

Hydro-meteorological network for flood monitoring and modeling

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ABSTRACT

Due to its highly fragmented geomorphology, Greece comprises hundreds of small- to medium-size hydrological basins, in which often the terrain is fairly steep and the streamflow regime ephemeral. These are typically affected by flash floods, occasionally causing severe damages. Yet, the vast majority of them lack flow-gauging infrastructure providing systematic hydrometric data at fine time scales. This has obvious impacts on the quality and reliability of flood studies, which typically use simplistic approaches for ungauged basins that do not consider local peculiarities in sufficient detail. In order to provide a consistent framework for flood design and to ensure realistic predictions of the flood risk –a key issue of the 2007/60/EC Directive– it is essential to improve the monitoring infrastructures by taking advantage of modern technologies for remote control and data management. In this context and in the research project DEUCALION, we have recently installed and are operating, in four pilot river basins, a telemetry-based hydro-meteorological network that comprises automatic stations and is linked to and supported by relevant software. The hydrometric stations measure stage, using 50-kHz ultrasonic pulses or piezometric sensors, or both stage (piezometric) and velocity via acoustic Doppler radar; all measurements are being temperature-corrected. The meteorological stations record air temperature, pressure, relative humidity, wind speed and direction, and precipitation. Data transfer is made via GPRS or mobile telephony modems. The monitoring network is supported by a web-based application for storage, visualization and management of geographical and hydro-meteorological data (ENHYDRIS), a software tool for data analysis and processing (HYDROGNOMON), as well as an advanced model for flood simulation (HYDROGEIOS). The recorded hydro-meteorological observations are accessible over the Internet through the www-application. The system is operational and its functionality has been implemented as open-source software for use in a wide range of applications in the field of water resources monitoring and management, such as the demonstration case study outlined in this work.

Keywords: ungauged basins; flood design; telemetry; open-source software

1. INTRODUCTION

Due to its highly fragmented geomorphology, the Greek territory comprises hundreds of small- to medium-size hydrological basins (~50 to 250 km²), in which often the terrain is fairly steep and the streamflow regime ephemeral. These are typically affected by flash floods that occasionally cause severe damages. Yet, the vast majority of these basins lack flow-gauging infrastructure providing systematic hydrometric data at fine time scales. For this reason, and despite the great scientific and technological advances in flood hydrology, everyday engineering practices still apply simplistic *recipes* (rules-of-thumb or semi-empirical approaches) that are easy to implement in ungauged areas, but do not consider local peculiarities in sufficient detail. The result is that the quality and reliability of hydrological studies, and, consequently, the safety and/or cost of the related flood-protection works suffer.

In order to provide a consistent framework for flood design and to ensure realistic predictions of the flood risk –a key issue of the 2007/60/EC Directive– it is essential to improve the monitoring infrastructures by taking advantage of modern measuring technologies, of remote access to the observation systems and of advanced data processing and management. At the same time, carefully conducted measurements in few selected catchments would allow field-testing the aforementioned recipes. In general, these recipes have been developed many decades ago, based on field data from few experimental catchments abroad. However, none of them has ever been validated against the peculiarities of the hydroclimatic regime and the geomorphological conditions of Greece.

In what follows, we describe the setting up, the characteristics and the operation of a telemetry-based hydro-meteorological network that has been installed in the framework of the research project DEUCALION ($\Delta\text{EYK}\Lambda\text{A}\text{I}\text{O}\text{N}$; complete title: *Estimation of flood flows in Greece under conditions of hydroclimatic variability: Development of physically-based conceptual-probabilistic framework and computational tools*; <http://deucalionproject.gr/>). The aim of the project is to offer an integrated framework for flood risk assessment on the river basin scale. This includes data monitoring, transfer, storage, visualization and processing tools, in conjunction with flood simulation and forecasting models, all provided as open source software. The aforementioned network, which extends over four river basins in Greece, will be the basis for validating the methodologies and the related tools. A key component is the hydrological simulation software, which is applied in one of the experimental basins. This sample case study is also described herein.

2. THE MONITORING NETWORK AND ITS SUPPORTING SOFTWARE

The purpose of the data collection is to estimate the discharge at the monitored cross-sections of the streams and the flood-producing rainfall in the watershed of interest. Based on this data, we strive to establish those factors that relate the basin's morphology and its hydrographic network to the discharge hydrograph at the basin's outlet generated by rainfall of a given spatio-temporal distribution. Because floods are, by definition, rare phenomena that occur without advance warning, it is important that the monitoring systems operate automatically, measuring at preset time intervals and logging the data that must be accessible remotely via telecommunication systems. In addition to the reliable monitoring of the hydro-meteorological quantities of interest, it is important to manage and process the collected data through the use of advanced information technology tools. Next are given details for both the networks and the information system.

