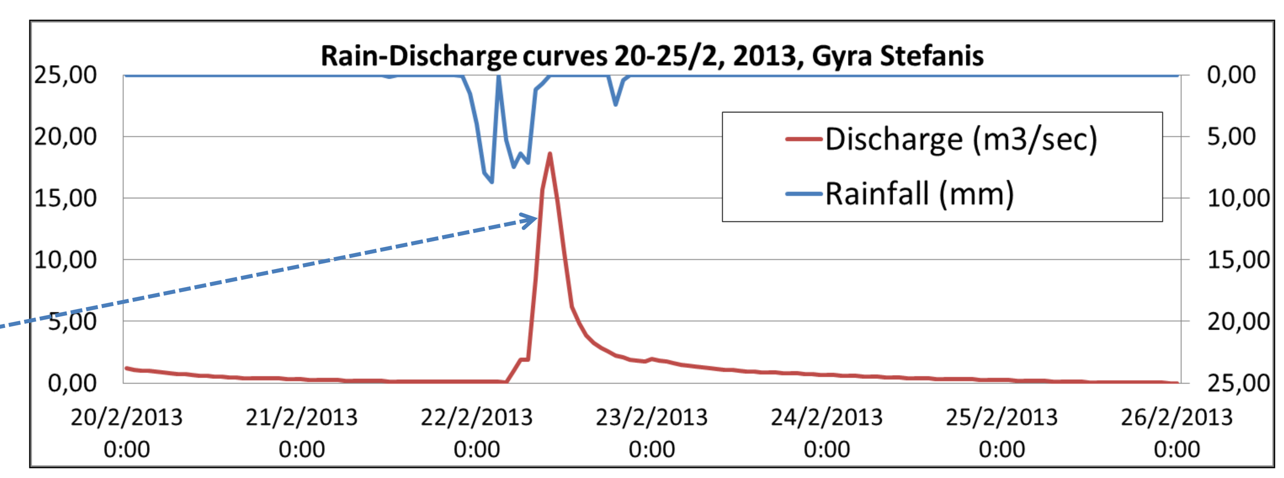


5. Areas of study – Flood events

Sarantapotamos river basin

✓ Total area of 144.6 km^2
✓ Annual precipitation: 300-400 mm
✓ Annual flow in the outlet: ~6 mm
✓ Ephemeral flow
✓ Very high permeability due to dominance of karstified limestone
✓ 2 hydrometric and 3 meteo stations
✓ 40 fatalities from floods in the last 50 years in the downstream area of Elefsina (with major urban and industrial development)

