Journal of Hydrology 550 (2017) 399–411

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Sub-daily runoff predictions using parameters calibrated on the basis of data with a daily temporal resolution

J.E. Reynolds [a,b,c,*], S. Halldin [a,b], C.Y. Xu [a,d], J. Seibert [a,e,f], A. Kauffeldt [a]

[a] Department of Earth Sciences, Uppsala University, Uppsala, Sweden
[b] Centre for Natural Disaster Science (CNDS), Uppsala, Sweden
[c] Instituto de Geociencias, Universidad de Panamá, Panamá, Panamá
[d] Department of Geosciences, University of Oslo, Oslo, Norway
[e] Department of Physical Geography, Stockholm University, Stockholm, Sweden
[f] Department of Geography, University of Zurich, Zurich, Switzerland

ARTICLE INFO

Article history:
Received 22 July 2016
Received in revised form 26 April 2017
Accepted 8 May 2017
Available online 15 May 2017
This manuscript was handled by A. Bardossy, Editor-in-Chief, with the assistance of Vazken Andrèassian, Associate Editor

Keywords:
Rainfall-runoff modelling
Parameter transferability
Temporal resolution
Modelling time-step
Flood forecasting

ABSTRACT

Concentration times in small and medium-sized basins (~10–1000 km^2) are commonly less than 24 h. Flood-forecasting models are thus required to provide simulations at high temporal resolutions (1 h–6 h), although time-series of input and runoff data with sufficient lengths are often only available at the daily temporal resolution, especially in developing countries. This has led to study the relationships of estimated parameter values at the temporal resolutions where they are needed from the temporal resolutions where they are available. This study presents a methodology to treat empirically model-parameter dependencies on the temporal resolution of data in two small basins using a bucket-type hydrological model, HBV-light, and the generalised likelihood uncertainty estimation approach for selecting its parameters. To avoid artefacts due to the numerical resolution or numerical method of the differential equations within the model, the model was consistently run using modelling time-steps of one-hour regardless of the temporal resolution of the rainfall-runoff data. The distribution of the parameters calibrated at several temporal resolutions in the two basins did not show model-parameter dependencies on the temporal resolution of data and the direct transferability of calibrated parameter sets (e.g., daily) for runoff simulations at other temporal resolutions for which they were not calibrated (e.g., 3 h or 6 h) resulted in a moderate (if any) decrease in model performance, in terms of Nash-Sutcliffe and volume-error efficiencies. The results of this study indicate that if sub-daily forcing data can be secured, flood forecasting in basins with sub-daily concentration times may be possible with model-parameter values calibrated from long time series of daily data. Further studies using more models and basins are required to test the generality of these results.

1. Introduction

Depending on the basin size and the dominant runoff mechanisms, basin response varies from a few hours to days for mesoscale basins (cf. Fig. 2 in Blöschl and Sivapalan, 1995). In many regions, such as Central America, where floods occur frequently and basins are usually small- or medium-sized with concentration times smaller than 24 h, there is a demand for flood-forecast models at sub-daily temporal resolutions. Applications of such hydrological models rely on the availability of good and sufficiently long time series of sub-daily rainfall and discharge observations for model calibration. However, long time series at sub-daily resolutions are rare, especially in developing countries. If observational data are at all available, they are often at a daily or monthly temporal resolution.

In this paper, a distinction is made between timescale, temporal resolution and numerical resolution. Timescale refers to the time span in which hydrological processes occur, temporal resolution refers to the time interval of the forcing and calibration data, whereas numerical resolution or modelling time-step refers to the time interval used in the model to calculate model states and fluxes.

Several approaches have been proposed to bridge the gap between the daily to monthly temporal resolution of the observational data and the timescale at which fast-flow processes occur. One approach is to use parameter sets calibrated at daily or coarser

---

* Corresponding author at: Department of Earth Sciences, Uppsala University, Uppsala, Sweden.

E-mail address: eduardo.reynolds@geo.uu.se (J.E. Reynolds).

http://dx.doi.org/10.1016/j.jhydrol.2017.05.012
0022-1694/

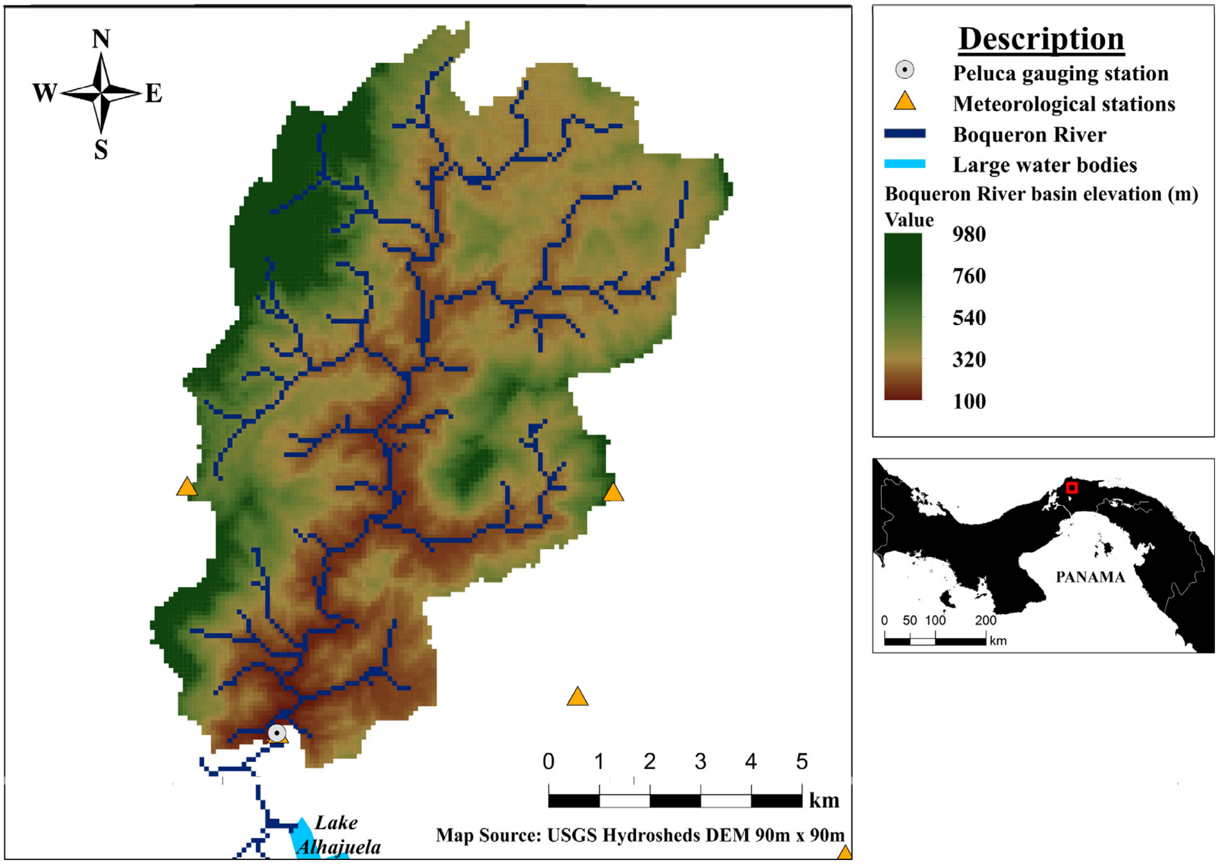


Fig. 1. Location of Boqueron River Basin at Peluca in Panama.

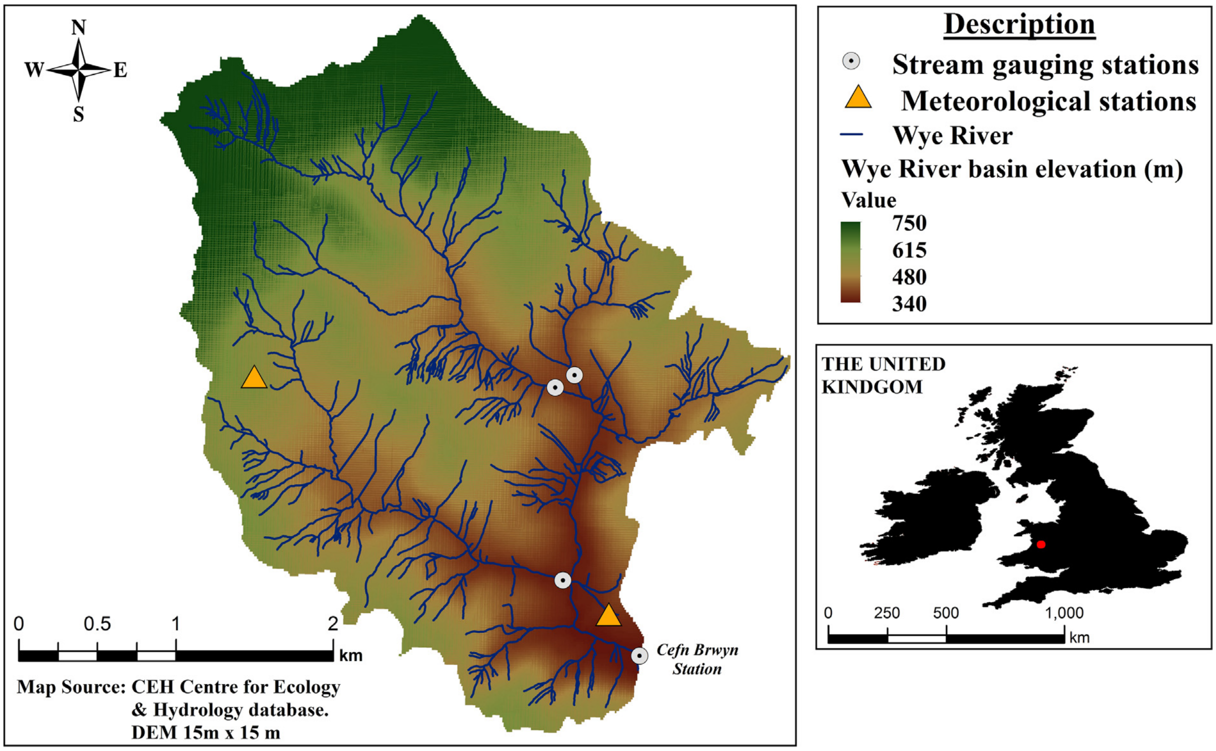


Fig. 2. Location of the Wye River Basin at Cefn Brwyn in Wales.

temporal resolutions to simulate runoff at sub-daily resolutions. This approach is applicable when a time series of sub-daily input data is or can be made available to force the model, but this method has been criticised due to inaccuracies of the parameter values calibrated at coarse temporal resolutions (Littlewood and Croke, 2008), due to poor model performance (Bastola and Murphy, 2013), or due to large runoff volume biases (Finnerty et al., 1997) when transferring parameters across temporal resolutions. In this respect, some authors state that calibrated parameters cannot be transferred across temporal or spatial resolutions without recalibration (Cullmann et al., 2006).