2.1 Telemetry-based hydro-meteorological monitoring network

The telemetric monitoring network comprises ten fully-equipped meteorological stations, five rain gauge stations and eight automatic hydrometric stations that have been installed in four pilot river basins, two in Attica-Boeotia and two in Peloponnese, ranging from ~ 10 to ~ 200 km² (Fig. 1). The hydrometric stations measure stage, using 50-kHz ultrasonic pulses or piezometric sensors (pressure transducers), or both stage (piezometric) and velocity via acoustic Doppler radar; measurements are always temperature-corrected. The measuring devices have been programmed to record the data in 15-minute intervals, and local storage capacity is provided for three-month data; 20-W photovoltaic panels feed the battery of each station, securing its electrical supply. Data transfer is made via GPRS or mobile telephony modems. The flow rating curves at the stage-recording stations are established through velocity measurements with a current meter; the flow estimates obtained with the acoustic Doppler radar are also verified periodically through current-meter measurements. The automatic meteorological stations have been located so as to provide good rainfall coverage over the basins. They record air temperature, pressure, relative humidity, wind speed and direction, and precipitation in 10-minute intervals, and also log data locally for 17 days. The data are accessible through a web application, described in section 2.2.

In Attica-Boeotia, two basins are studied: (a) the small Nea Penteli sub-basin (5.2 km²) of the upper reach of Chalandri stream, a semi-natural sub-basin in a not densely populated area of north Athens, and (b) the river basin of Sarantapotamos that discharges in the Bay of Eleusis, where two hydrometric stations are installed (basin area 67.5 km²; subsurface is mostly limestone). In Arcadia, central Peloponnese, we study the basin of the river Lousios (166.3 km², subsurface is largely limestone), a tributary of Alpheios river; a hydrometric station has been installed ~ 4 km upstream of the confluence of the two rivers. The river basin of Nedontas is located in Messinia, SW Peloponnese; the flows from Karveliotis sub-basin (mostly flysch subsurface) and from the upper Nedontas sub-basin (subsurface is mostly limestone) form the (lower) Nedontas, which discharges in the Bay of Messinia; flow stations have been installed on two tributaries (Karveliotis and Alagonia), and on Nedontas river (upstream basin area 120.8 km²), at the edge of the city of Kalamata. Another hydrometric station is expected to operate during this summer (2013), in the upper Nedontas sub-basin.

In all cases, care was taken to select cross-sections with stable geometry. Wherever possible, advantage was taken of existing manmade drops in the streambed that act as hydraulic controls, facilitating the indirect determination of discharge from stage measurements, e.g., Nea Penteli station and the outlet station of Nedontas (Fig. 1 upper right and lower left, respectively). At Alagonia, measurements are taken just upstream of a small weir-like manmade bump. At Oinoe and Gyra Stephanis (Sarantapotamos), and at Karveliotis, the cross-sections of the hydrometric stations are in prismatic underpasses made of concrete or stone (under road bridges), as shown in Fig. 1 upper left and lower left panes, respectively. At Oinoe and Karveliotis the underpasses are followed by a large drop of the streambed. Finally, the hydrometric station on Lousios is located under the old Atsicholos stone bridge and features an advanced acoustic Doppler radar for velocity measurements and a piezometric sensor for stage, shown in the lower right part of Fig. 1.