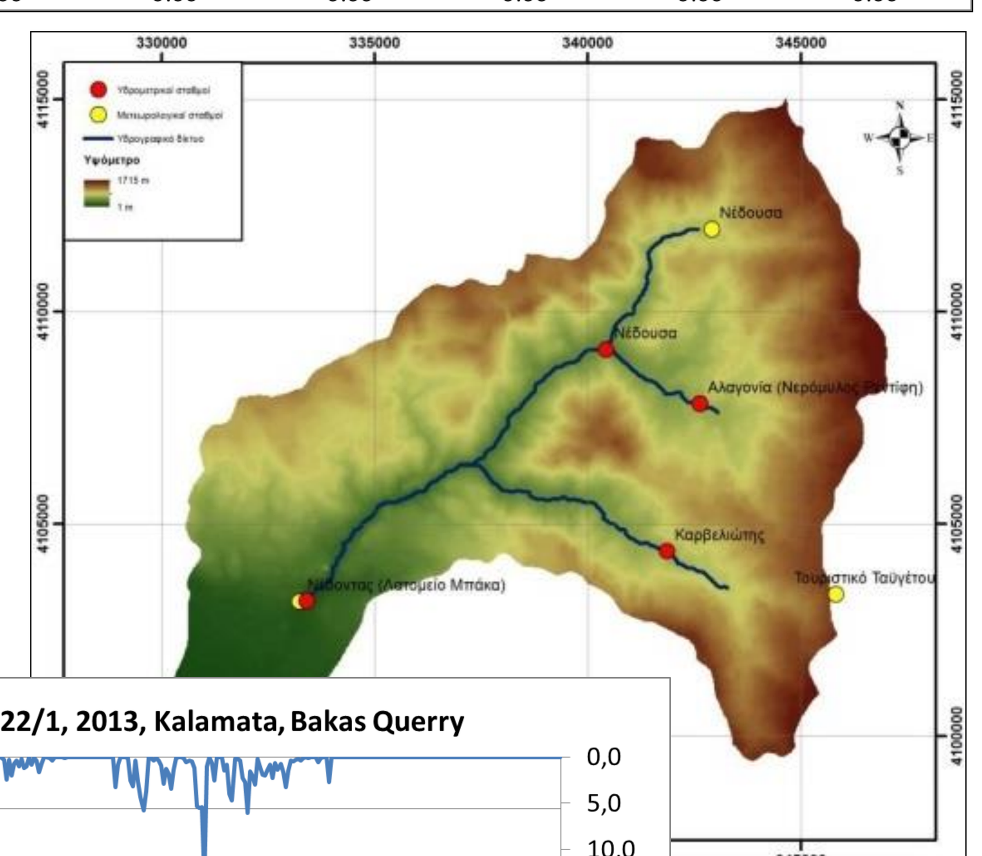


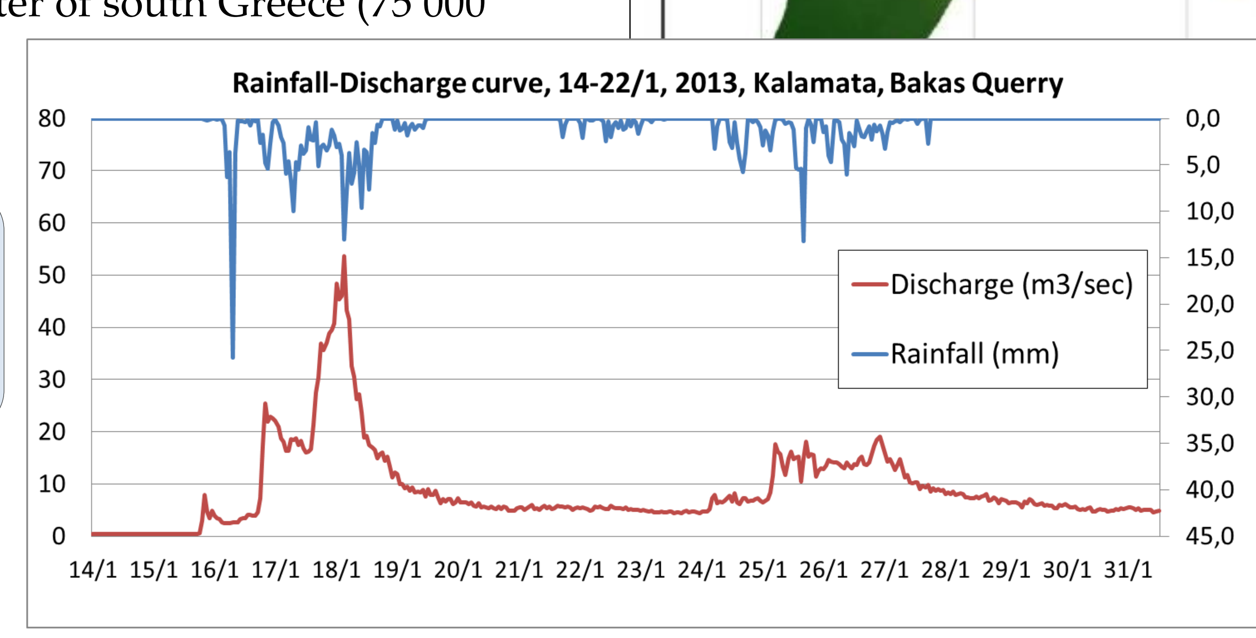


Studied flood event of 22-23/2/2013 with one fatality in Athens area

Nedontas river basin

✓ Total area of 120 km^2
✓ Annual precipitation: 600-800 mm
✓ Annual flow in the outlet: ~7 mm
✓ Medium variability of flow
✓ Significant heterogeneity of permeability (~1/3 of basin lies in flysch, ~2/3 in karstified limestones with negligible runoff generation)
✓ 3 hydrometric and 5 meteorological stations
✓ Outflows to the city of Kalamata, a major economic center of south Greece (75 000 residents)