Parameters calibrated at different temporal resolutions have been shown to vary considerably, to be dependent on the temporal resolution of data (Bastola and Murphy, 2013; Kavetski et al., 2011; Littlewood and Croke, 2008; Littlewood, 2007; Ostrowski et al., 2010; Wang et al., 2009) and to be influenced by the rainfall intensity-duration relationship (Wang et al., 2009). For a detailed review of dependencies on the temporal resolution of data see Ostrowski et al. (2010).

Causes of these dependencies have been attributed to the loss of information of the physical processes as the temporal resolution of the rainfall-runoff data used during calibration decreases (Littlewood and Croke, 2008, 2013; Ostrowski et al., 2010). However, it is not widely understood how the temporal resolution of input or calibration data affect parameter identifiability. Ostrowski et al. (2010) argue that dependencies of hydrological parameters on the temporal resolution of data exist for any model having an infiltration-excess-overland-flow component and that these dependencies might also be caused when the temporal resolution of the calibration data changes. As the flow data are averaged over coarser temporal resolutions, there will be a loss of information on the true dominant runoff-generation processes, which will be difficult to identify during calibration and will result in parameters not well identifiable, with large uncertainties and dependent on the temporal resolution of the data.

Since the early 1980s, scaling or adjustment procedures of model parameters have been proposed to deal with dependencies on the temporal resolution of data, giving indications that model parameters may be transferred across temporal resolutions without recalibration. Ostrowski and Wolf (1984) propose three methods based on linear, non-linear and stepwise relationships between temporal resolution and effective-rainfall intensities. Other methods adjust model parameters calibrated at one temporal resolution to account for changes when using them at other temporal resolutions (Nalbantis, 1995; Finnerty et al., 1997). The approach of Nalbantis (1995) consists of adjusting certain temporal-dependent-withdrawal parameters calibrated at the daily resolution, together with the daily states at the onset of flood events, before using them for simulating 1-h runoff. In the approach of Finnerty et al. (1997), model parameters are adjusted to compensate for runoff-volume biases, but this causes a complex and not fully understood redistribution of water between various runoff components in the model.

More recently, data temporal-resolution relationships of model-parameters have been reported (Bastola and Murphy, 2013; Littlewood and Croke, 2008; Ostrowski et al., 2010; Wang et al., 2009). For instance, Wang et al. (2009) suggest that the relationship between fast-response parameters at two temporal resolutions is proportional to the square root of the quotient found from dividing the lowest temporal resolution by the highest one of the two. The study on the impact of temporal resolution of data on parameter inference by Kavetski et al. (2011) shows that false strong parameter temporal-resolution trends emerge when unreliable modelling time-stepping schemes or numerical methods, such as the explicit Euler with no error control, are implemented to solve model equations. Kavetski et al. (2011) argue that the use of robust numerical methods and heteroscedastic residual-error models stabilises and reduces the strength of model-parameter dependencies on the temporal resolution of data. They furthermore reported that parameters describing slow-flow processes are relatively constant over a range of temporal resolutions, while those describing fast-flow processes are dependent on the temporal resolution of data and converge to constant values as the temporal resolution increases or approaches the timescale of the process they represent. Similarly, Littlewood et al. (2010) and Littlewood and Croke (2008) reported that model parameters become accurate and temporal-resolution independent when the temporal resolution of the data approaches zero. However, there is still the challenge of estimating these temporal-resolution-independent parameters when data are only available at a coarse temporal resolution.

The motivation of this study was to explore the possibilities of simulating sub-daily runoff where data at these resolutions are not available for calibration. We hypothesised that temporal-resolution dependencies of the parameters of bucket-type hydrological models, which are commonly used to solve water-related problems, may be neglected when a common numerical resolution or modelling time-step is implemented. Here, a methodology is proposed to treat empirically model-parameter dependencies due to the temporal resolution of the data and due to numerical issues (e.g. modelling time-step). The investigation was carried out for two basins, one in Panama and one in the United Kingdom, using the generalised likelihood uncertainty estimation (GLUE) framework and intended to answer the following questions:

- Can temporal-resolution dependencies of the parameters of a rainfall-runoff model be neglected when the model is run at a sufficiently small modelling time-step?
- Does model performance change when parameter sets calibrated at one temporal resolution are transferred across temporal resolutions without scaling? More specifically, can peak flows be as accurately simulated using parameter sets calibrated at the daily resolution as when parameter sets calibrated at higher temporal resolutions are used?

2. Material and methods

2.1. Study sites

The climate of Central America is highly variable in time and space and the effects of this variability on water resources and natural disasters, such as floods, need to be better understood. Few hydrological studies within this region are found in literature (e.g. Westerberg et al., 2011b). This can be partly attributed to data limitations including limited measurements, poor data quality and difficulties in accessing the available hydro-meteorological data (Reynolds, 2012).

In Panama, the Panama Canal is an important contributor to the national economy with its operations and related activities generating almost 10% of the national gross domestic product (Harmon, 2005). The tropical Boqueron River basin at Peluca, located within the Panama Canal drainage area (Fig. 1), was one of the basins used in this study. The 91 km^2 basin, which drains to Lake Alajuela, has 1–3 h lag times (i.e. time difference between the peak precipitation and the peak discharge), is predominantly covered by forests, and its elevation ranges from 100 to 980 m a.s.l. (USGS, 2016). The climate is characterised by a dry (January–April) and a wet season (May–December). The 1997–2011 mean annual rainfall is 3800 mm y^{-1} and runoff 2728 mm y^{-1}.

The headwater region of the temperate Wye River basin at Cefn Brwyn, located in mid-Wales (Fig. 2), was the second basin used in this study. The 10.6 km^2 basin is one of the Plynlimon research basins operated by the Center for Ecology and Hydrology (United Kingdom), and is predominantly covered by open moorland for grazing sheep. It is a flashy basin with 1–3 h lag times. Its elevation ranges from 341 to 735 m a.s.l. (CEH, 2016) and it is characterised by rolling hills. Most of the rainfall falls in the autumn and early winter months (October–January), while the late spring and early summer months are considerably drier. The mean annual rainfall and runoff are 2490 mm y^{-1} and 2170 mm y^{-1} respectively (NERC, 2003).

The choice of basins was based on the following reasons: (1) the Boqueron River basin represents a typical basin in Central America that frequently suffers effects of floods but, which at the same time had data at a high temporal resolution adequate for this kind of study; (2) the Wye River basin has been subject of many water-resource studies, and has been previously used as an empirical illustration of model-parameter dependencies on the temporal resolution of data (Littlewood, 2007; Littlewood et al., 2010; Littlewood and Croke, 2013, 2008); (3) both basins have similar features (e.g. sub-daily lag-times, drainage areas under 100 km^2) and different seasonalities.

2.2. Model forcing and runoff data

2.2.1. Boqueron River basin data

Hourly precipitation data were available from three stations within and one station neighbouring the Boqueron River basin for the period 1997–2011. The areal precipitation was estimated by Thiessen polygons. Precipitation datasets at different temporal resolutions were generated by aggregating the hourly data to 3-, 6-, 12- and 24-hourly time series. Stage at the Peluca station has been measured continuously using a float inside a stilling well and has been stored every 15 min. The gauge is located in a non-stationary river cross-section, where stage-discharge ratings are made at least once every month for verification of the rating curve and updates are made in case of changes over time. Although discharge gauging is subject to potentially significant uncertainties at natural cross-sections (McMillan et al., 2012; Westerberg et al., 2011a), the discharge data from the Peluca station were considered to be of sufficient quality for this study. The number of discharge measurements fulfilled the recommendations by the World Meteorological Organization (WMO) to control changes in the stage-discharge relation by at least ten flow measurements per year (WMO, 2010). Discharge data ($m^3\,s^{-1}$), available at 15-min resolution for the period 1997–2011, were converted to runoff units (mm h^{-1}) and then aggregated to different time series with a temporal resolution of 1, 3, 6, 12 and 24 h. Long-term daily mean values of potential evaporation were estimated using daily pan evaporation data, available for the period 1985–2010, from the Tocumen station, located about 36 km south-east of the basin.

The rainfall-runoff data were quality controlled for possible inconsistencies before modelling. Firstly, the long-term consistency of the data was evaluated by comparing the long-term runoff coefficient ($R_{C,LT} = 72\%$) to R_C of each individual year. A variation about ± 10 percentage points was found (i.e. 62–80%). This was considered to be an indication that the rainfall-runoff data were reasonably consistent. Secondly, the hourly runoff and rainfall data were visually compared to evaluate the consistency on event scale.

During this quality control, the rainfall data were not corrected and assumed to be true since no additional information about their uncertainties was available. It was estimated that the time of concentration of the basin was 6 h, and runoff pulses with longer delays than this threshold, or with larger volumes than their precedent rainfall (within the time span of the delay threshold) were removed and set as missing values. Less than 0.56% of the flow data were removed. For those few cases, it was assumed that the areal rainfall estimates may not have correctly characterised the true rainfall inputs to the basin or that the flow data were incorrect at those time steps; however, it was not possible to determine which of the two (or both) was false. Regardless if the rainfall data were correct or not, these data were still needed to force the model. However, omitting these evident uncertainties in the data would have affected the calibration of the parameters and would have been an additional source of uncertainty in the simulations. As a practical solution to avoid the previous issues, the observed runoff data at those time steps were not taken into account when calculating model performance in the calibration and validation periods. Even if the observed runoff data were true and included to compare against the predictions during the calibration and validation periods, there was no physical or empirical model that could produce accurate runoff simulations at those time steps if the forcing data did not correctly characterise the rainfall inputs to the basin.