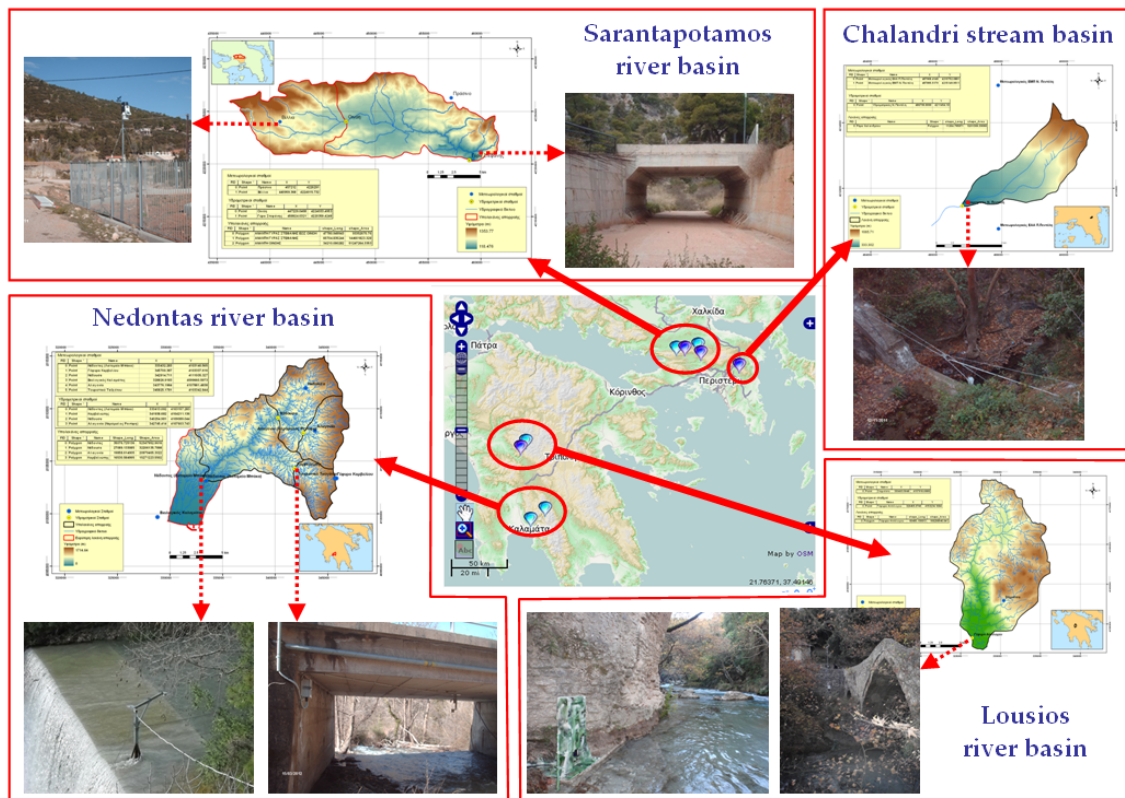


Figure 1. Hydro-meteorological monitoring network of DEUCALION project: (a) upper left panel: Sarantapotamos basin – meteo-station and concrete underpass where stages are measured; (b) upper right panel: sub-basin of upper Chalandri stream –suspended ultrasonic-pulse stage meter; (c) lower left panel: Nedontas basin –stage-metering by ultrasonic pulses; (d) lower right panel: Lousios basin –acoustic Doppler radar.

Certain characteristics of the metering devices are worth mentioning here. In the stage measurements, since the emitted ultrasonic pulse disperses, its echo is reflected from a finite area. For the particular instrument, the dispersion angle is 30° , thus for a target at a distance H from the source, the reflected signal comes from an area of radius $0.268H$ around the projection of the source point on the water surface; also, the target (water surface) cannot be closer than 50 cm, for which reason one must gauge the maximum expected stage at a cross-section to install the instrument properly, also considering that the measurement error increases with distance from the target. The measurement of flow velocity by acoustic radar exploits the Doppler phenomenon [1]. Two transmitter-receivers send, inside narrow cone beams, pulses of known frequency into the water body in a direction transverse to the mean flow. These pulses return to the transmitter-receivers after being reflected on particle-scatterers in the sampled water volume, with their frequency shifted due to the velocity of the scattering particles (Doppler effect). The so-called index velocity V_i is the flow velocity along the path of the pulse that is calculated from the frequency shift and the distance between source and scatterers. The flow velocity components in each cell are calculated from V_i trigonometrically. The index velocity must be determined through conventional velocity measurements for various stages and discharges Q , in order to set up an empirical $V_i(Q)$ relationship. The flow field is resolved in a number of cells over a certain distance from the source that depends on the signal strength relative to the measurement noise. The discharge is calculated by integration of the cell-velocities over the flow area, using certain parameters that are determined (hydrodynamically and via experiments) to fit field profiles.

2.2 Data transfer, storage, processing and visualization

The measuring instruments originate from various manufacturers, providing a variety of data transfer capabilities. Where possible, ADSL over PSTN has been selected for data transmission, considered to be the most stable and reliable option. Yet, in most sites data are transmitted automatically through GSM and GPRS services of the mobile telephone network. Existing infrastructure of both the National Observatory of Athens (NOA) and the National Technical University of

Athens (NTUA) has been utilized for the collection, processing and dissemination of data. As shown in Fig. 2, meteorological data are collected every 10 min from the monitoring network of NOA, and then transmitted to the server of NTUA using the HTTP protocol. Data are typically provided in form of text files. These may have different formats and lengths, depending on the type of a station's logger and the selected options. Some data are saved in form of small files, covering only limited time period. In other cases, new data are appended to a single file containing time series of all variables measured from a single station. The typical structure of such data files includes a header section containing metadata and a section with the actual time series. Although most vendors follow this structure, there are significant differences in formatting details from one system to another. In order to cope with this problem, an application called LoggerToDB has been developed as part of an open source project. LoggerToDB reads plain text data files, connects to the project's database, determines which records in the file are newer than those stored in the database and appends them. The application is configurable to a variety of file formats used by several monitoring systems. In some cases where file formats were unknown to the initial version of LoggerToDB, the capabilities of the software have been expanded making it compatible to the new format. The same application is used to populate the database with real-time data coming from the hydrometric stations. These are collected once daily using a proprietary software tool (LoggerNet), provided by the manufacturer of the specific stations.

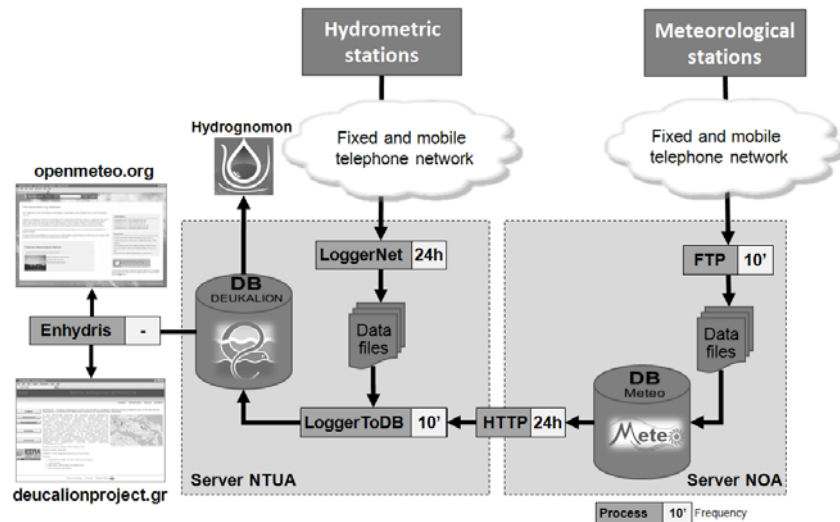


Figure 2: Schematic representation of the data collection and the publication procedures and schedules.