Studied flood events from 16 to 26/1/2013

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A hydrometeorological forecasting approach for basins with complex flow regime (2)

European Geosciences Union General Assembly 2015, Vienna, 12-17/4/2015, Session HS4.1/AS1.22/GM7.12/NH1.10

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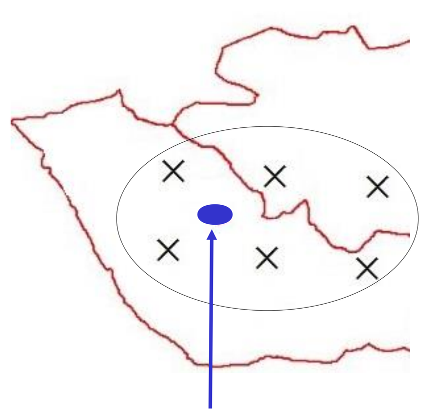
6. Outline of methodology

- **Calibration** of HYDROGEIOS model against observed hourly flows of the two basins for a 3-year period (semi-distributed approach for Sarantapotamos, lumped approach for Nedontas).
- Application of numerical weather prediction model WRF to provide **point rainfall forecasts** in the broader area of the two basins, which begin ~48 hours before the first observed peaks.
- Generation of **consecutive rainfall forecast** scenarios (8 for Sarantapotamos, 13 for Nedontas), with **lead time of 6 hours**.
- Transformation of point forecasts to **areal rainfall** via two alternative approaches (see sketch).
- Use of spatially aggregated rainfall forecasts to the calibrated HYDROGEIOS model and extraction of associated scenarios of flow forecasts.

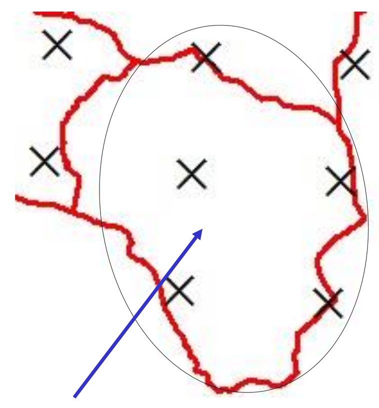
"Point" approach



Estimation of station rainfall as weighted sum of the neighboring grid points, where the weights are estimated by minimizing the difference between the forecasted and observed rainfall volumes; next, estimation of areal rainfall over each sub-basin using the Thiessen polygon method to the forecasted values of the stations.

Vilia station (Sarantapotamos)

"Surface" approach

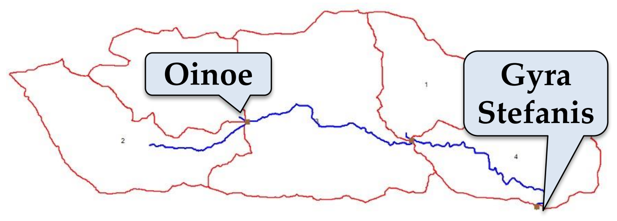


Estimation of areal rainfall of each sub-basin by averaging the forecasted values of all grid points inside or nearby the sub-basin.

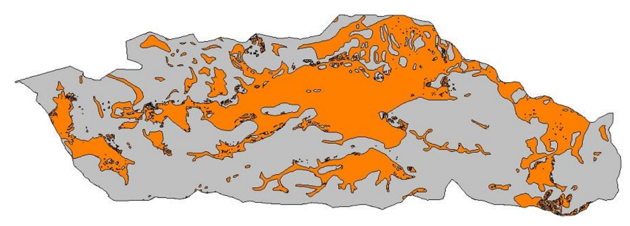
Sub-basin of Karveliotis tributary (Nedontas)