2.2.2. Wye River basin data

Within the Wye River basin, precipitation has been measured hourly by two meteorological stations, stage has been gauged at a 3-bay Crump profile weir and calculated discharge has been stored every 15 min. The rainfall-runoff data of the Wye River basin at Cefn Brwyn, used in this study were made available online at http://tdwg.catchment.org/datasets.html. Littlewood and Croke (2008, 2013), Littlewood (2007), Littlewood et al. (2010), who document the data, have used them for studies on data temporal-resolution dependencies. The data were at the 1-h temporal resolution, covered a 2-year period (1 Jan 1987–1 Jan 1989) and were not quality controlled for their use in this study since they were considered to have a high quality. Precipitation and runoff datasets at different temporal resolutions were generated by aggregating the hourly data to 3-, 6-, 12- and 24-hourly time series. Long-term monthly MORECS potential evaporation estimates for South Britain for the period 1961–1990, available from Kay and Davies (2008), were used as a reference for the basin but corrected for differences in altitude, based on a methodology by Finch and Hall (2001), before they were used for modelling.

2.3. Model scheme

The HBV model (Bergström, 1976; Lindström et al., 1997) is a bucket-type hydrological model that simulates river runoff through four different routines using precipitation, temperature and potential evaporation as input data. If potential evaporation data are lacking, monthly evaporation estimates based on, for instance, the Thornthwaite equation can be used. In this study, long-term daily mean values of potential evaporation were used for Boqueron, whereas long-term mean monthly values were used for the Wye. The model version used in this study was the HBV light (v4.0.0.8) from http://www.geo.uzh.ch/en/units/h2k/Services/HBV-Model.html (Seibert and Vis, 2012), with its standard model structure set up in a spatially lumped way (Fig. 3). Full details of the HBV model are given elsewhere (Bergström, 1992; Seibert and Vis, 2012) and only a brief description is given here.

The standard model structure (excluding the snow routine) has eight parameters (highlighted in **bold** in this paragraph). At every time step (t), rainfall (R) is separated into water filling the soil-moisture reservoir (S_M [mm]) and groundwater recharge based on the current water content of S_M, the maximum soil-moisture storage ($\boldsymbol{P_{FC}}$ [mm]) and a shape factor ($\boldsymbol{P_{BETA}}$ [−]). The actual evaporation (E_{act}) from the soil-moisture reservoir equals the potential evaporation (E_{pot}) when S_M is larger than $\boldsymbol{P_{FC}}$ times $\boldsymbol{P_{LP}}$ [−] and is linearly reduced for lower S_M values. Groundwater recharge (G_{RECH}) is added to the upper groundwater reservoir (S_{UZ}) and an amount of up to $\boldsymbol{P_{PERC}}$ [mm T^{-1}] (T denotes the modelling time-step being used) percolates to the lower groundwater reservoir (S_{LZ}). Runoff from S_{UZ} (Q_1) is computed by a non-linear function

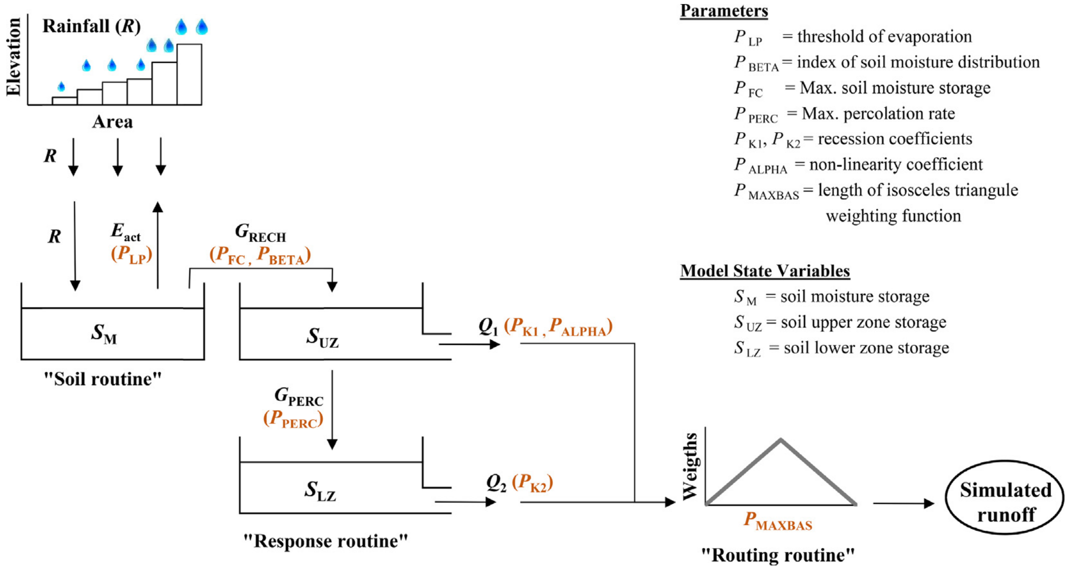


Fig. 3. Standard model structure of the HBV-model. Modified from Seibert and Vis (2012).

defined by the outflow coefficient $\boldsymbol{P_{K1}}$ $[T^{-1}]$ and the exponent $\boldsymbol{P_{ALPHA}}$ [−]. Runoff from S_{LZ} (Q_2) is computed as a linear function of the storage and the outflow coefficient $\boldsymbol{P_{K2}}$ $[T^{-1}]$. Conceptually, Q_1 and Q_2 represent the dominant fast and slow processes at the basin scale respectively. Finally, the total simulated runoff at one time step (the sum of Q_1 and Q_2) is routed on the following time steps by an isosceles triangular weighting function defined by $\boldsymbol{P_{MAXBAS}}$ [T] representing stream network routing. A list of equations for the standard model structure of the version HBV light can be found in Appendix A.

The choice of the HBV model was based on the following: (1) it requires only precipitation and a long-term estimate of potential evaporation as input, which were available in the two studied basins; (2) the model is well known and has been well tested globally, with good results in general for many applications with different physiographic and climatological conditions, e.g., for estimation of design floods (Harlin and Kung, 1992; Zeng et al., 2016), for flash-flood forecasting (Grillakis et al., 2010; Kobold and Brilly, 2006; Wöhling et al., 2006), for climate-change studies (Bergström, 1992; Hailegeorgis and Alfredsen, 2015) and for regionalisation studies (Seibert, 1999); and (3) the model fulfils the requirement of the study objective (i.e. it represents many bucket-type hydrological models used for water-resource planning, operational forecasting and hydrological research).

2.4. Numerical method

In the HBV-light version, the non-linear differential equation for estimating the groundwater recharge (Eq. (A1)) is solved numerically by adding the inputs to the soil-moisture reservoir in increments of 1 mm. Actual evaporation is computed based on the average value of S_M at the beginning and end of each modelling time-step. The input to S_{UZ} (groundwater recharge, G_{RECH}) and S_{LZ} (groundwater percolation, G_{PERC}) are added to the reservoirs first before the outflows of them (Q_1 and Q_2) are computed using the explicit Euler method at a given modelling time-step.

Explicit Euler and operator-splitting schemes are attractive because of algorithmic simplicity and computational speed. However, these simple methods can be numerically unstable and can return unreliable numerical solutions when used with an inadequate modelling time-step (e.g. daily and monthly) (Kavetski and Clark, 2011). These schemes are however expected to return numerical solutions approximate to the true or exact solution when the modelling time-step is sufficiently small.

In this study, to avoid results being affected by numerical artefacts or large numerical errors due to using the explicit Euler or operator-splitting schemes with modelling time-steps of different length, runoff at lower temporal resolutions than one hour were consistently simulated in a modelling time-step of 1 h regardless of the temporal resolution of the rainfall-runoff data. The 3-, 6-, 12- and 24-hourly rainfall datasets were disaggregated uniformly into 1-h time series to force the model (e.g. a daily precipitation of 24 mm was disaggregated into 24 1-h steps of 1 mm) and the 1-h runoff simulations were then aggregated to the temporal resolution of interest either for calibration or for simulation. In terms of numerical stability, a preliminary numerical experiment, where different numerical methods were compared to simulate daily runoff for the Boqueron River basin, showed that the explicit Euler method when used with a modelling time-step of 1 h and forced with uniformly disaggregated daily data, returned numerical solutions similar to those returned when the implicit Euler method was used in daily modelling time-steps. This adjustment of the modelling time-step assured that the behavioural parameter sets selected at coarse temporal resolutions were selected for the right reasons and not as a consequence of numerical artefacts.

2.5. Numerical experiments

The effects of the temporal resolution of data on model parameters were evaluated in two experiments. The first experiment was designed to answer whether it was possible to neglect temporal-resolution dependencies when the model is run at a sufficiently small modelling time-step. In this experiment, the existence of model-parameter dependencies on the temporal resolution of data was studied by comparing the distribution of parameter values calibrated from Monte Carlo (MC) simulations of 1-, 3-, 6-, 12- and 24-hourly runoff using the explicit Euler method while simulating in modelling time-steps of 1 h. The distribution of the behavioural parameter sets calibrated at all five temporal resolutions was compared. The second experiment was a cross-temporal-resolution comparison of model performance, where calibrated parameter sets were used to simulate runoff at the other four temporal resolutions for which they were not calibrated. This experiment was designed to answer the question concerning: (i) changes in model performance when transferring the parameter across temporal resolutions and (ii) whether parameters inferred at the daily resolution can simulate peak flows as accurately as when using parameter sets calibrated at higher temporal resolutions.

Ranges of parameter values from previous daily applications of the HBV model (Booij, 2005; Seibert, 1997) and the uniform probability distribution were used as a reference to generate 50,000 initial parameter sets for the MC simulations. After a preliminary exploration of the model space based on the objective functions used for calibration, the ranges of parameter values were adjusted to generate the final 50,000 parameter sets for the two basins (Table 1).

Model-parameter values were calibrated for the period 1 Jan 1998–31 Dec 2004 in the Boqueron River basin and 1 Jul 1987–31 Mar 1988 in the Wye River basin. We used 1 Jan 2005–31 Dec 2011 as validation period in Boqueron and 1 Apr 1988–31 Dec 1988 in Wye. The model warm-up period before calibration and validation was one year (1997 and 2004) for Boqueron but only 6 months (1 Jan 1987–31 Jun 1987 and 1 Oct 1987–31 Mar 1988) for Wye, because of the limited time span of the data.

