ACCURACY OF RUNOFF TIMING IN SIMULATIONS WITH THE HYDROLOGIC MODELS

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Summary: *Hydrological models are developed to simulate the catchment response from the meteorological data and have numerous practical applications. The hydrologic models are also frequently applied in the assessment of the climate change impacts to provide hydrologic simulations with projections of climate variables under some specified climate change scenario. To obtain reliable projections, robust hydrologic models are required. Model efficiency is usually quantified in terms of the performance measures or hydrologic signatures such as mean flows, flow duration curve or seasonal runoff distribution. The timing of runoff is rarely considered as a signature although it is of crucial importance when assessing the effects of climate change such as the earlier occurrence of floods. In this paper, we evaluate the performance of the hydrologic model for the Toplica River basin in reproducing different signatures including the runoff timing. The results show good model performance, which is, however, not supported by the agreement of the observed and simulated runoff timing indicators. We therefore strongly suggest enclosure of these timing indicators in a model evaluation procedure, especially for the models intended for assessment of climate change impacts.*

Keywords: *flow seasonality, flood timing, hydrological modelling, hydrologic signatures, model evaluation*

1 INTRODUCTION

Rainfall-runoff modelling is the basis for many water resources engineering and management projects. It has to be applied in cases when the design flows cannot be deduced from the available hydrologic measurements, either because the flows are needed at an ungauged site or because the effects of some future measures or scenarios have to be assessed. Such is also the case of the assessments of the climate change effects on the hydrologic regimes and water management. These assessments are usually made by running the hydrologic models with the input consisting of the projections of climate variables under some specified climate change scenario.

Before running a hydrologic model with the hypothesized climatic input, the model has to be calibrated to provide a plausible representation of the rainfall-runoff processes in

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the catchment under certain conditions. Usually, the model is calibrated against a set of the observed data and validated on a separate set of the observed data [1]. However, the models are simplified representations of the catchment processes, so the simulated runoff is subject to uncertainties. These uncertainties stem from different simplifications of processes taken into account, their spatial and temporal discretisation and the methods applied to describe these processes.

Performance of the hydrologic models can be assessed in different ways and is always driven by the model purpose [2]. For example, if the model is built to provide design flows needed for sizing flood control structures, then the peak flows are of the main interest and the model is primarily expected to reproduce peak flows, while other flood hydrograph features are not reproduced accurately. Models intended for continuous simulations are usually expected to reproduce properly the entire observed hydrograph.

In addition to the frequently used goodness-of-fit measures, model performance is assessed by means of hydrological signatures, which represent characteristics of a catchment hydrologic behaviour [3]. Commonly considered signatures include flow statistics such as the mean value, the coefficient of variation and flow percentiles, autocorrelation of flows (usually one-day autocorrelation) and baseflow index. Signatures related to flood duration curves (FDCs) are also frequently analysed. These are computed from three FDC segments: namely, the high-flow (0-0.05 probability of exceedance), mid-flow (0.2-0.7) and low-flow (0.7-1). The goodness-of-fit measures are computed from the differences between the observed and simulated flow series, and they reflect accuracy in reproducing entire observed flow series. On the other hand, hydrological signatures provide additional information regarding model performance; specifically, they can indicate model components that do or do not perform well. For example, performance in reproducing mid- and high-flow FDC segment is generally conditioned on the accuracy in simulating soil water content, and performance in the low-flow FDC segment, along with the baseflow index, depends on the accuracy of the baseflow simulations [4]. Hydrological signatures that suggest accuracy in reproducing runoff volume are runoff ratio are the mean and median flows, while the accuracy in flow dynamics is quantified in terms of variance (e.g. coefficient of variation), FDC slopes and streamflow series autocorrelation [5]. Performance in extreme flows is usually assessed by means of flow percentiles, while duration and frequency of these events are represented by duration or number of days with flows above/below a certain threshold [5]. Generally, several signatures have to be analysed jointly to obtain reasonable results [6]. However, the signatures have to be selected carefully since more signatures can indicate the same runoff characteristic, which would bring redundancy in the results [7].