7. Results in Sarantapotamos basin

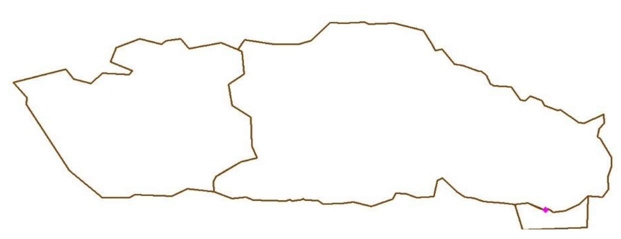
7.1 Model schematization and calibration



Delineation of sub-basins and hydrographic network; multisite calibration (two flow stations)



Formulation of two HRUs based on CN values (grey areas CN<50; orange areas CN>50)

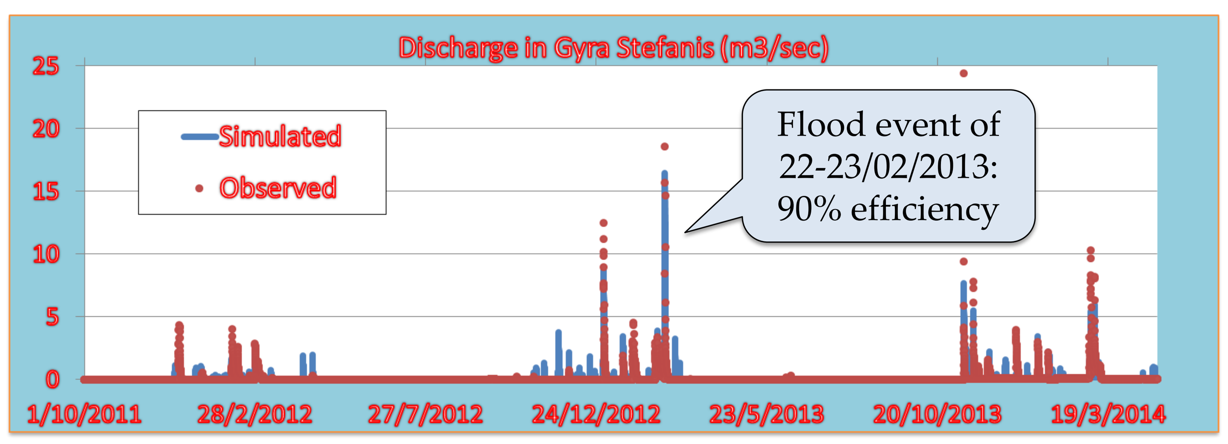


Groundwater cells; the downstream cell accounts the underground losses of the basin

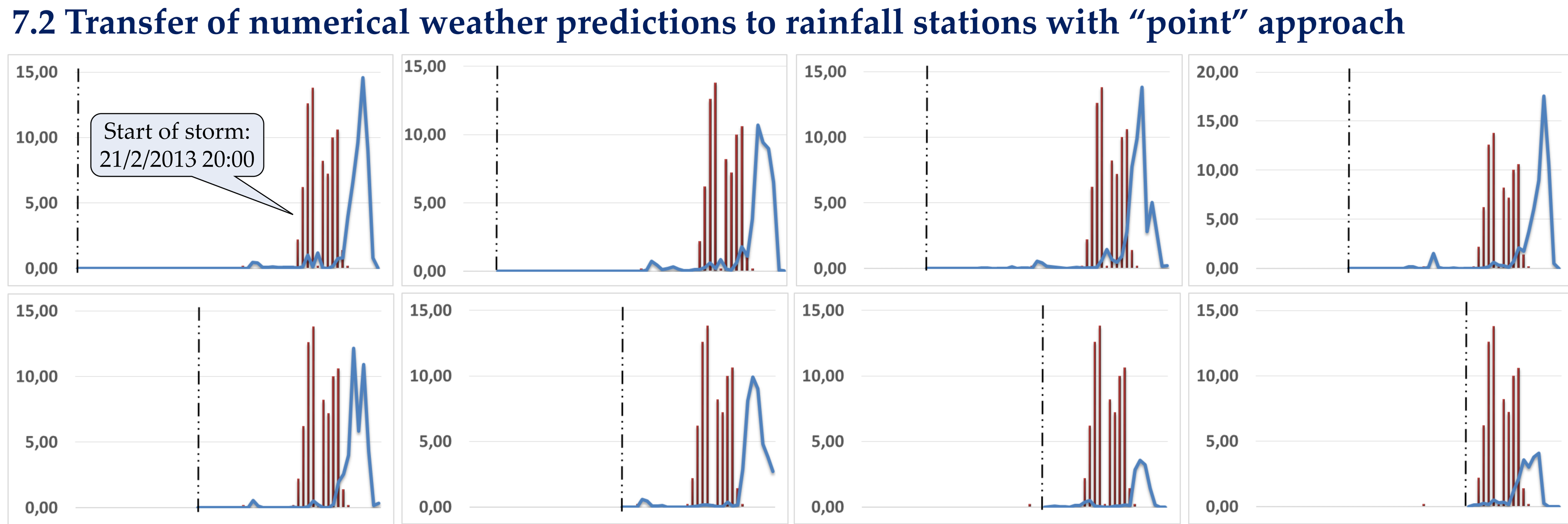
Calibration: 01/05/2011-30/04/2013
Validation: 01/05/2013-30/04/2014