2.6. Model calibration and performance evaluation

Behavioural parameter sets depend on the objective function chosen for model calibration (Jie et al., 2016; Prakash et al., 2015). Two of the most widely used objective functions in hydrological modelling were used in this study: Nash-Sutcliffe efficiency (R_{eff}) and volume-error (V_{E}) (definitions in Appendix B). The first is a statistic measure commonly used to assess the goodness-of-fit of the simulated hydrographs, which tends to depend mostly on fitting periods with high flow conditions, whereas the second is an indicator of the agreement between the averages of the simulated and observed runoff (i.e. long-term water balance). The values of the two objective functions were transformed into membership functions (X_1 and X_2) and then joined into a single measure (F):

$$X_1 = \begin{cases} 1, & \text{if} |V_{\mathrm{E}}| \leqslant 0.10 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$X_2 = \max\left(0, \frac{R_{\mathrm{eff}}}{R_{\mathrm{eff,max}}}\right) \tag{2}$$

$$F = \min(X_1, X_2) \tag{3}$$

where $R_{\mathrm{eff,max}}$ is the maximum Nash-Sutcliffe efficiency value that was obtained at a certain temporal resolution. F varies between 0 and 1 with larger values indicating better fits. Behavioural parameter sets at every temporal resolution were considered those that gave an F score equal to or higher than 0.95.

3. Results

3.1. Effects of the temporal resolution of data on the distribution of behavioural parameters

Nash-Sutcliffe efficiencies (R_{eff}) for the Boqueron River basin were higher when simulating runoff at daily than at sub-daily resolutions, whereas equally good efficiencies were found across the temporal resolutions for the Wye River basin. The latter was the case during the calibration and validation periods (Table 2). R_{eff} values were higher at every temporal resolution by ~0.1 in the validation than in the calibration period in the Boqueron River basin, assumingly caused by period differences in data quality or hydrological activity. No such difference was found for the Wye River basin. Volume-error efficiencies (V_{E}) were similar during calibration and validation periods for both basins.

The model performance was higher in Wye than in Boqueron. Reasons explaining the lower Boqueron values include a larger spatial variability (soil, vegetation, land use, rainfall) in this basin, causing stronger non-linearities and threshold effects, as well as greater uncertainties associated with discharge gauging in its natural cross-section.

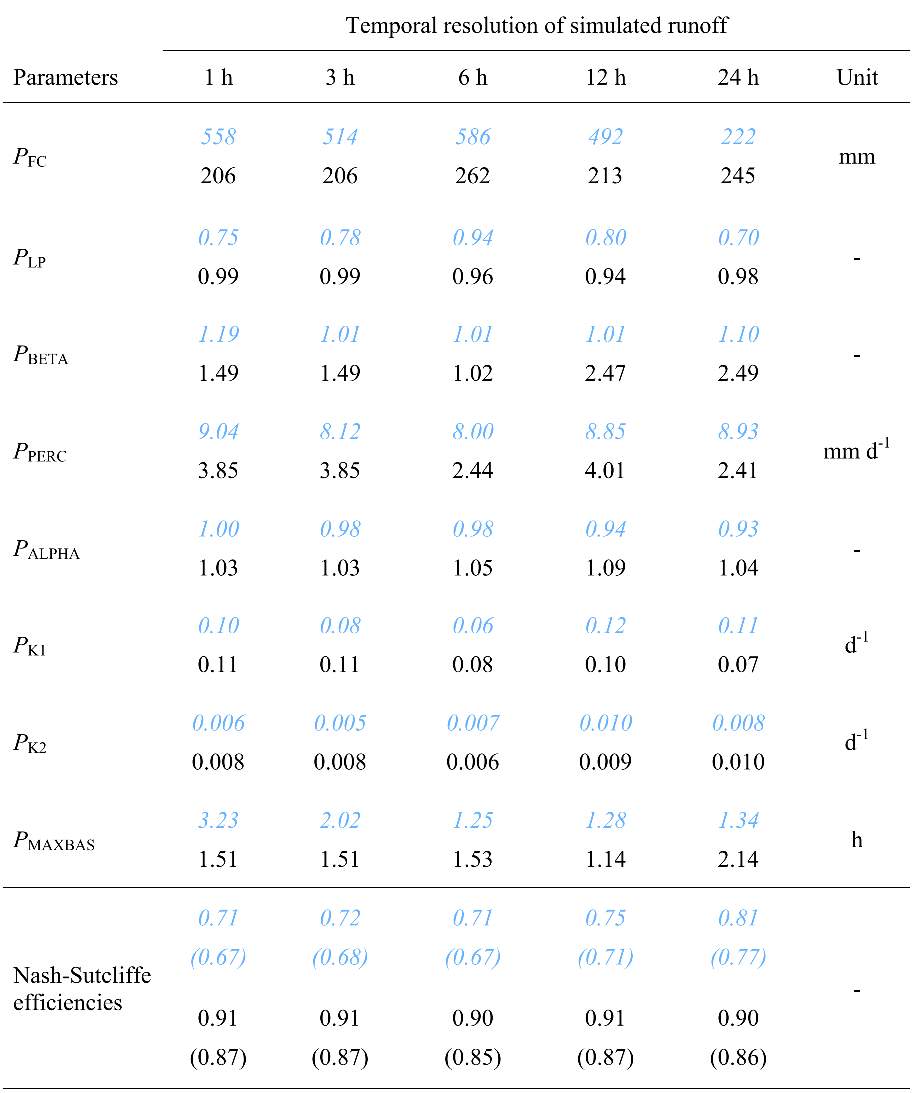
A comparison between the optimised parameter sets found at the different temporal resolutions for the two basins (Table 2) showed smaller and less variable P_{FC} values for the Wye than for the Boqueron, while the opposite held true for P_{BETA}. This was considered to be consistent with the degree of sensitivity of these parameters with respect to R_{eff} at the two basins (shown for the 1-h case, Fig. 4), in which P_{FC} was more sensitive in Wye and P_{BETA} was more sensitive in Boqueron. The interaction of P_{FC} and P_{BETA} (Eq. A1) may explain the sensitivity found in one basin but not in the other and smaller values of them imply larger groundwater recharge (G_{RECH}). The optimised P_{LP} values were larger for Wye than for Boqueron, which implies that actual evaporation took longer to reach potential evaporation in the former than in the latter basin. In terms of the volume-error, only P_{FC}, P_{LP} and P_{BETA} showed a high sensitivity at all temporal resolutions in both basins, but volume errors smaller than 0.10 were possible along the value ranges of these parameters.

The optimised values of P_{ALPHA} and P_{K1} for the two basins were relatively similar in magnitude and the optimised values of P_{PERC} were larger for Boqueron than for Wye (i.e. inputs to the lower groundwater reservoir, S_{LZ}, were larger in the Boqueron). These three parameters, which all affect Q_1, were considerably more sensitive with respect to R_{eff} than the slow-response parameter, P_{K2}, which affect Q_2, in both basins. The behaviour of the groundwater-related parameters were considered to be consistent

Table 1
Final ranges of the parameter values used for the MC simulations in the two studied basins.

Parameter	Description	Boqueron	Wye	Unit
		Min – Max	Min – Max	
Soil Moisture Routine				
P_{FC}	Maximum soil-moisture storage	200–600		mm
P_{LP}	Soil-moisture value above which actual evaporation reaches potential evaporation.	0.7–1.0		–
P_{BETA}	Determines the relative contribution to runoff from rainfall	1.0–2.5		–
Response Routine				
P_{PERC}	Threshold parameter	2.4–9.6	2.4–7.2	mm d^{-1}
P_{ALPHA}	Non-linearity coefficient	0.5–1.0	0.6–1.1	–
P_{K1}	Storage coefficient 1	0.0024–0.12	0.0048–0.12	d^{-1}
P_{K2}	Storage coefficient 2	0.005–0.01		d^{-1}
Routing Routine				
P_{MAXBAS}	Length of isosceles triangular weighting function	1.0–6.0	1.0–4.0	h

Table 2
Optimised parameter values and model performance of selected behavioural parameter sets (Nash-Sutcliffe model efficiency, maxima and minima) at five temporal resolutions in the Boqueron (blue, italic) and Wye (black) River basins during calibration. For R_{eff} values, minima values are given in parentheses in addition to the maxima values.



	Temporal resolution of simulated runoff					
Parameters	1 h	3 h	6 h	12 h	24 h	Unit
P_{FC}	*558* 206	*514* 206	*586* 262	*492* 213	*222* 245	mm
P_{LP}	*0.75* 0.99	*0.78* 0.99	*0.94* 0.96	*0.80* 0.94	*0.70* 0.98	-
P_{BETA}	*1.19* 1.49	*1.01* 1.49	*1.01* 1.02	*1.01* 2.47	*1.10* 2.49	-
P_{PERC}	*9.04* 3.85	*8.12* 3.85	*8.00* 2.44	*8.85* 4.01	*8.93* 2.41	mm d^{-1}
P_{ALPHA}	*1.00* 1.03	*0.98* 1.03	*0.98* 1.05	*0.94* 1.09	*0.93* 1.04	-
P_{K1}	*0.10* 0.11	*0.08* 0.11	*0.06* 0.08	*0.12* 0.10	*0.11* 0.07	d^{-1}
P_{K2}	*0.006* 0.008	*0.005* 0.008	*0.007* 0.006	*0.010* 0.009	*0.008* 0.010	d^{-1}
P_{MAXBAS}	*3.23* 1.51	*2.02* 1.51	*1.25* 1.53	*1.28* 1.14	*1.34* 2.14	h
Nash-Sutcliffe efficiencies	*0.71* *(0.67)* 0.91 (0.87)	*0.72* *(0.68)* 0.91 (0.87)	*0.71* *(0.67)* 0.90 (0.85)	*0.75* *(0.71)* 0.91 (0.87)	*0.81* *(0.77)* 0.90 (0.86)	-

with the dominant runoff mechanisms of both basins, fast-flow processes (i.e. surface and near-surface runoff) as reflected in the contributions from Q_1 during calibration (65% for Wye and 55% for Boqueron).