A web application for supervision and management of monitoring stations (ENHYDRIS), supported by a data processing tool (HYDROGNOMON), comprise the soft component of the network, which is illustrated in Fig. 3. ENHYDRIS is an open-source platform for data collection, storage and visualization. It can store long time series in an efficient way, resulting in using small space and high speed retrieval. Moreover, static information related to the monitoring network (in terms of geographical entities) is provided by the geospatially enabled database. The software is extensible to the needs of researchers, scalable to the growth of measurement networks and to the increase of users and data, and serves the data with widely adopted formats. For instance, it offers an API, through which multiple applications can be developed independently and installed as plug-ins; it can also work in a distributed database scheme.

Information by ENHYDRIS is disseminated in various ways. In particular, the data are published to the web site of the project (deucalionproject.gr) as well as the openmeteo.org site; the latter is an open source initiative, devoted to the distribution of free hydrometeorological data and software worldwide [2]. Through the official website one can have access to all related information, provided in the form of tables, charts and maps. The way the information is organized corresponds to the basins under monitoring and the type of the installed stations. Users can list all stations or the stations that are installed in a specific geographical area. Subsequently, they can navigate to the homepage of each specific station. They can also navigate to the same page by selecting the station projected on the map, which is provided either in full screen mode or embedded in other web pages. By clicking with the mouse on the stations icon useful station characteristics appear along with the link to the station homepage. The homepage of each station is divided in the upper section containing all station characteristics and a map showing the location of the station and the lower section listing

the time series of the parameters monitored. By clicking on a specific time series, the user goes to the corresponding homepage, where are provided time series metadata, a quick preview of the measurements in form of a chart with zooming capabilities and a link for downloading the full time series as textfile. Finally, through the website one can monitor in form of charts parameters measured in every station as well as in each one of the four basins. This application provides users the flexibility to select and project the exact time period of interest in a time frame, from daily to monthly, focusing on specific historical events. According to the projected timeframe, summary statistics are also provided, such as maximum, minimum, average values and sums.

The time series are readable by HYDROGNOMON, which is a free software application for the analysis and processing of hydro-meteorological time series. The program implements typical data processing applications, such as time step aggregation and regularization, interpolation, regression analysis, infilling of missing values, consistency tests, data filtering, graphical and tabular visualization of time series, etc. It also employs more advanced tasks, including evapotranspiration modeling, stage-discharge analysis, statistical analysis, lumped rainfall–runoff simulations, etc.

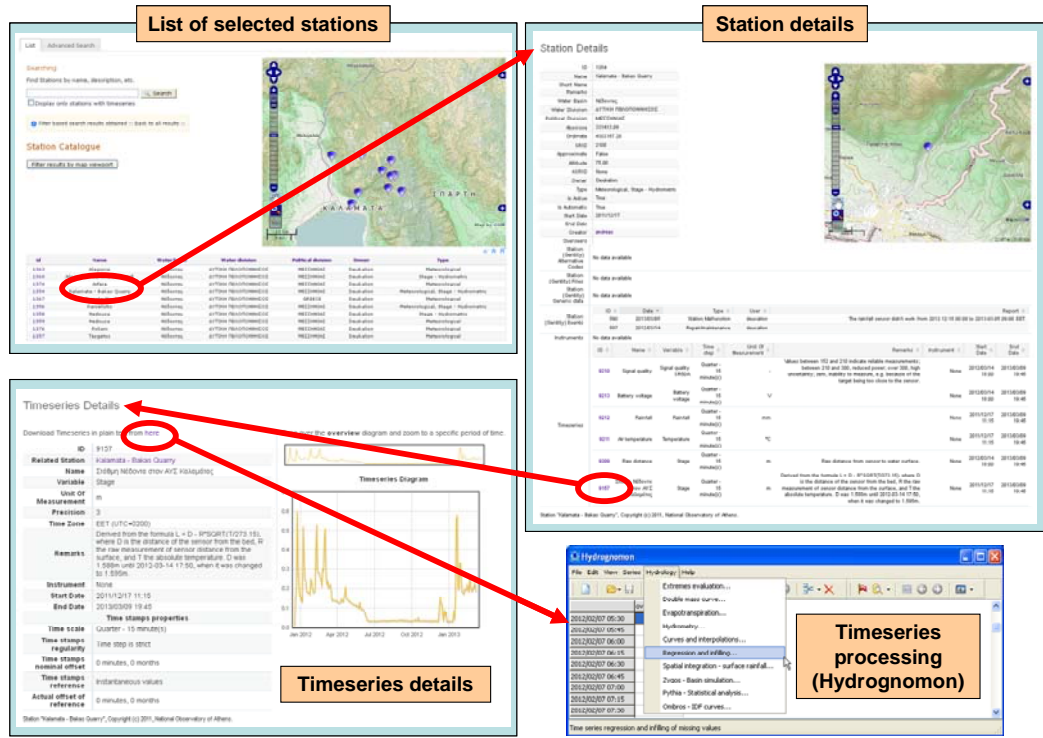


Figure 3. Main components of the data processing and visualization system (Enhydris and Hydrognomon).