Basin outlet	NSE	High flow NSE (*)
Calibration	0.697	0.742
Validation	0.528	0.324

(*) Nash-Sutcliffe efficiency (NSE) considering flow values greater than the mean



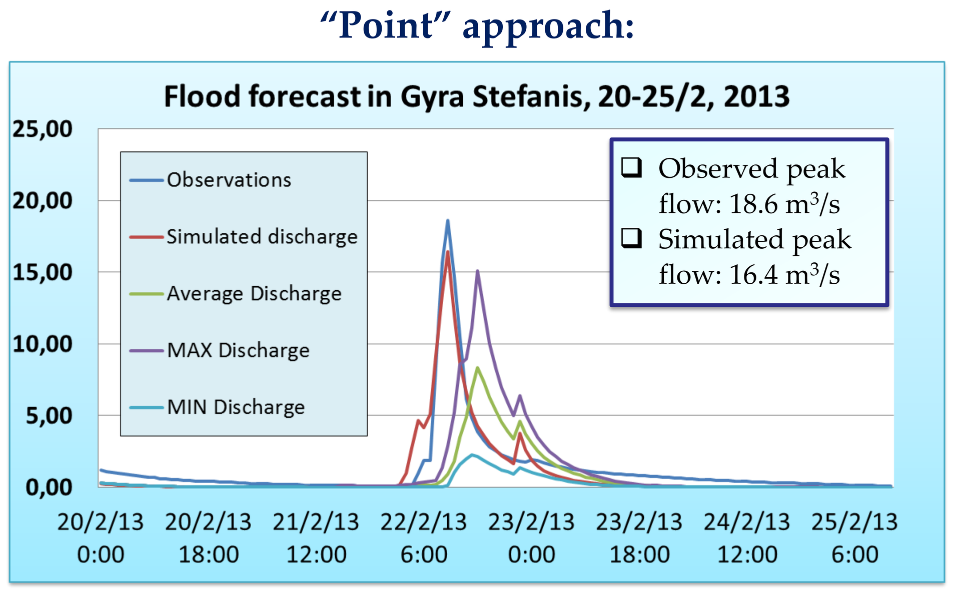
7.2 Transfer of numerical weather predictions to rainfall stations with "point" approach



Dashed Line: Start of forecast period for each scenario **Dark Red Bars:** Observed Precipitation in Vilia Station **Blue Solid Line:** Forecasted Precipitation in Vilia Station with "point" approach