The optimised parameter values of the routing parameter, P_{MAXBAS}, were smaller for Wye than for Boqueron. For the Wye River basin, P_{MAXBAS} was slightly sensitive with respect to R_{eff} at temporal resolutions equal to or higher than 6 h, but not for lower temporal resolutions (12 and 24 h). Whereas for the Boqueron River basin, P_{MAXBAS} was highly sensitive at sub-daily, but less sensitive at the daily resolution.

The distribution of the behavioural parameter values for the two basins were relatively constant across the temporal resolutions and did not show model-parameter dependencies on the temporal resolution of data except for a slight shift of the routing-routine parameter, P_{MAXBAS}, when moving from sub-daily to daily (Fig. 5). Outliers were found for P_{PERC}, P_{ALPHA}, P_{K1} and P_{MAXBAS} at some temporal resolutions, but the percentages of them at every resolution were less than 2.2%, and they had a negligible impact on the simulated discharge bounds.

3.2. Parameter transferability across temporal resolutions

Both basins presented similar behaviour in terms of changes in model performance when run with parameters calibrated at temporal resolutions other than the one of the simulation. The V_E values remained virtually constant across all combinations of calibration and simulation temporal resolutions. The parameter sets calibrated at the temporal resolution of simulated runoff gave Nash-Sutcliffe (R_{eff}) efficiency values with the smallest spread. A small R_{eff} decrease was seen for both basins when the parameters calibrated at the daily were used to simulate sub-daily runoff (Fig. 6). However, the 99th and 50th percentile R_{eff} values showed a small variation for all simulated temporal resolutions irrespective of the calibration temporal-resolution.

Some decrease in R_{eff} was noticeable when parameters calibrated at the 3-, 6-, 12- and 24-h resolutions were used to simulate 1-h runoff, but similar 99th and 50th percentile R_{eff} values were found across all temporal resolutions. R_{eff} values were more or less equal when parameters calibrated at sub-daily resolutions were used to simulate 3-, 6-, 12- and 24-h runoff.

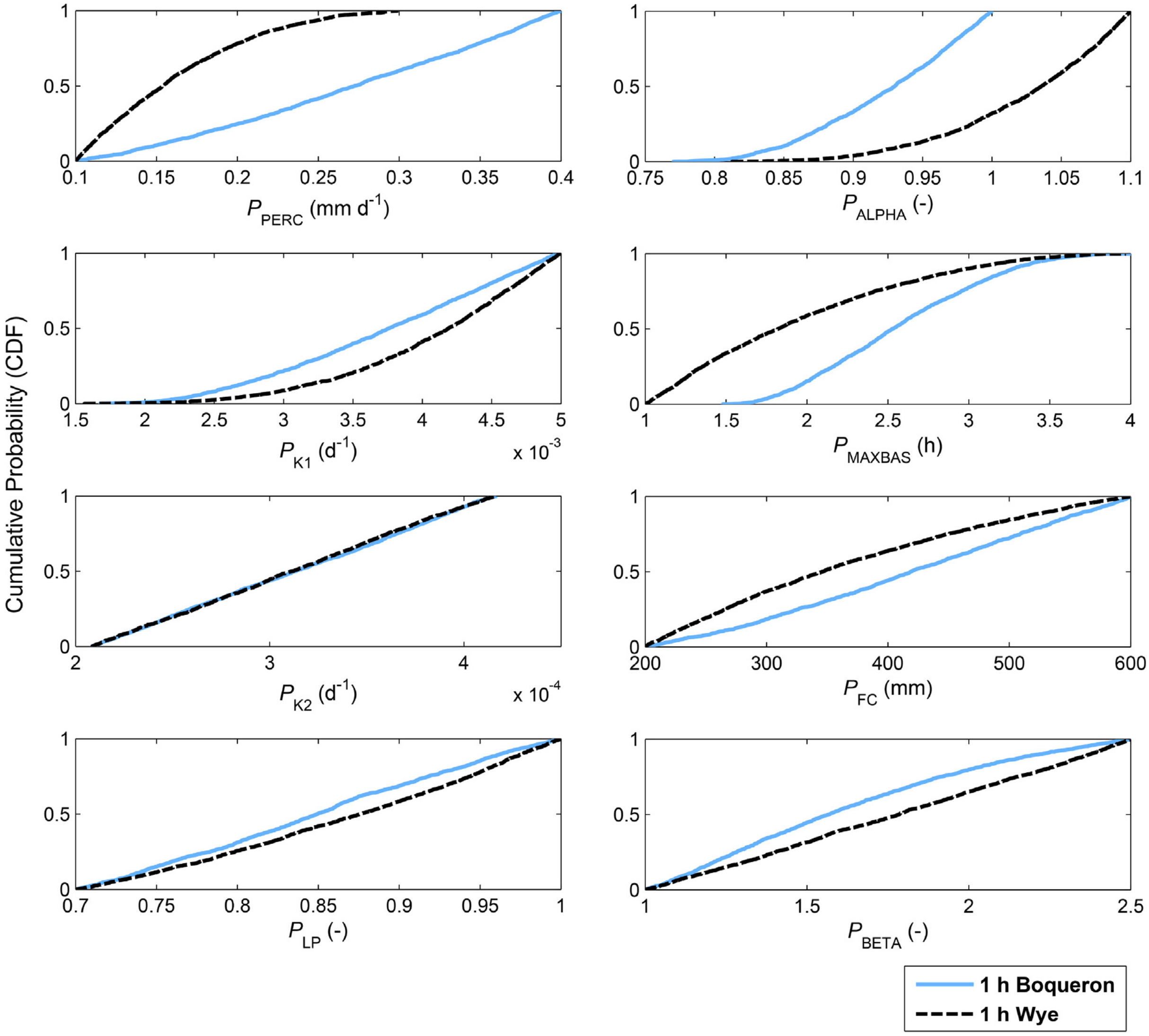


Fig. 4. Sensitivity analysis of behavioural parameter values calibrated at the 1-h temporal resolution for the Boqueron and Wye River basins.

A cross-temporal-resolution comparison of simulated discharge at sub-daily resolutions for the Boqueron River (Fig. 7) and Wye River (Fig. 8) basins, using parameters calibrated at their respective temporal resolutions and at the daily, showed that simulations for all sub-daily resolutions were similar irrespective of the calibration temporal-resolution. For the Wye, all parameter sets were able to well reproduce the precedent flow and recession limb of the peak but less well in its rising limb and magnitude.

4. Discussion

The two questions defining the objective of this study were both answered in a clear way and the overall results suggested that parameter sets calibrated at one temporal resolution may be used without scaling at other temporal resolutions. The generality of our results is so far restricted to one model and two basins. The model selected for this study, HBV light (Seibert and Vis, 2012), represents a class of bucket-type models that have been used extensively by practitioners. A more complex, physically-based-distributed model could have been chosen but would have required data that are not always available, especially not in developing countries, and also because simple lumped bucket-type models, as the one used herein, have shown to provide as good modelling results as when using more complex models when discharge prediction is the only variable of interest (Beven, 2001; Franchini and Pacciani, 1991; Yan et al., 2016). This work took advantage of the availability of long time series of hourly data at two small basins to investigate the effect of temporal resolution of data on parameters. With the suggested methodology, sub-daily data will only be needed for simulation.

4.1. Effects of the temporal resolution of data on the distribution of behavioural parameters

When the explicit Euler method was used with a 1-h modelling time-step, data temporal-resolution dependence of the calibrated parameter values at the two basins was almost non-existent. No model-parameter dependencies on the temporal resolution of the data like those previously reported (Bastola and Murphy, 2013; Littlewood and Croke, 2008; Littlewood, 2007; Ostrowski et al., 2010; Wang et al., 2009) were found in this study. This difference might be explained by the numerical method implemented to simulate runoff at the different temporal resolutions. Here the modelling time-step was fixed to one value (i.e. 1 h), which resulted in robust numerical solutions and in temporal-resolution-independent parameters, whereas previous studies used the