For catchments with pronounced seasonality, the signatures can be calculated over different seasons [8]. Accuracy in reproducing flow seasonality is usually assessed by comparing mean monthly flows over the entire simulation period. By considering mean monthly flows, variation in model performance from one year to another is disregarded. However, good model performance in this regard is crucial for numerous applications. For example, the climate change impact studies require that the model has a good representation of the timing of runoff in addition to commonly considered hydrologic signatures. This is especially important if the climate change effects on the earlier occurrence of floods need to be assessed. In this paper, we propose several timing indicators to expose model performance in terms of runoff timing. These indicators are calculated from simulated flows series by the 3DNet-Catch hydrologic model developed for the Toplica catchment. The goal of the study is to examine the sensitivity of the model performance in terms of runoff timing to different model calibration strategies.

The paper is organised as follows. Section 2 describes the Toplica catchment and available data, the 3DNet-Catch hydrologic model, the modelling setup and the calibration strategies, and the runoff timing indicators. The results are presented and discussed in Section 3, while Section 4 concludes the paper.

2 METHODOLOGY

2.1 Catchment and Data

The Toplica River is a 136 km long tributary of the Južna Morava River (Figure 1). The Toplica catchment upstream of the Doljevac stream gauge covers an area of 2,052 km^2 and ranges in elevation between 190 and 2,017 m a.s.l., with the mean elevation of 621.8 m a.s.l. The catchment is mainly covered with deciduous forest with about 1% of the urbanised areas. Smonitza and acid, brown and podzolic soils prevail in the catchment. The Toplica River exhibits distinct seasonality with high flows in early springs due to combined rainfall and snowmelt, while low flows occur in late summers and early autumns. The largest flood events at Doljevac were observed in the late 1950s and early 1960s, with the maximum flow of 538 m^3/s observed in 1955. There are no statistically significant trends in mean annual flows or annual maxima at Doljevac.

Table 1 shows the hydrologic and meteorological data available for the modelling. The hydrologic simulations are conducted with precipitation and temperature observations at four meteorological stations, three of which are situated at low altitudes. Given the large gap in the precipitation observations at Kopaonik, the period from 1980 to 2013 is only considered in this paper. Mean flow at Doljevac during the considered period is 8.8 m^3/s. Mean annual precipitation in the catchment in the same period is 646 mm.

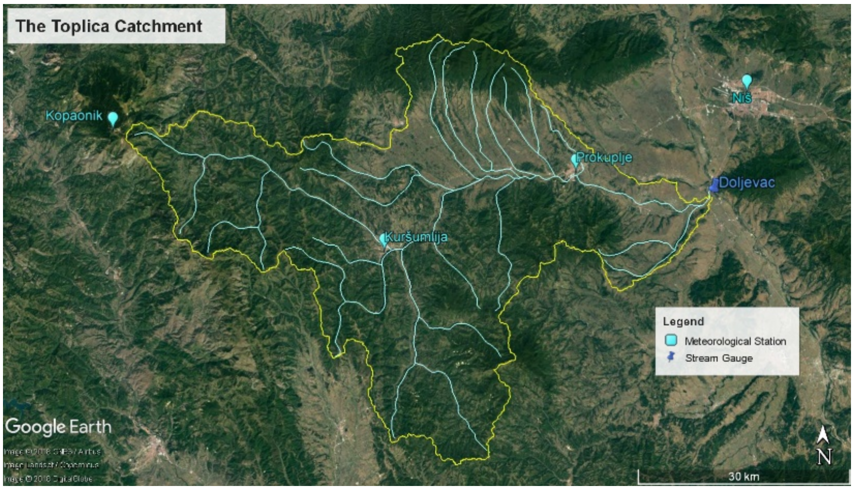

Figure 1. The Toplica River catchment.

Table 1. The stream gauge and the meteorological stations in the Toplica catchment.

Observed variable	Station	Elevation (m a.s.l.)	Latitude / Longitude	Available record
Q	Doljevac	190.41*	43º 11’ / 21º 49’	1950-2013
P, T	Kopaonik	1711	43º 17’ / 20º 48’	1967-1974, 1980-2013
P, T	Kuršumlija	383	43º 08’ / 21º 16’	1961-2013
P, T	Prokuplje	266	43º 14’ / 21º 36’	1951-2013
P, T	Niš	204	43º 20’ / 21º 54’	1947-2013

* Zero datum of the staff gauge.