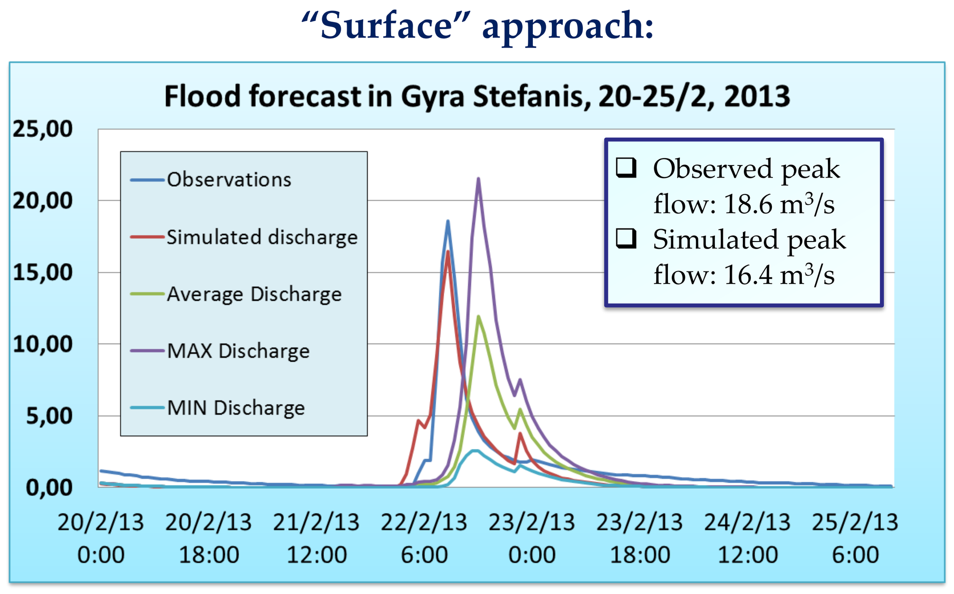
7.3 Forecasted flood event (HYDROGEIOS model driven with scenarios of areal rainfall)

"Point" approach:



- Closest forecast scenario: 15.1 m^3/s (80% of observed peak flow), with lead time 40 hours;
- Average forecast of all the 15 scenarios: 8.4 m^3/s (45% of observed);
- Difference in mainly due to rainfall forecasts.

"Surface" approach:



- Closest forecast scenario: 21.5 m^3/s (116% of observed peak flow), with lead time 40 hours;
- Average forecast of all the 15 scenarios: 11.9 m^3/s (64% of observed);
- 5 hour hysteresis of the forecasted flow peak due to rainfall forecasts.