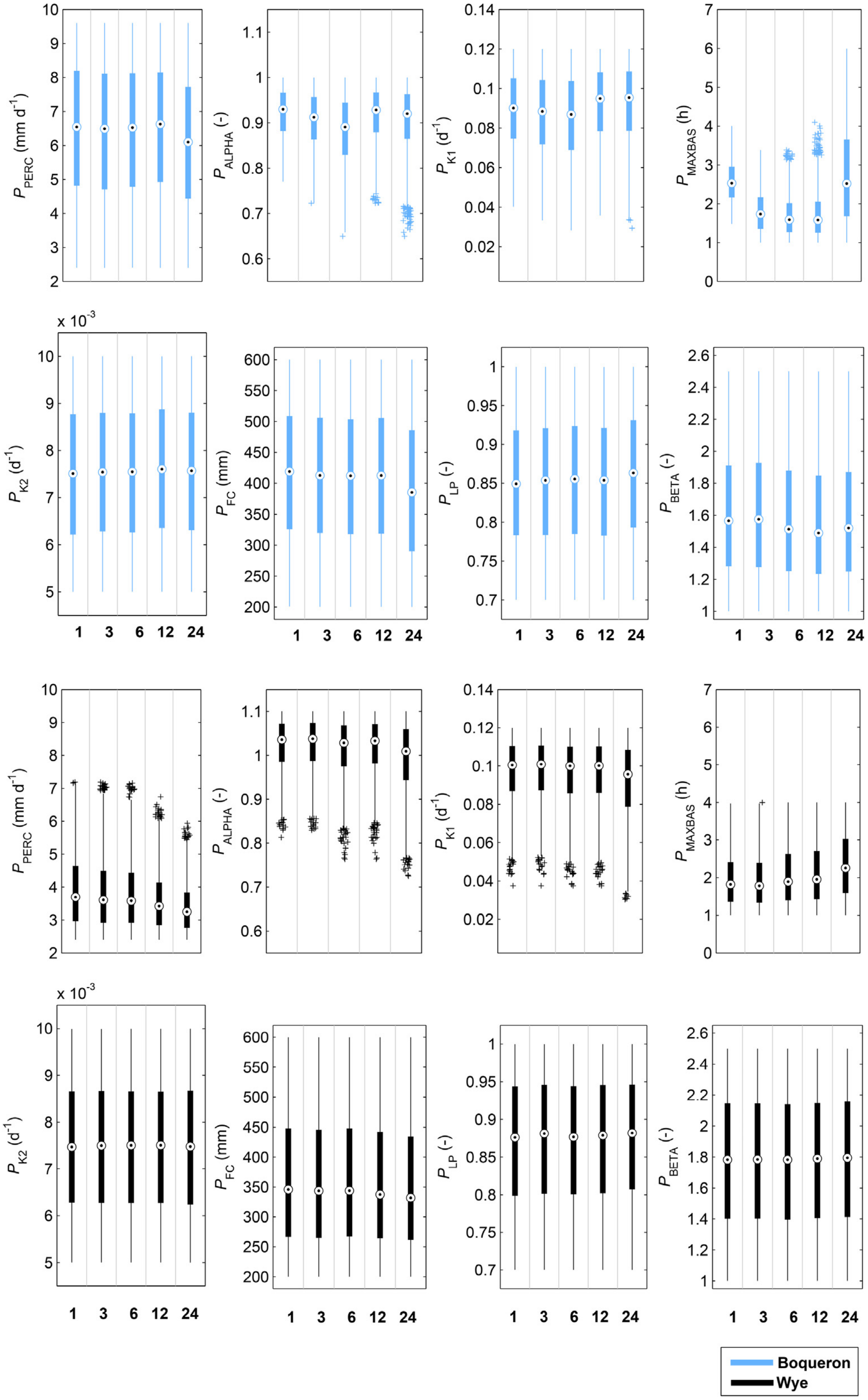


Fig. 5. Boxplots of behavioural parameter values calibrated at different temporal resolutions for the Boqueron and Wye River basins.

temporal resolution of the calibration data as the modelling time-step. The results found herein supported the finding of Kavetski et al. (2011) that robust numerical integration reduces parameter temporal-resolution dependence. Other reasons may be related to the model structure used in this study. Therefore, it is desirable to extend our methodology to additional models with fewer or more parameters to test the generality of our results in terms of model performance and identifiability of the model parameters. Although data temporal-resolution dependencies were not found in this study, there may still be dependencies when processes at

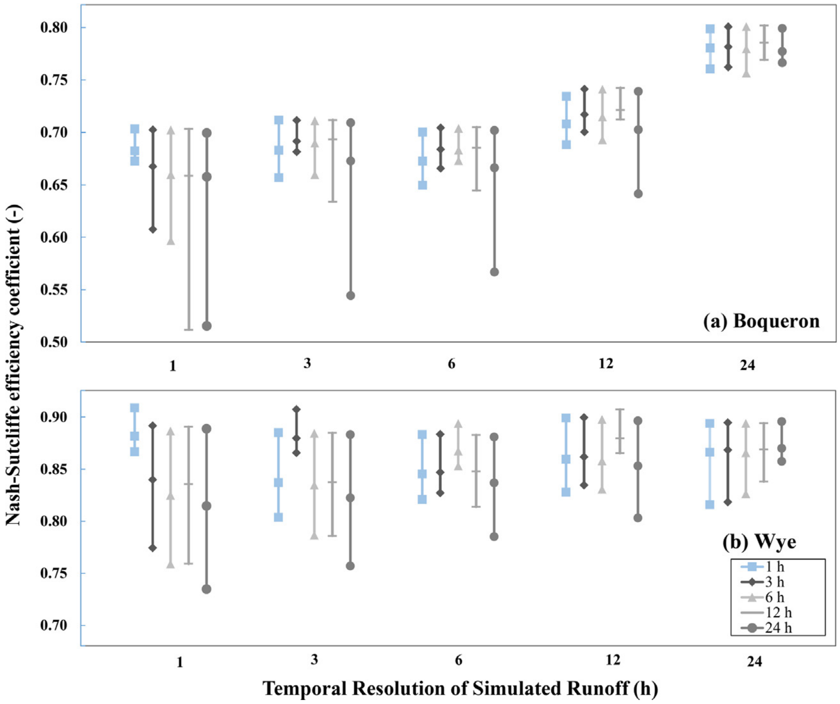


Fig. 6. 1st (bottom), 50th (middle) and 99th (top) percentiles of Nash-Sutcliffe efficiency at five simulation temporal resolutions for (a) Boqueron and (b) Wye River basins when using parameters originally calibrated at five different temporal resolutions (legend in the figure).

sub-hourly timescales are exposed by high temporal-resolution data (Kavetski et al., 2011).

Implicit Euler methods or exact solutions can be used to guarantee numerical robustness but numerical limitations can also be overcome by running a model with an explicit Euler scheme and with a small modelling time-step. The simplicity of the explicit scheme with a 1-h modelling time-step provided a practical and sufficiently robust integration in this case which allowed us to run a large number of Monte Carlo simulations without problems.

The slight shift of P_{MAXBAS} values when moving from sub-daily to daily may have been caused by equifinality problems (Beven, 2009). P_{MAXBAS} became insensitive at lower temporal resolutions than the concentration times for Boqueron ($\leq$6 h) and Wye ($\leq$4 h). In fast-response basins, caution must thus be taken when defining value ranges of parameters related to fast-response processes at coarse or low temporal resolutions because unrealistic values of these parameters may turn out as behavioural at those resolutions, but when transferred to higher temporal resolutions (at which these parameters can be identified) result in poor simulations. When fast-response parameters are calibrated at coarser temporal resolutions than the timescales of the processes they represent, they may show dependencies on the temporal resolution of data even when reliable numerical methods are used (Ostrowski et al., 2010).

In the literature, it is argued that model parameters become temporal-resolution independent when the temporal resolution of the rainfall-runoff data used for calibration approaches zero (Littlewood and Croke, 2008), whereas our result support the idea that parameters become independent of the temporal resolution of data when the modelling time-step is sufficiently small but larger than zero. By separating modelling time-step from the temporal resolution of the data, it was possible to study data temporal-resolution dependencies free from numerical errors that could otherwise corrupt sensitivity analyses, model calibration, result interpretation and model uncertainty analyses (Kavetski et al., 2011; Kavetski and Clark, 2011; Michel et al., 2003).

4.2. Parameter transferability across temporal resolutions

Calibrated parameter sets that were transferred across temporal resolutions in both basins showed similar behaviour in terms of changes in model performance. The cross-temporal-resolution comparison of Nash-Sutcliffe efficiencies (R_{eff}) showed a performance decrease when parameter sets calibrated at lower temporal resolutions than 1 h were used to model at this temporal resolution, perhaps because the model structure was too simple to represent processes at this temporal resolution and because parameter information content was too limited at lower temporal resolutions than 1 h.

When parameter sets calibrated at the daily were used to simulate runoff at sub-daily resolutions, R_{eff} decreased only slightly in comparison to when parameter sets calibrated at those temporal resolutions were used. This slight decrease in performance may have been caused by the low sensitivity of P_{MAXBAS} at the daily resolution in both basins, which could have caused the selection of parameter values non-representative at sub-daily resolutions.

The cross-temporal-resolution comparison of volume errors, V_E showed no bias in any of the basins when parameters calibrated at one temporal resolution were used for simulations at any other temporal resolution, contrary to previous findings (Finnerty et al., 1997). This contradiction could probably be explained by the incorporation of all behavioural parameter sets in our study instead of using a single set without considering data and model uncertainties.

The performance decrease when transferring calibrated parameter values across temporal resolutions was much smaller than previously reported (Bastola and Murphy, 2013). This difference may have been caused by the numerical method implemented in our study.

Daily parameters could reproduce peak flows in both basins at sub-daily temporal resolutions almost as well as parameters calibrated at those sub-daily resolutions. It was difficult, however, irrespective of the calibration temporal-resolution, to reproduce