2.2 The 3DNet-Catch Hydrological Model

The 3DNet-Catch hydrologic model is used for runoff simulations. The model comprises three routines intended for runoff volume simulations, and runoff and channel routing routines [9]. Runoff volume is simulated with the interception, snow and soil routine. Rainfall interception by canopy is simulated by applying a simple bucket method. Precipitation at air temperatures below the rainfall-snowfall discrimination one is considered as snow. Total snowfall is added to a snowpack. The snowpack balance also includes sublimation and snowmelt, which is computed with a simple degree-day method. The soil routine represents a key model feature. The soil is represented in the model by a surface soil layer and several subsurface ones, all of which may have different properties such as thickness or porosity. Surface runoff is initially estimated by the SCS method, but it can be augmented by excess water in the subsurface layer(s). Percolation from a layer is computed with an equation that is obtained by combining the water balance and nonlinear outflow equations, with the Brooks-Corey [10] relation for unsaturated hydraulic conductivity. Water evaporates from bare soil, while transpiration occurs in the subsurface soil layer(s). Capillary rise is not simulated. Surface runoff is routed through a linear reservoir resulting in direct runoff. Percolation for the soil column is routed through a nonlinear groundwater reservoir with a threshold. Water volume below the threshold is routed by applying a nonlinear outflow equation, while the excess volume of water is routed through a single linear reservoir. The former yields baseflow and the latter results in fast groundwater response. The model setup varies from lumped to fully-distributed. Spatially distributed model setups also include channel routing, which is based on the linear reservoir method.

In this paper, a semi-lumped setup is applied, in which the Toplica catchment is represented by ten 100 m-wide elevation zones. The parameters are common to all zones, but mean catchment precipitation and temperature are adjusted for each zone to account for the change in elevation. Potential evapotranspiration is computed with the Hargreaves method [11].

2.3 The Modelling Setup

The 3DNet-Catch model of the Toplica River catchment is calibrated using three objective functions over two calibration periods. To obtain the best possible fit to high flows, three objective functions that put emphasis to this flow segment are used [12]: Nash-Sutcliffe efficiency *NSE* [13], Kling-Gupta efficiency *KGE* [14] and root-meansquare error *RMSE*. The model is calibrated (1) over the full available record period (1981-2013), and (2) during the 15-year long period that encompasses highest flows in the available record, i.e. the wet period (1996-2011). Calibrating the model over the wet period aims at obtaining the model that accurately reproduces high flows. The model calibration is based on optimisation of the parameter values according to chosen objective function. Each calibration starts with a sampling of one thousand parameter sets from the uniform distribution over the selected parameter ranges by applying the Latin Hypercube sampling procedure. The parameter sets are optimised by applying the AMALGAM-SO optimisation suite [15]. The best performing parameter set is selected from the optimised parameter population and retained for further analyses. In this way, an ensemble of six simulated flow series is obtained for three objective functions and two periods. All simulations are carried out with daily time step and over water years, with one year for the model spin-up.

2.4 Indicators of Runoff Timing

The studies aimed at detecting a change in runoff timing typically use the date of the occurrence of a fixed percentage of annual runoff volume (ARV) as timing indicators [16] [17]. Other indicators are also possible, such as the date of the maximum annual flood, starting or ending dates of ice conditions on rivers [18] or the “pulse day” [19], which is considered to be the date of spring onset. The pulse day is defined as the ordinal number of the day in which the negative difference between the streamflow mass curve and the average streamflow mass curve is the greatest. In this paper, we consider the following timing indicators: dates of occurrence of 5, 10, 50, 90 and 95 percent of ARV, and the pulse day.

Statistical analysis of the dates as random variables is much easier if they are treated as directional statistics. The dates as the directional statistics can be represented in polar coordinates by angles and with unit radius. The advantage of such representation is that some dates that seem far away on a linear time axis (e.g. late December and early January) appear close in polar coordinates [19]. The angular coordinate θ of the directional date statistic is defined by:

$$\theta = \frac{j}{N_{ann}} 360° \tag{1}$$

where j is the ordinal number of the day in a year according to the Julian calendar (i.e. the Julian day), and N_{ann} is the number of days in a year (365 or 366 for a leap year).

