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Ungauged drainage basins: Investigation on the basin of Peneios River, Thessaly, Greece

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Abstract: The effect on flow prediction accuracy of the lack of streamflow data is investigated. For this a testing framework is set up which involves three stages. In the first stage a deterministic physics-based distributed rainfall-runoff model is calibrated. The selection of this model category is dictated by the will to minimise the number of parameters that need calibration. These parameters are the "sensitive parameters" which primarily affect simulated flows. All other parameters are set to their default values or values based on hydrologic experience. The Nash-Sutcliffe Efficiency (NSE) is selected as the metric of model performance. In the second stage the basin is considered as ungauged and sensitive parameters are synthetically generated using the uniform distribution. Thus a frequency distribution of NSE is obtained. The third stage involves the comparison of simulated flows obtained in the first two stages of analysis. The Precipitation-Runoff Modelling System, version IV (PRMS-IV) is selected as the simulator of hydrological processes. The system subdivides the basin into Hydrological Response Units (HRUs). The test basin was the Peneios river basin at the gauging station of Sarakina. This is located in the Thessaly Water District, central Greece and has an area of 1076 km^2. Results indicated that the sensitive parameters of the model are seven in number. Upper extreme values of the distribution of NSE in the case with the ungauged basin were found to be close to values of the calibrated model, whereas the mean NSE was lower by 34%.

Key words: Ungauged basins; Precipitation-Runoff Modelling System (PRMS); Hydrological Response Units; Peneios river

1. INTRODUCTION

Very often hydrologists are faced with ungauged basins in the sense that no streamflow records are available in them. As a result, modelling of hydrological processes in these basins becomes problematic. In response to the challenge regarding flow prediction in ungauged basins the International Association of Hydrological Sciences (IAHS) launched the international initiative known as "Predictions in Ungauged Basins" or PUB (Hrachowitz et al., 2013). The initiative covered the decade 2003-2012 and it was aimed at formulating and executing scientific programs that would achieve progress in predictions in ungauged basins. It was recognised that this requires changing the traditional paradigm that involves empiricism and model calibration into a new paradigm that focuses on extending the theoretical knowledge regarding the hydrological processes of the studied system. The change of paradigm would allow the improvement of existing models as well as the development of new models that effectively account for the variability of hydrological processes in both time and space. In the new paradigm, hydrology is the main scientific domain having interfaces with geology, topography, ecology and climatology. The accomplishments of PUB are related to the heterogeneity of data and processes, models and the associated uncertainty, basin classification and new hydrological theory. Within the general framework for hydrological modelling as this was set by the PUB Initiative, a modelling experiment is carried out with the aim to objectively respond to the question "What is the expected reduction of model performance if a basin is considered as ungauged?". The methodology towards this aim is outlined in section 2. The effort is focused on a gauged basin presented in section 3. Section 4 is devoted to results, while some conclusions are included in section 5.

2. METHODOLOGY

2.1 General

Starting from the general goal of this work, it is natural to limit our scope to conceptual and physics-based models, since these are generally assumed to represent physical processes through their structure and parameterisation. This fact created the general belief that, in order to achieve a certain level of predictive power, such models require less information on basin response than empirical models do. Also, our scope is limited to the daily time step. The selected model that fulfils the above requirements is briefly described in sub-section 2.2, while its calibration is discussed in sub-section 2.3. The full setting of our modelling experiment is outlined in sub-section 2.4.