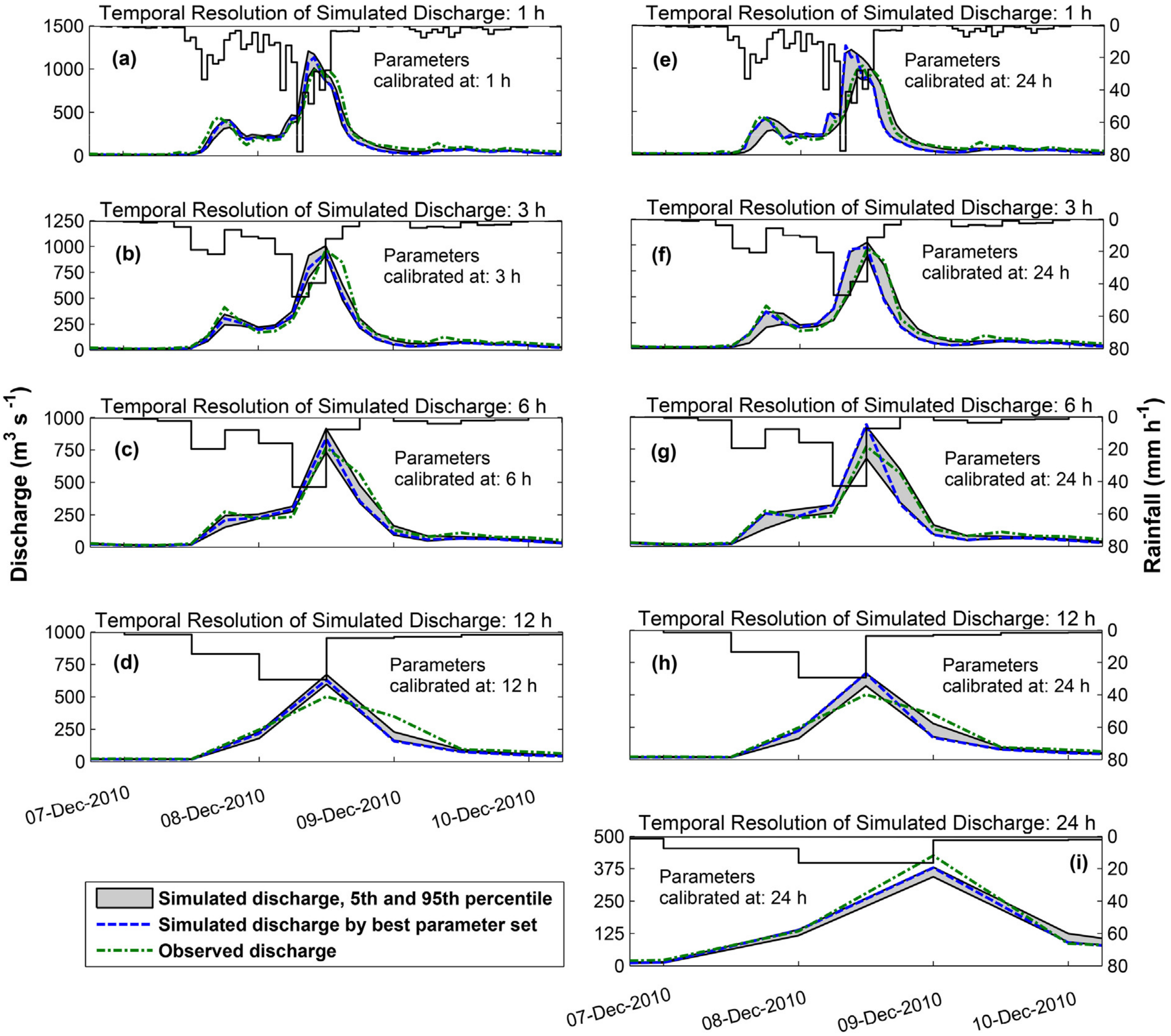


Fig. 7. Simulations at the Boqueron River basin at Peluca of the highest 1-h peak flow during the validation period 1 Jan 2005–31 Dec 2011. Discharge was simulated using parameters calibrated at the same temporal resolution as the simulation (a–d) and at the daily (e–i). Discharge simulations, within the 5th and 95th percentile uncertainty bounds as well as with the best parameter set, are given together with observed discharge and measured rainfall.

the highest peak flows in the Wye River basin in the validation period. We assumed that this was related to the model structure, or the short length of the calibration period, which may not have captured the full dynamics.

5. Conclusions

The starting point of this study was the need for flood forecasting at sub-daily temporal resolutions in regions where data availability at these resolutions is limited. The study demonstrated that:

1. Model-parameter dependencies on the temporal resolution of data were almost non-existent when the explicit Euler method was run with a modelling time-step of 1 h regardless of the temporal resolution of the rainfall-runoff data used for calibration.
2. When parameters calibrated at one temporal resolution were transferred to other temporal resolutions without any scaling, runoff could be simulated with moderate (if any) decrease in Nash-Sutcliffe and volume-error efficiencies.
3. Parameters calibrated at the daily provided peak-flow simulations almost as good as parameters calibrated at sub-daily resolutions.
4. These findings imply that if sub-daily forcing data can be secured, flood forecasting in basins with sub-daily concentration times may be possible with model-parameter values calibrated from long time series of daily data, as long as the modelling time-step for model calibration is sufficiently small.

Finally, it must be emphasised that the results found herein are valid for two small basins and one model structure. The generality of our results can only be proven when the methodology is tested on other models and basins where other hydrological processes dominate.

Author contributions

C.Y. Xu and J. Seibert designed the experiments, and J.E. Reynolds executed them. J.E. Reynolds prepared the manuscript with contributions from all co-authors.

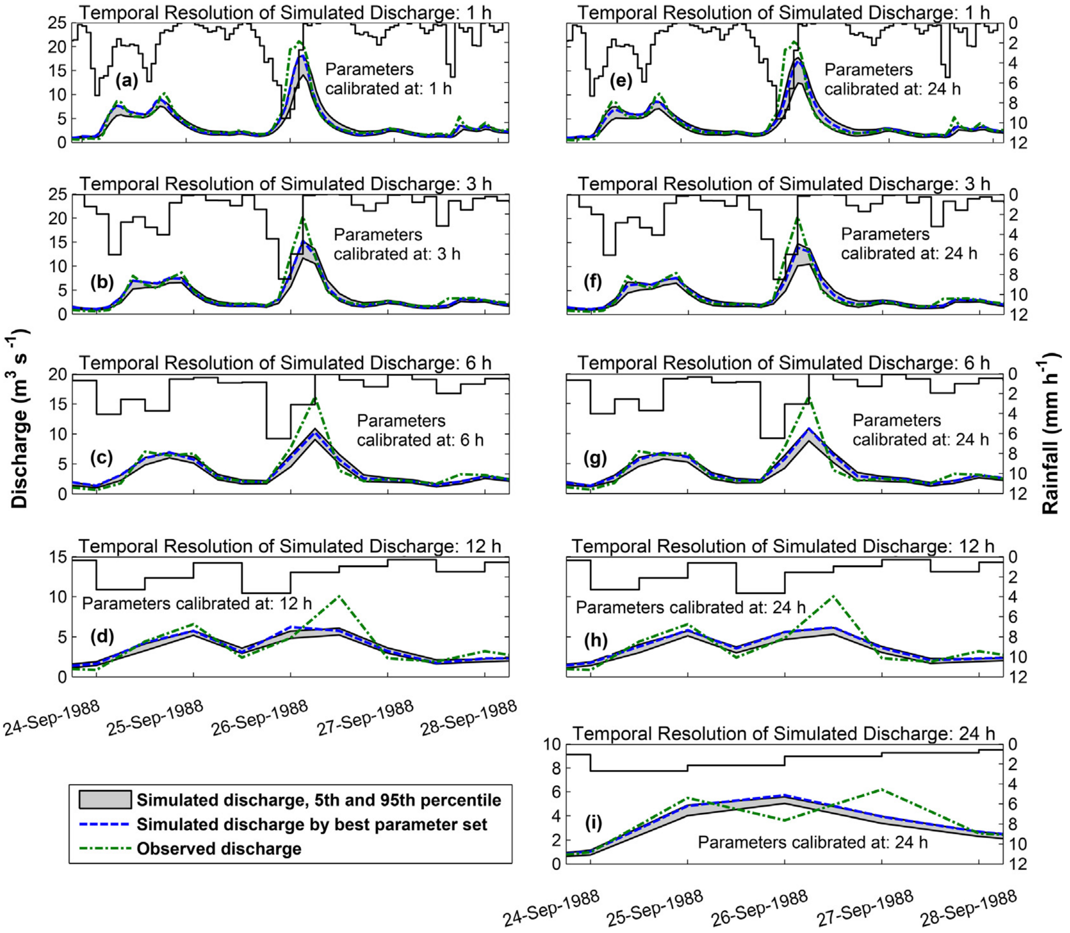


Fig. 8. Simulations at the Wye River basin at Cefn Brwyn of the highest 1-h peak flow during the validation period 1 Apr 1988–31 Dec 1988. Discharge was simulated using parameters calibrated at the same temporal resolution as the simulation (a–d) and at the daily (e–i). Discharge simulations, within the 5th and 95th percentile uncertainty bounds as well as with the best parameter set, are given together with observed discharge and measured rainfall.

Acknowledgements

This research was carried out within the CNDS research school, supported by the Swedish International Development Cooperation Agency (Sida) through their contract with the International Science Programme (ISP) at Uppsala University (contract number: 54100006).

The authors thank the Panama Canal Authority (ACP) that provided the rainfall and discharge data from the Boqueron River basin and the Department of Hydrometeorology at Empresa de Transmisión Eléctrica, S.A. (ETESA) that provided the pan-evaporation data. The authors also thank Ian Littlewood who provided the data from the Wye River basin and Shervan Gharari, who together with two anonymous reviewers gave us valuable comments and suggestions that help us improve the manuscript.

Appendix A: List of equations for the standard model structure of HBV light in this study

Soil-moisture routine equations:

$$\frac{G_{\mathrm{RECH}}}{R} = \left(\frac{S_{\mathrm{M}}}{P_{\mathrm{FC}}}\right)^{P_{\mathrm{BETA}}} \tag{A1}$$

$$E_{\mathrm{act}} = E_{\mathrm{pot}}\left[\min\left(\frac{S_{\mathrm{M}}}{P_{\mathrm{FC}}P_{\mathrm{LP}}}, 1\right)\right] \tag{A2}$$

$$\frac{\mathrm{d}S_{\mathrm{M}}}{\mathrm{d}t} = R - G_{\mathrm{RECH}} - E_{\mathrm{act}} \tag{A3}$$

Response routine equations:

$$G_{\mathrm{PERC}} = \min(S_{\mathrm{UZ}}, P_{\mathrm{PERC}}) \tag{A4}$$

$$Q_1 = P_{\mathrm{K1}} S_{\mathrm{UZ}}^{(1+P_{\mathrm{ALPHA}})} \tag{A5}$$

$$\frac{\mathrm{d}S_{\mathrm{UZ}}}{\mathrm{d}t} = G_{\mathrm{RECH}} - G_{\mathrm{PERC}} - Q_1 \tag{A6}$$

$$Q_2 = P_{\mathrm{K2}} S_{\mathrm{LZ}} \tag{A7}$$

$$\frac{\mathrm{d}S_{\mathrm{LZ}}}{\mathrm{d}t} = G_{\mathrm{PERC}} - Q_2 \tag{A8}$$

$$Q_t = Q_1 + Q_2 \tag{A9}$$

Routing routine equations:

$$Q_{\mathrm{sim},t} = \sum_{i=1}^{P_{\mathrm{MAXBAS}}} c_{(i)} Q_{(t-i+1)} \tag{A10}$$

$$c_{(i)} = \int_{i-1}^{i} \left(\frac{2}{P_{\mathrm{MAXBAS}}} - \left|u - \frac{P_{\mathrm{MAXBAS}}}{2}\right| \frac{4}{P_{\mathrm{MAXBAS}}^2}\right) \mathrm{d}u \tag{A11}$$

Appendix B: Definition of objective functions in this study

Objective functions	Description	Definition
R_{eff}	Nash-Sutcliffe efficiency	$1-\frac{\sum(Q_{\text{obs}}-Q_{\text{sim}})^2}{\sum(Q_{\text{obs}}-\overline{Q_{\text{obs}}})}$
V_{E}	Volume error	$\frac{\sum(Q_{\text{sim}}-Q_{\text{obs}})}{\sum Q_{\text{obs}}}$

References

Bastola, S., Murphy, C., 2013. Sensitivity of the performance of a conceptual rainfall–runoff model to the temporal sampling of calibration data. Hydrol. Res. 44, 484–493. http://dx.doi.org/10.2166/nh.2012.061.