3. SAMPLE HYDROLOGIC FLOOD MODELLING APPLICATION

3.1 The modelling framework HYDROGEIOS

In the context of the project we aim to establish improved flood modelling approaches that are consistent with the hydroclimatic and geomorphologic characteristics of the Greek basins. The most challenging part of this research involves the development of continuous hydrological simulation tools, which will be coupled with meteorological and hydraulic models for flood simulation and forecasting. This section describes synoptically the modelling framework that is based on the recently upgraded version of HYDROGEIOS software (<http://itia.ntua.gr/en/softinfo/25/>) and its test application to the pilot river basin of Nedontas [3].

HYDROGEIOS is a GIS-based tool, which implements a conjunctive (i.e., surface and ground water) hydrological model, combined with a system-oriented water management scheme. Since the initial modeling orientation was towards complex management problems in modified river basins, it was applicable for monthly simulations [4, 5]. As already mentioned, in the context of project, the software was improved to also support daily and hourly time steps, thus being

suitable for the representation of flood processes at the river basin scale. Characteristic forms of the modeling suite are illustrated in Fig. 4.

The representation of the hydrosystem fluxes is based on a semi-distributed schematization of the river basin (i.e., the whole catchment is divided to sub-basins that are interconnected through the hydrographic network), a multicell delineation of the groundwater flow field, and a network-type representation of the water management components (hydraulic structures, water uses and constraints). The formulation of input spatial data, by means of geographical layers, is implemented in MapWindow, which is an open-source GIS platform (Fig. 4). A minimum geo-dataset is required for the estimation of the basin's characteristics at the typical scale of 1:50 000. This contains an elevation model, land cover and/or land use information, and a geology-related layer. A typical project uses relevant datasets, mainly a 50×50 m digital elevation model (DEM), the Corine Land Cover, and a hydro-lithology map. For flood simulation, topographic stream cross-sections are also required, at the 1:500 scale, e.g., by means of relevant topographic maps.

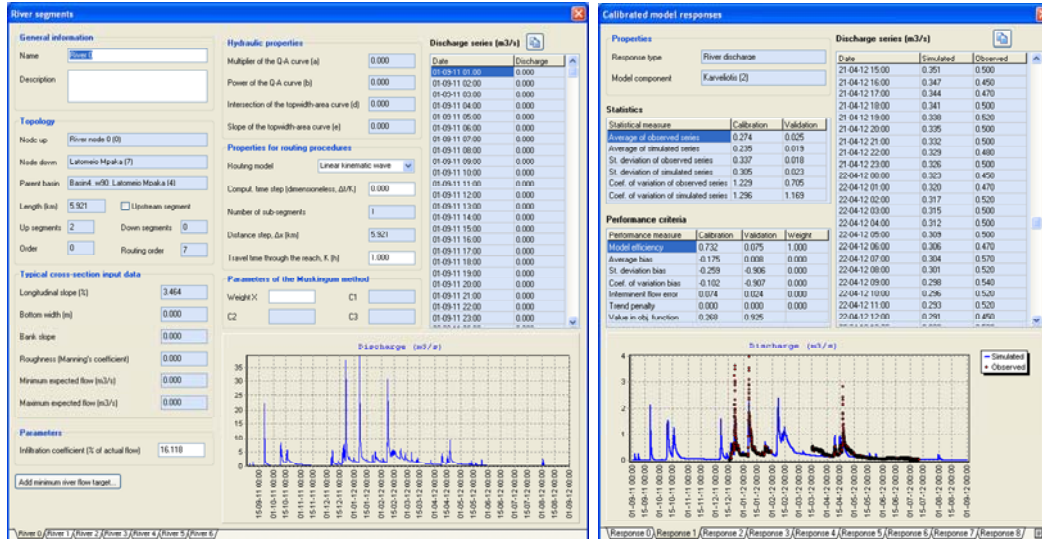


Figure 4. Characteristic forms of HYDROGEOIOS software (left: river data; right: simulated vs. observed time series).

The hydrographic network is extracted from the DEM, considering control points such as flow measurement stations, diversion nodes, etc. The network conveys surface runoff from the sub-basins, where different hydrological stresses are assigned, in terms of precipitation and potential evapotranspiration (PET) time series. The surface hydrological processes and related model parameters are considered homogeneous within the so-called Hydrological Response Units (HRUs). These represent soil types, defined by the classification of properties such as permeability, land cover, terrain slope, etc. At each basin partition (i.e. combination of sub-basin and HRU), a conceptual rainfall-runoff model is employed, which transforms precipitation into real evapotranspiration, percolation and surface runoff. In monthly simulations, six parameters per HRU are used while for finer time steps an extra parameter is introduced, to better represent the unsaturated zone processes. This parameterization approach provides important flexibility, since the user can adjust the number of HRUs and, consequently, the total number of the model parameters, which are subject to calibration.