2.2 The rainfall-runoff model

In this work we use the well-known Precipitation Runoff Modelling System (PRMS) (Leavesley et al., 1983) developed and maintained by U.S. Geological Survey (USGS). PRMS is classified as a distributed model which, in addition, is physics-based. It divides the study basin into a number of Hydrological Response Units (HRUs) as done in other models such as HYDROGEIOS (Efstratiadis et al., 2008) and the Soil Water Assessment Tool (SWAT (Arnold et al., 1999). Hydrological processes in each one of the HRUs are considered homogeneous and are simulated using physical laws or empirical relationships (Markstrom et al., 2015). Water is moving between storage elements representing various forms of water storage. The outputs from these elements contribute to the total basin flow. Precipitation (rainfall or snowfall) that is not intercepted by vegetation reaches the soil zone or the impervious zone. Surface, sub-surface and groundwater flows contribute to the total basin flow. The model employs five types of spatial units, i.e., the basin as a whole, river segments, HRUs, lakes and sub-basins. PRMS uses 17 “processes” that correspond to physical processes or to procedures for data management. The processes are the following: (1) Basin Definition; (2) Cascading Flow Process; (3) Solar Table Process; (4) Time Series Data; (5) Temperature Distribution; (6) Precipitation Distribution; (7) Combined Climate Distribution; (8) Solar Radiation Distribution; (9) Transpiration Period; (10) Potential Evapotranspiration; (11) Canopy Interception; (12) Snow; (13) Surface Runoff; (14) Soil-Zone; (15) Groundwater; (16) Streamflow; (17) Summary. These processes are implemented using 36 modules.

2.3 Model calibration

Model calibration is performed manually through a series of repeated simulations. The simulated daily streamflows obtained on output are aggregated into monthly streamflows which are then compared to observed monthly streamflows. The well-known Nash-Sutcliffe Efficiency (NSE) metric is used for the evaluation of model performance. This is expressed as

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{N}\left(Q_t - \mathrm{QS}_t\right)^2}{\sum_{t=1}^{N}\left(Q_t - \overline{Q}\right)^2} \tag{1}$$

where Q_t is the observed streamflow in month t with mean equal to $\overline{Q}$, QS_t is the simulated streamflow, and N is the number of observations.

2.4 The modelling experiment

A framework for a modelling experiment is set up which is comprised of the following steps: (1) In a preliminary stage, the PRMS model is run with the purpose to identify model parameters which exert a significant influence on simulated streamflows; these are called the 'sensitive' parameters, whereas the remaining parameters are the 'insensitive' parameters and are henceforth set to their default values; (2) the model is calibrated and validated using the NSE criterion of equation 1 applied on hydrological data from the basin selected for study; up to now the basin is considered as gauged; (3) the sensitive parameters are considered as unknown quantities that are modelled as random variables following the uniform distribution within the parameter intervals given by Markstrom et al. (2015); (4) a set of N combinations of sensitive parameters is randomly generated using Monte Carlo simulation; (5) by setting the insensitive parameters equal to their default values as proposed by Markstrom et al. (2015), N different full parameter sets are formed; this approach is inspired from the well-known GLUE method (Beven and Binley, 1992) and has been used also in uncertainty analysis (e.g., Nalbantis and Lymperopoulos, 2012); (6) the model is run N times, each one corresponding to one of the above N parameter sets; (7) NSE is computed for each model run, which results in a sample of N NSEs; (8) statistics of the latter are compared to the NSE value of step 2 (in validation). Evidently, in steps 3 through 6 the study basin is considered as ungauged.

3. STUDY BASIN AND DATA

3.1 The study basin

The Peneios river basin is the main river basin of the Thessaly Water District in central Greece. It covers an area of 9448 km^2 out of 13153 km^2 of the district as a whole. In this work we have chosen a headwater sub-basin of the Peneios river with its outlet at the Sarakina hydrometric station. The test basin is located in the North-western part of the entire Peneios basin. Its hypsometry and hydrographic network are shown in Fig. 1.

The Peneios river basin at Sarakina has a surface area of 1076.1 km^2 and mean ground elevation equal to 823.1 m. Its minimum, maximum and median ground elevation is 171.90 m, 2169.01 m and 785.00 m respectively.

3.2 Data used

Daily precipitation depths were collected for seven raingauges within and in the vicinity of the basin. These were provided by the National Bank for Meteorological and Hydrological Information, (Hydroscope) maintained by the Special Secretariat for Water, Ministry of Environment and Climate Change of Greece. Data were processed so as to remove statistical inhomogeneity and gaps (Gourgoulios, 2016). Daily maximum and minimum air temperatures were used for the assessment of potential evapotranspiration using the Hargreaves method (Hargreaves and Samani, 1985) and data from the station Megali Kerasia. Monthly streamflows for the period from January 1959 to February 1985 were employed which have been obtained from raw data of the Sarakina hydrometric station (Nalbantis and Koutsoyiannis, 1997). The Digital Elevation Model (DEM) of the study area was provided by the National Cadastre and Mapping Agency of Greece at the resolution of 5 m. The basin DEM allowed obtaining the spatial distribution of ground elevation (Fig, 1) and ground slope (Fig. 2). Land cover data was obtained from the EU project known as CORINE 2000. Land cover categories within the basin were found to be 19 in number, while the total number of categories in the project is 44. Categories were grouped to form the five land cover categories required by PRMS IV (Fig. 3).