To avoid outliers in the series of dates, the directional date statistic is transformed so that a new origin is set as the date of the larger angular coordinate of two most distant dates [17]. For example, if two most distant dates are 15th May 2009 (equal to 133° in angular coordinates) and 15th November 2009 (315°), then the latter date becomes the new origin. If we denote the angular coordinate of the new origin with θ_0, then the transformed directional date series are given with:

$$\theta' = \theta - \theta_0 \tag{2}$$

Therefore, to evaluate the rainfall-runoff model performance in terms of timing, we compare the simulated and the observed transformed angular coordinates of the dates of the occurrence of 5, 10, 50, 90 and 95 percent of ARV, and the pulse day.

3 RESULTS AND DISCUSSION

The results of calibrating the 3DNet-Catch model over the full record period 1981-2013 (FRP) and wet period 1996-2011 (WP) are shown in Figure 2. The model efficiency is represented by the performance measures used for the calibration (*KGE*, *NSE*, *RMSE*) and three additional measures: coefficient of determination (R^2), volumetric efficiency (*VE*) and bias in runoff volume. The R^2 value indicates model performance in reproducing overall runoff dynamics, while the remaining two measures expose performance in reproducing the runoff volume [12].

Regardless of the calibration strategy, the model satisfactorily reproduces flow dynamics, which is supported by high values of *KGE*, *NSE* and R^2 and by low *RMSE* values. Generally, there are no significant differences in reproducing runoff dynamics among the three objective functions. However, the simulations with parameter sets obtained over FRP slightly outperform those with parameters optimised over WP. This result can be attributed to the fact that the FRP ensemble is calibrated over this period. It also suggests that the model should be exposed to various hydrologic conditions during calibration so that longer calibration periods are generally preferred.

Although bias in runoff volume is not explicitly considered in the calibration, the model accurately reproduces the observed runoff volume, particularly for FRP. The simulations with parameter sets optimised with respect to *RMSE* reproduce runoff volume better than the sets obtained with respect to *KGE* and *NSE*.

Figure 3 presents the considered percent values of ARV and their timings. The model properly reproduces the ARV percentages: correlation coefficient between the observed and simulated ARV percentages amounts to ~0.8. However, significant deviations can be noticed in some years: for example, observed ARV is considerably overestimated in 2008 and underestimated 1983 by all ensemble members. Most importantly, these discrepancies are not detected by the volume-related performance measures, which suggest high simulation accuracy in terms of runoff volume.

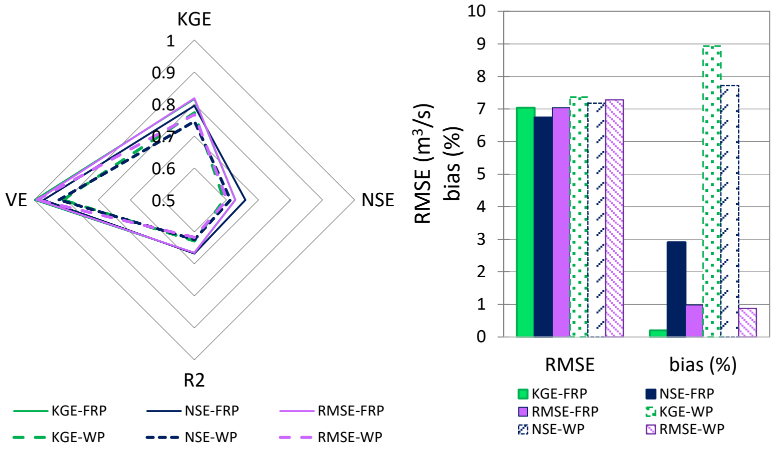

Figure 2. Performance of the 3DNet-Catch model calibrated using KGE, NSE and RMSE objective functions over the full record period (FRP) and the wet period (WP).