The groundwater simulation problem mainly involves the estimation of baseflow (i.e., groundwater runoff through springs) and the underground losses (e.g., groundwater transfer to the sea). Here we follow a multi-cell approach, where the aquifer is delineated into non-rectangular cells. This approach allows for describing complex geometries on the basis of the physical characteristics of the groundwater system (e.g., geology), through parsimonious structures [6]. Each cell corresponds to a conceptual tank, to which two parameters are assigned (conductivity, specific yield). Springs and underground losses are also modelled as virtual tanks of very large base, which allows keeping almost constant hydraulic head. For given stresses, the groundwater field problem is solved by a numerical scheme. These stresses are areal inflows due to percolation, inflows due to infiltration underneath each river segment and outflows due to pumping. We remark that percolation is output of the surface hydrological model, whereas infiltration and pumping are output of a flow allocation model, which is described next. Due to process interactions, simulation follows a looped architecture within each time step, which requires one or two cycles to converge.

Finally, regulated flow through man-made structures (if they exist) and portions of the hydrographic network is modelled with the aid of a water management network. This has as nodal inflows the surface and the groundwater runoff, as nodal outflows the withdrawals for water uses, and as distributed fluxes the water losses due to infiltration and river discharge. Major hydraulic works are also represented as well as their interactions with the natural system. The optimal allocation of the hydrosystem fluxes is tackled as a network linear programming problem where virtual unit costs, positive or negative, are assigned either to prohibit undesirable fluxes or to force fulfilling the used-defined targets and constraints.

In hourly simulations, we also follow a two-step procedure that represents routing phenomena. First, we employ a linear reservoir scheme to propagate the surface runoff generated from each sub-basin to the corresponding outlet node. This scheme uses a recession coefficient per sub-basin, which is handled as unknown parameter, as well as the time of concentration, which is estimated through the Giandotti formula. Next, we employ the routing of total runoff (i.e., surface and baseflow) along the hydrographic network, for which two modelling options are available. In the case of channels of relatively steep slope, we employ a kinematic-wave model, implementing a temporal transfer of the hydrograph from the upstream to the downstream node. On the other hand, in case of mild slopes, it is preferable to employ a Muskingum diffusive-wave scheme that implements a non-linear transformation of the input hydrograph [7, 8]. The former approach requires only the time lag for each stream reach, while the Muskingum scheme requires two parameters.

A major issue within any modelling attempt is the estimation of the model parameters, on the basis of observed data. HYDROGEIOS embeds an advanced calibration module that provides a number of statistical and empirical criteria for model fitting on multiple responses (river and spring discharge, hydraulic heads), as well as various options regarding the definition of the feasible search space. The best-compromise parameter values are detected through the evolutionary annealing-simplex algorithm [9].

3.2 Study area and hydrological data

The study area was the pilot river basin of Nedontas, comprising four meteorological and three hydrometric stations (a fourth station is planned to be installed next summer in Nedousa). The simulation period for the model testing was one hydrological year (from 1/9/2011 to 31/8/2012), for which we extracted the hourly time series for the two stress inputs, i.e., precipitation and PET, at the sub-basin scale. To estimate PET we employed a semi-empirical approach, which, as explained herein, uses temperature as single meteorological input. Thus, the unique relative variable that was retrieved from the ENHYDRIS database was the ten-minute average air temperature. Moreover, we used all available hydrometric data (after transforming river stage observations to discharge), in order to calibrate the model parameters, by minimizing the departures between the simulated and the observed flow data at the three measuring stations.

Taking advantage of the related applications of HYDROGNOMON, we employed some essential processing of the raw precipitation and temperature data. First, we checked for unreasonable or infeasible values (e.g., negative rainfall), which were removed. Next, we aggregated the 10-minute data, in order to obtain the hourly precipitation and mean hourly temperature time series. Finally, we filled the missing hourly values through linear regression analysis. We mention that the installation of the telemetric network was made progressively, from December 2011 to February 2013, thus the data records do not extend over the same time period. For this reason, for most variables of interest, it was essential to fill the missing values, using observed data from neighbouring stations.

As shown in Fig. 5, the river basin was divided in seven sub-basins, as explained in section 3.3. The areal integration of point precipitation and temperature over the sub-basins was made using the Thiessen method, corrected for elevation. We assumed an annual rain slope value of 0.75 mm/m (which is typical for the broader region) and employed this value to “transfer” the point rainfall observation from the elevation of the meteorological stations to the average elevation of each sub-basin. Similarly, we applied a correction of temperature, assuming a decrease rate of 0.0065°C/m.

For hourly PET estimations we followed a two-step procedure. First, we calculated the monthly PET values over all sub-basins, using the simplified Penman-Monteith formula proposed by [10]:

$$E = \frac{a R_a + b}{1 - c T_a} \quad (1)$$

where R_a (kJ/m²) is the extraterrestrial solar radiation, which is function of latitude and time, T_a (°C) is the temperature, and a , b and c are regional parameters. According to Tegos *et al.* (2013), who investigated the spatial variability of the model parameters over Greece, their optimal values for the area of Kalamata are $a = 0.000053$ kg/kJ, $b = 0.064$ kg/m²

and $c = 0.0253^{\circ}\text{C}^{-1}$. Using these values, we computed the monthly PET for each sub-basin as function of monthly temperature, and next we employed an empirical disaggregation approach. In particular, we assumed that the daily PET is proportional to the ratio of the daily to monthly temperature, and then we divided by 24, to obtain the hourly values.