The intersection of ground slope and land cover map layers provided us with the HRUs. Then all

HRUs with an area below 1.5 km^2 were attached to adjacent HRUs to obtain 199 HRUs in the final model configuration.

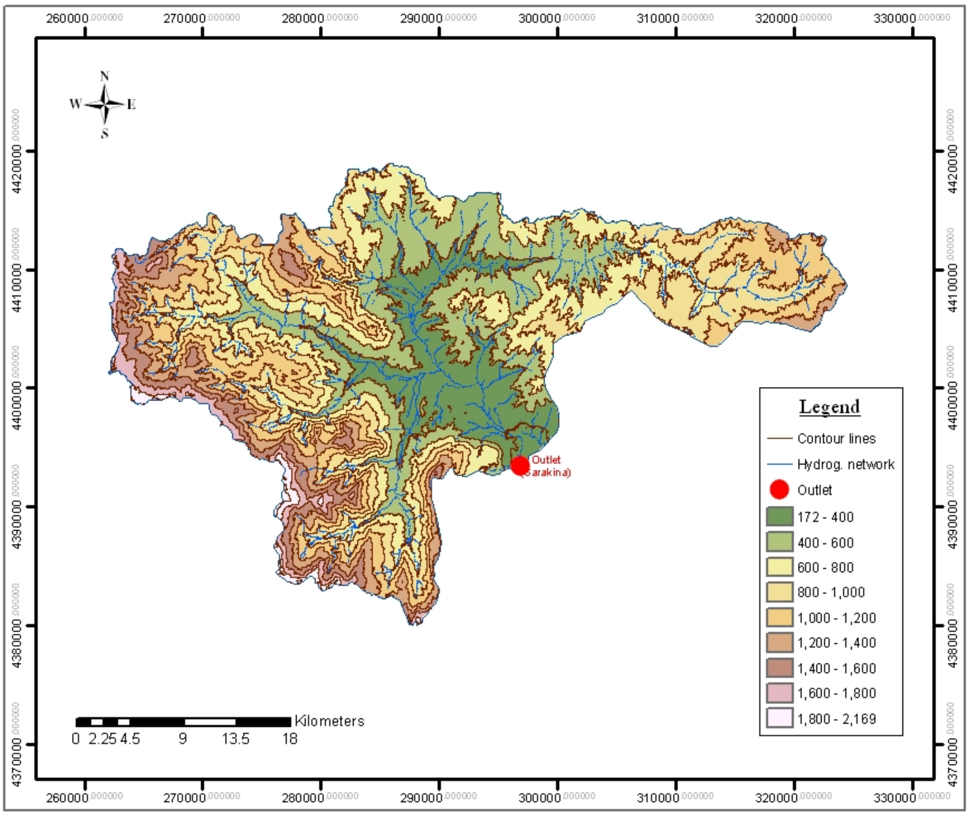

Figure 1. The Peneios river basin at Sarakina.