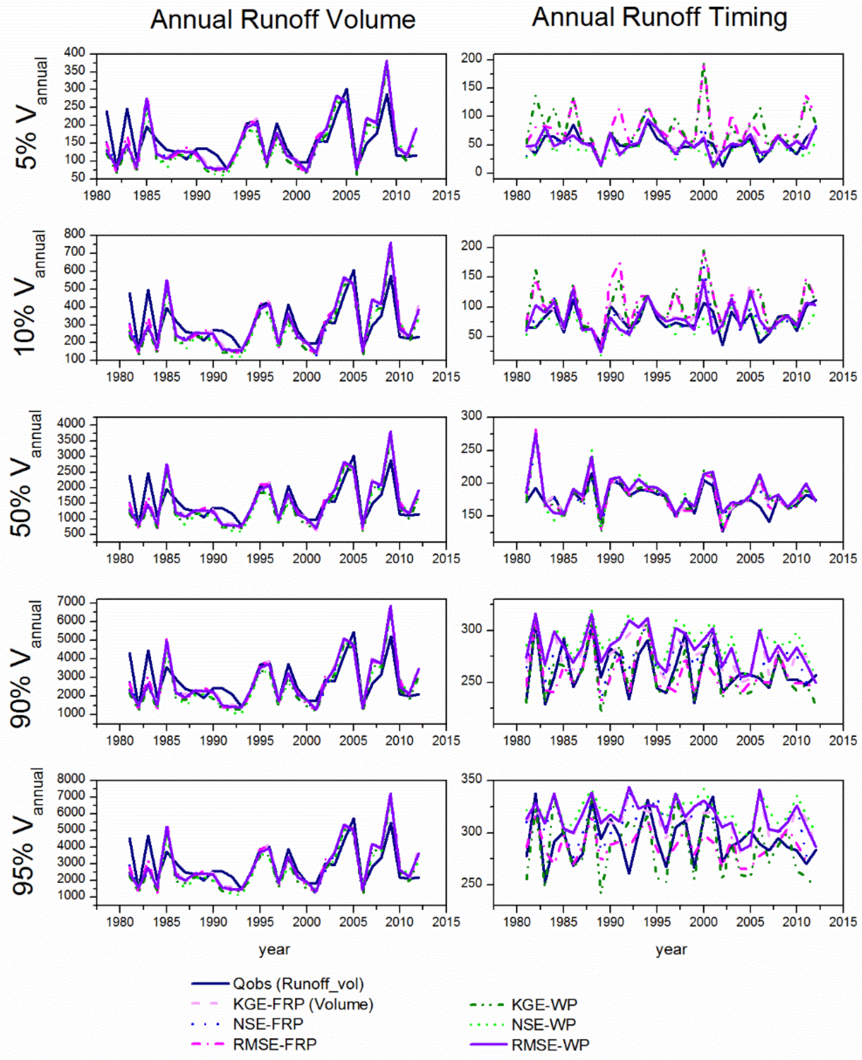

Figure 3. Percentage of annual runoff volume: the volume values and timings.

As for the timings, the model satisfactorily reproduces the timing of the 50% ARV, although pronounced discrepancies in 1982 and 2006 are apparent. Performance in timings of other considered ARV percentages is slightly lower, which is indicated by noticeable deviations from the observations. Graphs in Figure 3 show that the timings of the 5% and 10% ARV are overestimated by most ensemble members, i.e. delayed compared to the observations. Discrepancies in timings of the 90% and 95% ARV take both sings and do not follow any regular pattern. This means that simulated volume values occur earlier than the observed in some years, while are delayed in others. Although performance in terms of volume timings does not differ significantly across the ensemble, the FRP-*RMSE* simulation slightly outperforms the remaining ones.

Figure 4 complements the analysis of the timings by showing the pulse day timing of the observed and simulated flow series. These graphs generally suggest wide agreement in timings of the pulse day, although all ensemble members resulted in one or two outliers with the simulated pulse days in September (1982 and 1988). All ensemble members perform similarly in terms of the pulse day timing, so no calibration strategy is shown superior compared to the others.