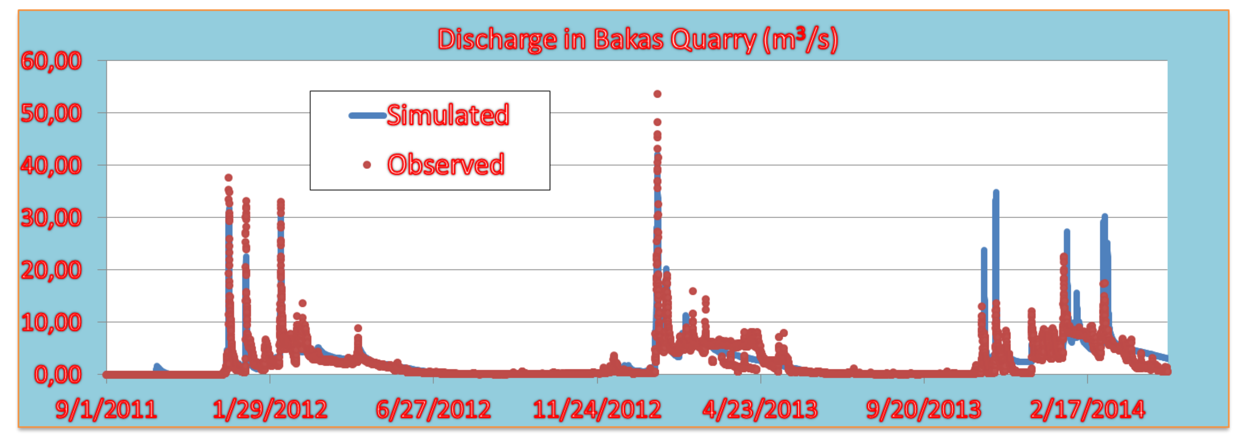
8. Results in Nedontas basin

8.1 Model schematization and calibration

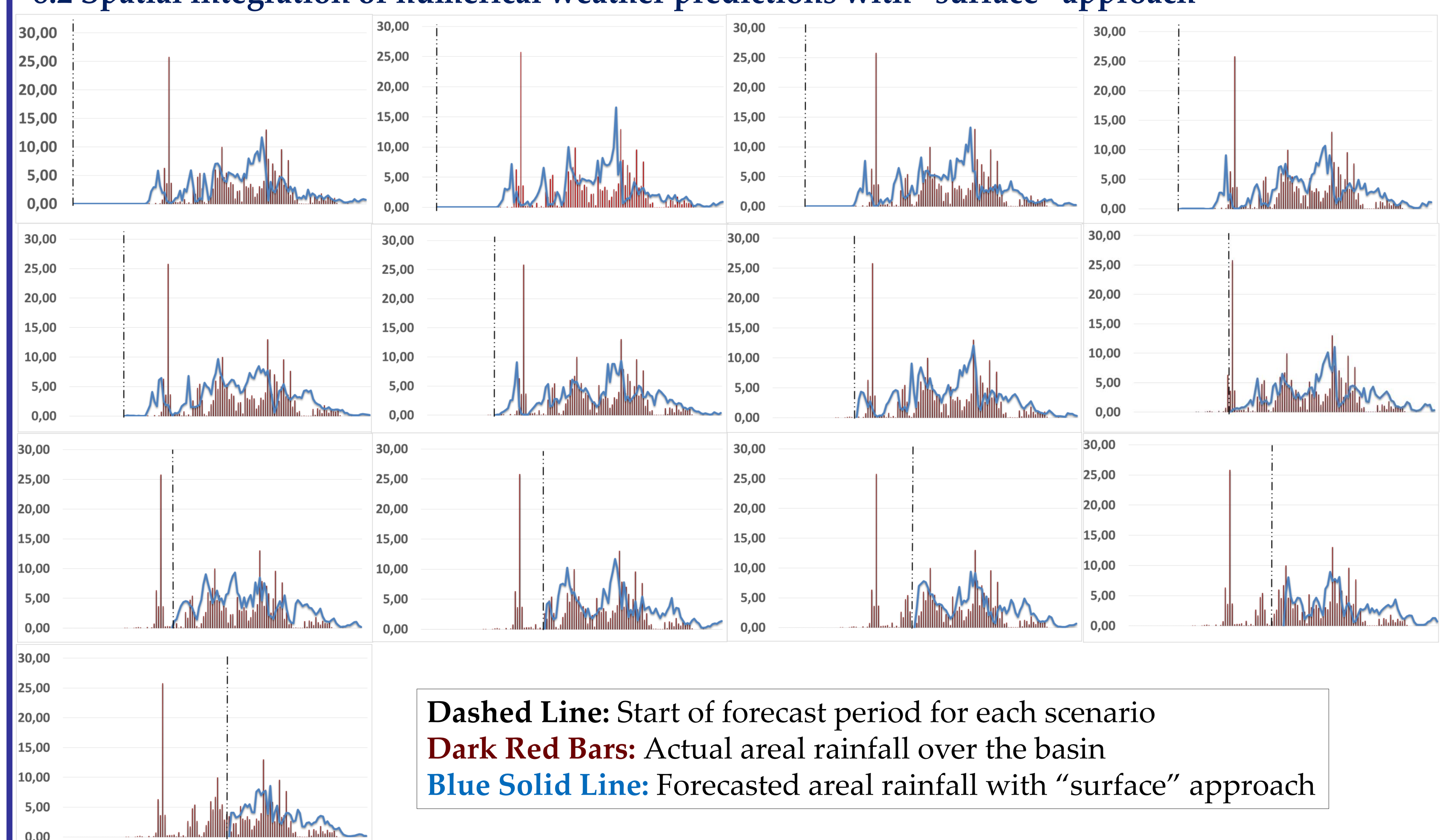
Lumped approach (one parameter set for the entire catchment, estimated via calibration against the observed flows at the basin outlet)