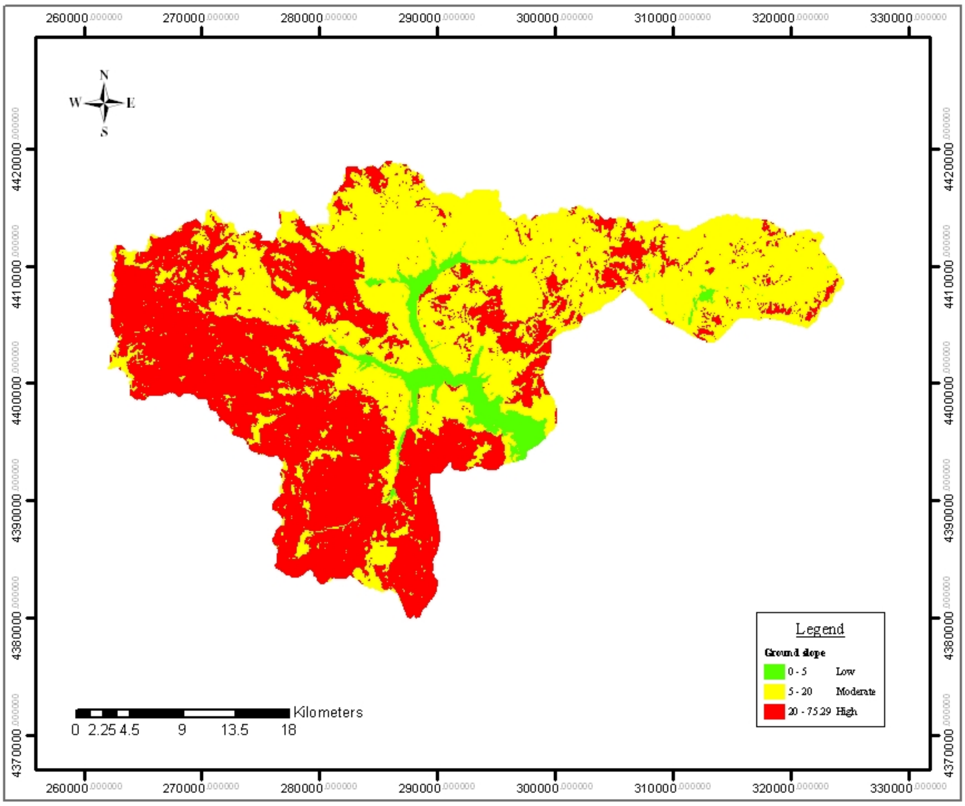

Figure 2. Ground slope in the Peneios river basin at Sarakina.

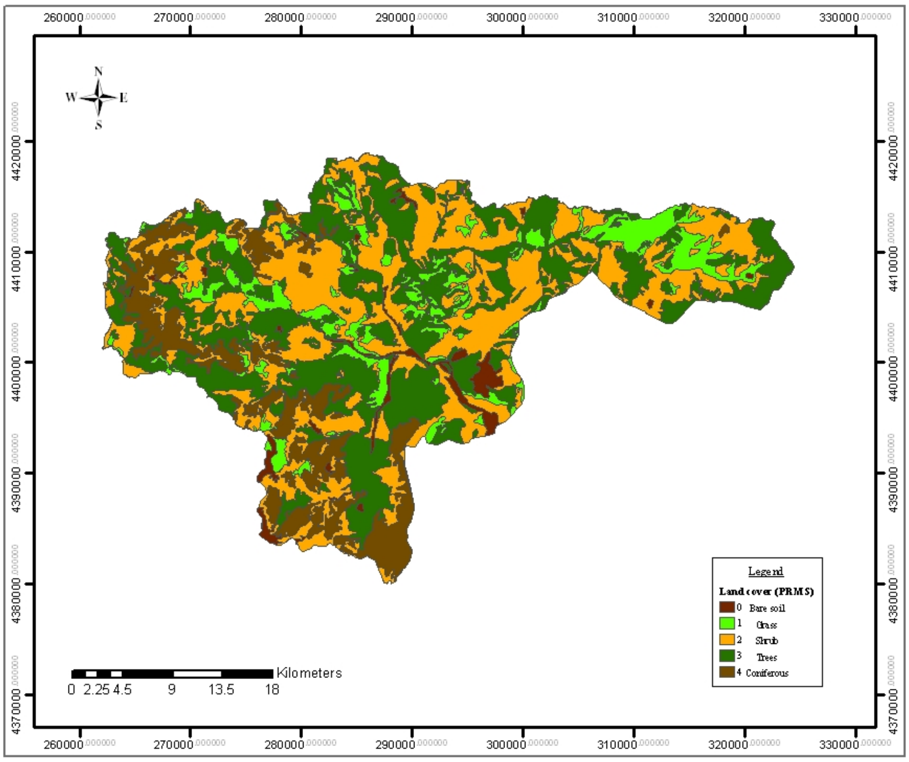

Figure 3. PRMS land cover categorisation in the Peneios river basin at Sarakina.