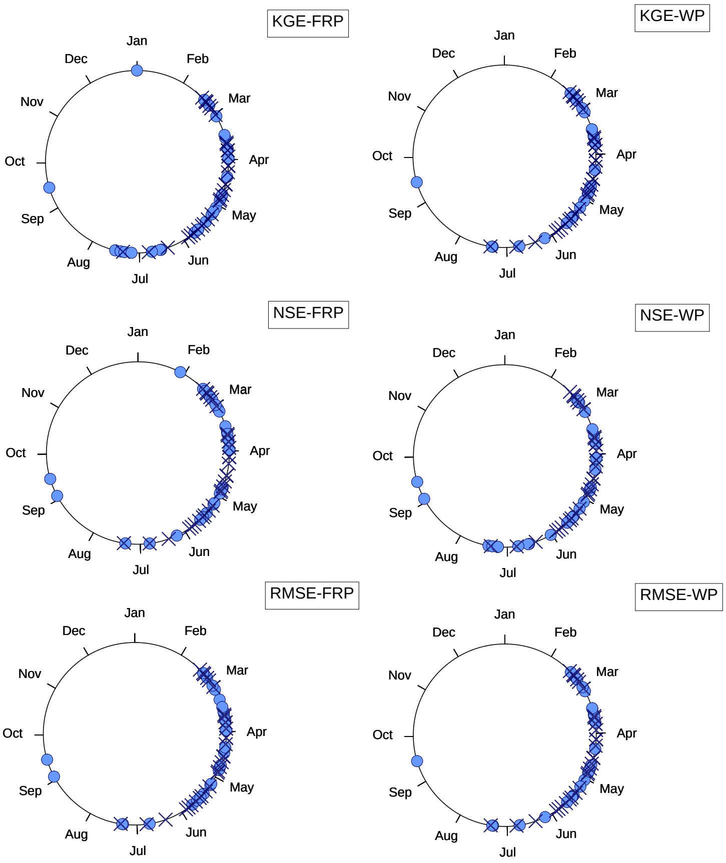

Figure 4. Timings of the pulse day. Cross marks indicate observations and circles denote simulation results.

4 CONCLUSIONS

Notwithstanding a satisfactory overall performance in reproducing runoff dynamics and high accuracy in reproducing runoff volume, the considered runoff timing indicators suggest discrepancies in timings between the observed and simulated runoff. The best performance is obtained in reproducing timings of the pulse day and 50% of the annual runoff volume. Performance in other annual runoff percent values (5%, 10%, 90% and

95%) is lower. No apparent pattern is detected in discrepancies between the timings of the observed and simulated runoff. No calibration strategy is proven superior over the other considered in terms of reproducing volume timings. These results suggest that high model efficiency, quantified in terms of commonly used performance measures, does not warrant that the runoff timing is accurately reproduced. Therefore, application of the presented timing indicators is highly recommended particularly if a model is intended for assessment of the climate change impacts. In this way, a model would be thoroughly evaluated. Further research is needed to analyse the sources of these discrepancies and to incorporate these indicators in the model calibration strategies.

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OCENA VREMENA POJAVE OTICAJA U HIDROLOŠKIM MODELIMA

Rezime: *Hidrološki modeli služe za simulacije oticaja sa slivova na osnovu meteoroloških podataka, a koriste se u mnogim inženjerskim zadacima. Oni se često koriste i za ocenu uticaja klimatskih promena tako što sprovode simulacije sa projekcijama meteoroloških veličina prema nekom scenariju promene klime. Za pouzdane hidrološke projekcije potrebni su robusni hidrološki modeli. NJihova efikasnost se obično kvantifikuje različitim pokayateljima i hidrološkim karakteristikama kao što su srednji protoci, kriva trajanja protoka ili unutargodišnja raspodela protoka. Vreme pojave oticaja se ređe razmatra kao hidrološka karakteristika iako je veoma važna u razmatranjima uticaja klimatskih promena kao što je ranija pojava velikih voda. U ovom radu se razmatra efikasnost hidrološkog modela za sliv reke Toplice u reprodukovanju nekih hidroloških karakteristika, uključujući i vreme pojave oticaja. Rezultati pokazuju da je efikasnost modela dobra, ali da slaganje simuliranih i osmotrenih indikatora vremena pojave oticaja na to ne ukazuju. Zato se preporučuje da se indikatori vremena pojave oticaja uključe u postupak evaluacije modela, posebno za modele koji su namenjeni oceni uticaja klimatskih promena.*

Ključne reči: *sezonska raspodela oticaja, vreme pojave oticaja, hidrološko modeliranje, hidrološke karakteristike, evaluacija modela.*