The most difficult part of data processing was the construction of discharge time series on the basis of raw hydrometric data. As mentioned in section 2.1, the three gauging stations (Karveliotsis, Alagonia, and basin outlet) provide stage data in 15-minute intervals. In fact, these data require pre-processing, namely removal of negative values and adjustment to an offset stage value (typically, few centimetres) that corresponds to dry conditions (i.e. zero flow). A proper selection of the offset is of key importance, since the estimation of both the baseflow as well as the time of baseflow interruption are key elements for a consistent representation of the hydrological and groundwater mechanisms of the basin.

Next step, after retrieving the corrected stage data, was the calculation of 15-min discharge time series. In general, this task requires either using theoretical hydraulic formulas (e.g., Manning's equation) or establishing empirical stage-discharge relationships (also referred to as rating curves). In the absence of flow measurements (apart from few sporadic measurements during the low-flow period), the unique option was the use of theoretical relationships. In this vein, we took advantage of the favourable geometrical and hydraulic characteristics of the three cross-sections, where the stage recorders are installed (particularly in the outlet station). In all cases, we assumed that the measured stage corresponds to the critical flow depth y_c , which in turn allows estimating the discharge q by the simplified formula:

$$q = w g^{1/2} y_c^{3/2} \quad (2)$$

where w is the flow width (which is assumed equal to the cross-section width) and g is the acceleration of gravity (9.81 m/s^2). Further analysis, based on the FLOW3D software (<http://www.flow3d.com/>), which employs detailed hydraulic simulation by representing the flow field in three dimensions, proved that eq. (2) underestimates high flows. By combining the two approaches, we obtained the final discharge time series, at 15-minute resolution, that were next aggregated to hourly time intervals. The hourly flows at the three gauging stations were the major information for the calibration of HYDROGEIOS model.

3.3 Model schematization, parameterization and calibration

As illustrated in Fig. 5, the river network comprises the main branch of Nedontas and its two major tributaries, partially represented by the hydrometric stations of Karveliotsis and Alagonia, respectively. The study basin, which is defined upstream the hydrometric station of Kalamata, extends over 120.8 km^2 , and is divided in seven sub-basins. The latter were defined by setting a flow accumulation threshold of 10 km^2 and by introducing additional nodes to the station sites. For the delineation of soil processes we defined two HRUs corresponding to low and high permeable soils (their classification was based on detailed hydrogeological data). We did not incorporate other types of information, e.g., land use, since more than 90% of the basin is covered by similar vegetation types (i.e., forests).

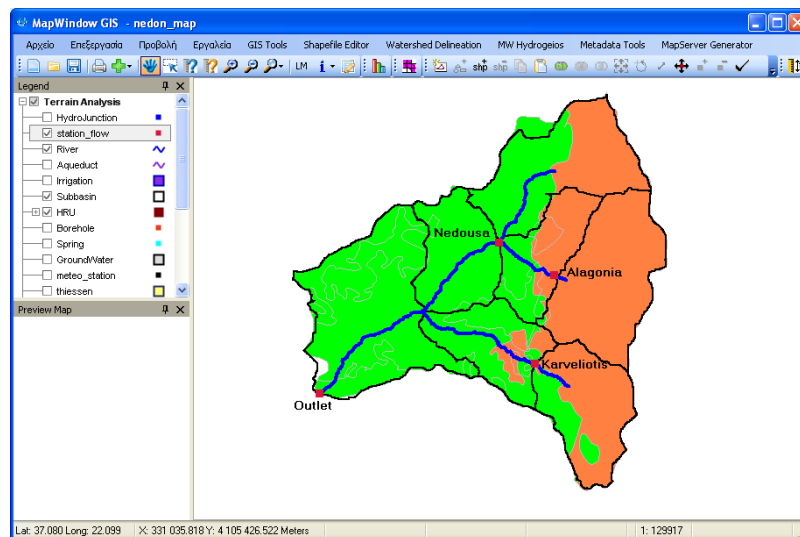


Figure 5. Characteristic layers of geographical data for Nedontas river basin (sub-basins, river network, hydrological response units, hydrometric stations) in the MapWindow environment.

In order to represent the groundwater flow field and the baseflow generation mechanisms, we introduced a conceptual groundwater cell under each sub-basin that receives the aggregated percolation from the overlaying soil partitions. We also assumed a virtual cell downstream, to represent underground leakages to the adjacent aquifer system, which in turn are conducted to the sea. Therefore, a coarse network of interconnected tanks was formulated to simulate the actual groundwater cycle. Finally, four springs were assumed, located at the corresponding flow control sites, to account for the baseflow. As already explained, a virtual cell of infinite area represents each spring.