4. RESULTS

4.1 Case with gauged basin

Preliminary model runs showed that, for our test basin, only seven out of the 41 model parameters can be classified as sensitive (step 1 of modelling experiment). These are hs_krs, smidx_coef, smidx_exp, soil_moist_max, soil_rechr_max, soil2gw_max, and ssr2gw_rate. For detailed explanation of parameters the reader is asked to refer to Markstrom et al. (2015).

In step 2 of sub-section 2.4, the model is calibrated using daily series of observed precipitation and air temperature for the period from October 1973 to September 1980, i.e., seven hydrological years. Also, the hydrological year 1972-73 is used as a warm-up period. The methodology described in sub-section 2.3 is followed, which gave NSE = 0.553. Model validation is performed on data from the period from October 1980 to September 1985, while NSE was found equal to 0.531, a value which is close to that of the calibration. This indicates some level of model robustness, although the model performance can be characterised as low. The simulated and observed streamflows are depicted in Fig. 4.

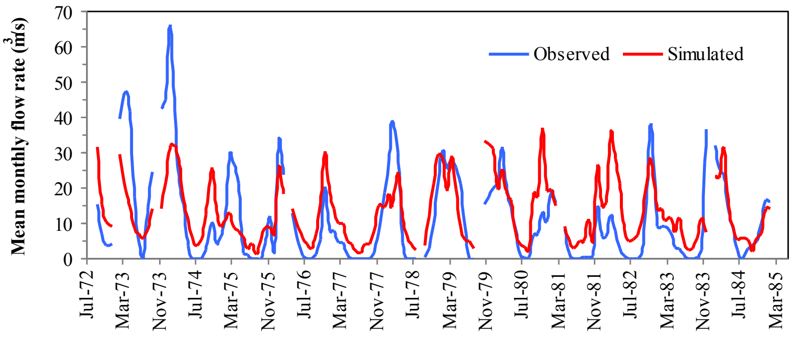

Figure 4. Observed and simulated monthly streamflows in the Peneios river basin at Sarakina

4.2 Case with ungauged basin

Steps 3 through 7 of the modelling experiment of sub-section 2.4 are executed using a number of sensitive parameter sets equal to 100. Statistics of NSEs for the generated parameter sets are given in Table 1. As seen in this table, the bulk of NSE quantiles is well below the value of NSE obtained in validation (step 2), whose probability of non-exceedance is between 0.95 and 0.975.

Table 1. Quantiles of NSE in the case with ungauged basin

Probability of non-exceedance	NSE quantile	Difference from NSE in validation (%)
0.025	0.201	-62.2
0.05	0.275	-48.2
0.1	0.305	-42.6
0.25	0.324	-39.0
0.5	0.364	-31.5
0.75	0.411	-22.6
0.9	0.462	-12.9
0.95	0.501	-5.7
0.975	0.579	9.0

5. CONCLUSIONS

In this work a simple approach was followed with the purpose to objectively assess the possible loss in performance of a rainfall-runoff model in the case that the model is applied to an ungauged basin. Our investigations revealed the following:

1. Since, in ungauged basins, the model structure should faithfully represent hydrological processes, a complex model of the conceptual type was necessarily chosen, which was PRMS.
2. To simplify the treatment of model parameters in the case with an ungauged basin, the parameter set was partitioned into sensitive and non-sensitive parameters based on their influence on simulated runoff. Then, stochastic simulation was applied only to the sensitive parameters; these were found to be seven in number out of a total of 41.
3. Although the model efficiency in the case with a gauged basin (in validation) was rather poor, this efficiency is expected to be highly improbable (within the upper 5% of the model efficiency distribution).
4. If, in the case of an ungauged basin, multiple model runs are performed, the median value of model efficiency is expected to be lower than the efficiency of the calibrated model (case with gauged basin) by about 34%.
5. It is therefore confirmed that extra information is required to reduce the above-mentioned loss of model efficiency before attempting to exploit runoff predictions of an uncalibrated model of the type tested in this work.

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