Calibration: 01/09/2011-31/05/2013
Validation: 01/06/2013-30/04/2014

Basin outlet	NSE	High flow NSE
Calibration	0.868	0.827
Validation	0.587	0.584



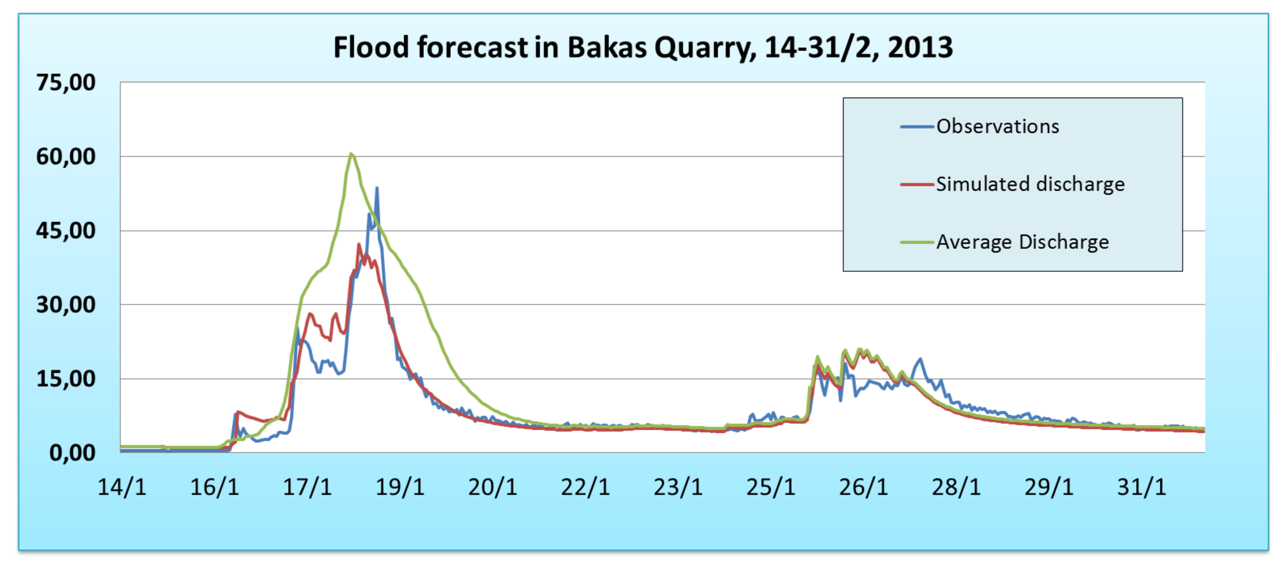
8.2 Spatial integration of numerical weather predictions with "surface" approach



Dashed Line: Start of forecast period for each scenario
Dark Red Bars: Actual areal rainfall over the basin
Blue Solid Line: Forecasted areal rainfall with "surface" approach

8.3 Forecasted flood event (HYDROGEIOS model driven with scenarios of areal rainfall)

- Observed flood peak: 53.6 m^3/s;
- Peak flow estimated through the hydrological model: 42.2 m^3/s;
- Closest forecast scenario: 53.7 m^3/s (100.6% of the observed peak flow) with lead time 36 hours;
- Average forecast of all the 15 scenarios: 60.5 m^3/s (113% of the observed peak flow);
- 7 hour hysteresis of the forecasted flow peak due to rainfall forecasts.



9. Conclusions

- Flash floods affecting relatively small river basins of complex flow regime can be satisfactory predicted, provided that a continuous hydrological simulation model that accounts for the heterogeneity of the basin characteristics and the interactions between surface and groundwater processes has been effectively calibrated.
- It is strongly recommended to employ a simple yet effective spatial integration procedure to estimate the areal rainfall (to be next used as input to the hydrological model), based on the average value of point rainfall forecasts over the area of interest (basin or sub-basin).
- Both case studies showed that the closest predictions of the observed flood were estimated using the rainfall forecast scenario provided 36-48 hours before the beginning of the storm event.
- The perspectives of combining WRF with HYDROGEIOS model should be further investigated, towards establishing an operational flood forecasting system for complex Mediterranean basins.

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