The model parameters for hourly simulation were assigned as follows: (a) 7 parameters for the rainfall-runoff component of each HRU ($2 \times 7 = 14$ parameters); (b) one recession parameter for each sub-basin (7 parameters); (c) one conductivity parameter for each one of the actual and virtual cells (totally $7 + 1 + 4 = 12$ parameters); and (d) a single leakage coefficient, assigned to the downstream reach that accumulates the runoff losses due to infiltration. For the rest of river segments, the leakage coefficient was set to zero, while the specific yield parameter was set equal to 10% for all groundwater cells. Finally, the time lag parameter for the kinematic wave method, which is a characteristic property of the river network, was empirically estimated, on the basis of the length and slope of each individual segment.

Under the above assumptions, there are 34 unknown control variables to be calibrated against the time series of observed discharge, at Karveliotis, Alagonia and the basin outlet, which cover a period from five to seven months of continuous flow (from the mid-December 2011 to July 2012). In this vein, we formulated a multicriteria performance measure, in which we aggregated the three efficiency measures (usually referred to as Nash-Sutcliffe efficiency is the typical goodness-of-fit criterion in hydrological calibrations). Simulation starts at 1/9/2011, thus before the beginning of the wet season, which allows for assuming negligible initial soil moisture.

Although the observed hydrographs provide enough information for optimizing the parameters that affect the surface runoff processes, in the absence of groundwater-related measurements there remains significant uncertainty with respect to the groundwater parameters. In order to ensure at least a realistic representation of the model state variables, by means of seasonal fluctuation of tank storages and spring flows, we also set a penalty term that prohibits generating unreasonable trends and other abnormal patterns in the simulated time series.

The optimization of model parameters against the performance measure was carried out through a hybrid strategy that combines human experience and optimization tools. This strategy ensured a good fitting of the modelled to the observed data, as indicated from the efficiency values that are achieved in the three control nodes (Alagonia: 0.77; Karveliotis: 0.59; Nedontas outlet: 0.95). In Fig. 6 are compared the observed and simulated hydrographs in two of three stations (Alagonia and basin outlet). The model represents with high accuracy the flow regime at the basin outlet, which is the focus of the modelling study. In particular, it reproduces almost perfectly the three major flood events of 2012. On the other hand, in the two upstream sub-basins, the predictive capacity of the model is less satisfactory, mainly because there is much more uncertainty in the derivation of the rating curves in the specific stations. We expect that in due course we will establish more consistent stage-discharge relationships on the basis of direct flow measurements. Moreover, we are planning to use recent data in order to extend the flow time series, thus increasing the calibration period.

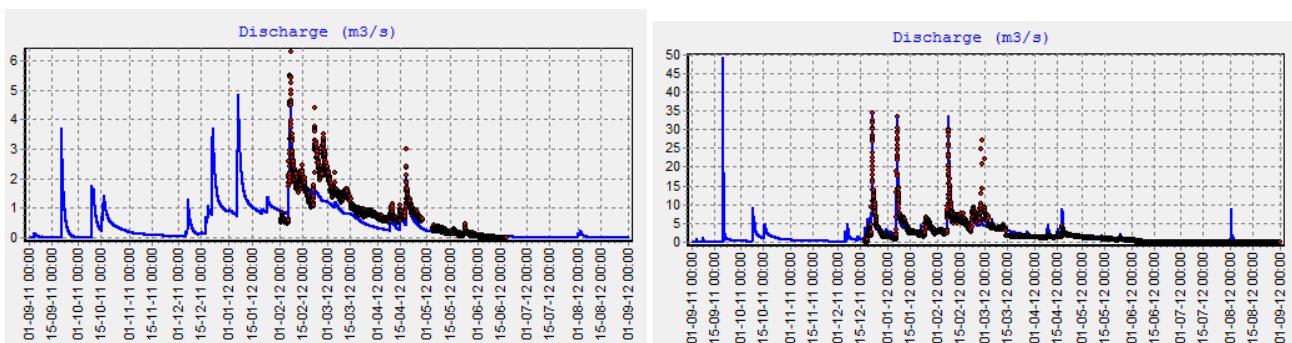


Figure 6. Simulated vs. observed hourly flow data at the stations of Alagonia (left) and the outlet of Nedontas basin (right).

4. SUMMARY AND CONCLUSIONS

We have presented a telemetry-based automatic hydro-meteorological monitoring network and its open-source software support tools (a web-based application for storing, visualizing and managing geographical and hydro-meteorological data, a tool for data analysis and processing and an advanced model for flood simulation), and have demonstrated its use in a sample study case. The databases of this already operational system are being continuously enriched with data and its capabilities are currently being enhanced.

Around HYDROGEIOS, additional modeling components are under development, in particular a stochastic rainfall generator, a hydraulic simulation tool and a numerical weather prediction tools. The integrated system will be used for both physically and statistically consistent evaluation of flood risk, through stochastic simulation (i.e. by running the hydrological model with synthetic rainfall time series), as well as for real-time flood forecasting, where the model is fed with ensembles of short-term rainfall predictions. In this context, the monitoring network plays a key role, since both approaches require reliable hydro-meteorological data; especially the forecasting approach requires data in near real-time and the co-operation of all components, from the measuring instruments to the models themselves, under a common information platform.

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