Bergström, S., 1992. The HBV model – its structure and applications. Swedish Meteorological and Hydrological Institute (SMHI) RH No 4. Norrköping, Sweden.

Bergström, S., 1976. Development and application of a conceptual runoff model for Scandinavian catchments. Swedish Meteorological and Hydrological Institute (SMHI) RHO 7. Norrköping, Sweden.

Beven, K.J., 2009. Environmental Modelling: An Uncertain Future? Routledge.

Beven, K.J., 2001. Rainfall-Runoff Modelling. The Primer, Rainfall-Runoff Modelling.

Blöschl, G., Sivapalan, M., 1995. Scale issues in hydrological modelling: a review. Hydrol. Process. 9, 251–290. http://dx.doi.org/10.1002/hyp.3360090305.

Booij, M.J., 2005. Impact of climate change on river flooding assessed with different spatial model resolutions. J. Hydrol. 303, 176–198. http://dx.doi.org/10.1016/j.jhydrol.2004.07.013.

CEH, 2016. Centre for Ecology & Hydrology database [WWW Document]. URL https://catalogue.ceh.ac.uk/documents/91961a0f-3158-4d00-984d-91eb1e03e8bd (accessed 3.7.16).

Cullmann, J., Mishra, V., Peters, R., 2006. Flow analysis with WaSiM-ETH – model parameter sensitivity at different scales. Adv. Geosci. 9, 73–77. http://dx.doi.org/10.5194/adgeo-9-73-2006.

Finch, J.W., Hall, R.L., 2001. Estimation of Open Water Evaporation. Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD.

Finnerty, B.D., Smith, M.B., Seo, D.-J., Koren, V., Moglen, G.E., 1997. Space-time scale sensitivity of the Sacramento model to radar-gage precipitation inputs. J. Hydrol. 203, 21–38. http://dx.doi.org/10.1016/S0022-1694(97)00083-8.

Franchini, M., Pacciani, M., 1991. Comparative analysis of several conceptual rainfall-runoff models. J. Hydrol. 122, 161–219. http://dx.doi.org/10.1016/0022-1694(91)90178-K.

Grillakis, M.G., Tsanis, I.K., Koutroulis, A.G., 2010. Application of the HBV hydrological model in a flash flood case in Slovenia. Nat. Hazards Earth Syst. Sci. 10, 2713–2725. http://dx.doi.org/10.5194/nhess-10-2713-2010.

Hailegeorgis, T.T., Alfredsen, K., 2015. Comparative evaluation of performances of different conceptualisations of distributed HBV runoff response routines for prediction of hourly streamflow in boreal mountainous catchments. Hydrol. Res. 46, 607–628. http://dx.doi.org/10.2166/nh.2014.051.

Harlin, J., Kung, C.-S., 1992. Parameter uncertainty and simulation of design floods in Sweden. J. Hydrol. 137, 209–230. http://dx.doi.org/10.1016/0022-1694(92)90057-3.

Harmon, R.S., 2005. An Introduction to the Panama Canal Watershed, in: The Río Chagres: A Multidisciplinary Profile of a Tropical Watershed. Springer, Netherlands. http://dx.doi.org/10.1007/1-4020-3297-8, pp. 19-28.

Jie, M.-X., Chen, H., Xu, C.-Y., Zeng, Q., Tao, X., 2016. A comparative study of different objective functions to improve the flood forecasting accuracy. Hydrol. Res. 47, 718–735. http://dx.doi.org/10.2166/nh.2015.078.

Kavetski, D., Clark, M.P., 2011. Numerical troubles in conceptual hydrology: approximations, absurdities and impact on hypothesis testing. Hydrol. Process. 25, 661–670. http://dx.doi.org/10.1002/hyp.7899.

Kavetski, D., Fenicia, F., Clark, M.P., 2011. Impact of temporal data resolution on parameter inference and model identification in conceptual hydrological modeling: insights from an experimental catchment. Water Resour. Res. 47, W05501. http://dx.doi.org/10.1029/2010WR009525.

Kay, A.L., Davies, H.N., 2008. Calculating potential evaporation from climate model data: a source of uncertainty for hydrological climate change impacts. J. Hydrol. 358, 221–239. http://dx.doi.org/10.1016/j.jhydrol.2008.06.005.

Kobold, M., Brilly, M., 2006. The use of HBV model for flash flood forecasting. Nat. Hazards Earth Syst. Sci. 6, 407–417. http://dx.doi.org/10.5194/nhess-6-407-2006.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., Bergström, S., 1997. Development and test of the distributed HBV-96 hydrological model. J. Hydrol. 201, 272–288. http://dx.doi.org/10.1016/S0022-1694(97)00041-3.

Littlewood, I.G., 2007. Rainfall-streamflow for ungauged basins: uncertainty due to modelling time-step. In: 11th Conference of the Euromediterranean Network of Experimental and Representative Basins (ERB), Luxembourg, 20–23 September 2006. pp. 149–155.

Littlewood, I.G., Croke, B.F.W., 2013. Effects of data time-step on the accuracy of calibrated rainfall–streamflow model parameters: practical aspects of uncertainty reduction. Hydrol. Res. 44, 430. http://dx.doi.org/10.2166/nh.2012.099.

Littlewood, I.G., Croke, B.F.W., 2008. Data time-step dependency of conceptual rainfall—streamflow model parameters: an empirical study with implications for regionalisation. Hydrol. Sci. J. 53, 685–695. http://dx.doi.org/10.1623/hysj.53.4.685.

Littlewood, I.G., Young, P.C., 2010. Preliminary comparison of two methods for identifying rainfall-streamflow model parameters insensitive to data time-step: the Wye at Cefn Brwyn, Plynlimon, Wales. In: British Hydrological Society's Third International Symposium, Role of Hydrology in Managing the Consequences of a Changing Global Environment, Newcastle University, 19–23 July, pp. 539–543.

McMillan, H., Krueger, T., Freer, J., 2012. Benchmarking observational uncertainties for hydrology: rainfall, river discharge and water quality. Hydrol. Process. 26, 4078–4111. http://dx.doi.org/10.1002/hyp.9384.

Michel, C., Perrin, C., Andreassian, V., 2003. The exponential store: a correct formulation for rainfall—runoff modelling. Hydrol. Sci. J. 48 (1), 109–124. http://dx.doi.org/10.1623/hysj.48.1.109.43484.

Nalbantis, I., 1995. Use of multiple-time-step-information in rain-fall runoff modelling. J. Hydrol. 165, 135–159. http://dx.doi.org/10.1016/0022-1694(94)02567-U.

Natural Environment Research Council (NERC), 2003. Hydrometric Register and Statistics 1996–2000. Centre for Ecology and Hydrology, Wallingford, UK.

Ostrowski, M., Bach, M., Desimone, S.V., Gamerith, V., 2010. Analysis of the Time-Step Dependency of Parameters in Conceptual Hydrological Models. Technische Universität Darmstadt, Darmstadt, Germany, p. 31.

Ostrowski, M., Wolf, U., 1984. Effects of temporal decomposition on parameter estimation for 24 hydrological models (in german). Gewässerkundliche Mitteilungen 28, 37–40.

Prakash, O., Srinivasan, K., Sudheer, K.P., 2015. Adaptive multi-objective simulation–optimization framework for dynamic flood control operation in a river–reservoir system. Hydrol. Res. 46, 893–911. http://dx.doi.org/10.2166/nh.2015.171.

Reynolds, J.E., 2012. Usability of Standard Monitored Rainfall-Runoff Data in Panama, Juan Diaz River Basin M.S. thesis (No. ISSN 1650-6553 Nr 242). Uppsala University, Uppsala, Sweden. 62 pp.

Seibert, J., 1999. Regionalisation of parameters for a conceptual rainfall-runoff model. Agric. For. Meteorol. 98–99, 279–293. http://dx.doi.org/10.1016/S0168-1923(99)00105-7.

Seibert, J., 1997. Estimation of parameter uncertainty in the HBV model. Nord. Hydrol. 28 (4/5), 247–262.

Seibert, J., Vis, M.J.P., 2012. Teaching hydrological modeling with a user-friendly catchment-runoff-model software package. Hydrol. Earth Syst. Sci. 16, 3315–3325. http://dx.doi.org/10.5194/hess-16-3315-2012.

USGS, 2016. U.S. Geological Survey [WWW Document]. URL http://hydrosheds.cr.usgs.gov/datadownload.php?reqdata=3demg (accessed 3.7.16).

Wang, Y., He, B., Takase, K., 2009. Effects of temporal resolution on hydrological model parameters and its impact on prediction of river discharge/Effets de la résolution temporelle sur les paramètres d'un modèle hydrologique et impact sur la prévision de l'écoulement en rivière. Hydrol. Sci. J. 54 (5), 886–898. http://dx.doi.org/10.1623/hysj.54.5.886.

Westerberg, I., Guerrero, J.-L., Seibert, J., Beven, K.J., Halldin, S., 2011a. Stage-discharge uncertainty derived with a non-stationary rating curve in the Choluteca River, Honduras. Hydrol. Process. 25, 603–613. http://dx.doi.org/10.1002/hyp.7848.

Westerberg, I.K., Guerrero, J.L., Younger, P.M., Beven, K.J., Seibert, J., Halldin, S., Freer, J.E., Xu, C.Y., 2011b. Calibration of hydrological models using flow-duration curves. Hydrol. Earth Syst. Sci. 15, 2205–2227. http://dx.doi.org/10.5194/hess-15-2205-2011.

WMO World Meteorological Organization, 2010. Manual on Stream Gauging, Volume II – Computation of Discharge (WMO-No. 1044).

Wöhling, T., Lennartz, F., Zappa, M., 2006. Technical Note: Updating procedure for flood forecasting with conceptual HBV-type models. Hydrol. Earth Syst. Sci. Discuss. 10, 783–788. http://dx.doi.org/10.5194/hess-10-783-2006.

Yan, R., Huang, J., Wang, Y., Gao, J., Qi, L., 2016. Modeling the combined impact of future climate and land use changes on streamflow of Xinjiang Basin, China. Hydrol. Res. 47 (2), 356–372. http://dx.doi.org/10.2166/nh.2015.206.

Zeng, Q., Chen, H., Xu, C.-Y., Jie, M.-X., Hou, Y.-K., 2016. Feasibility and uncertainty of using conceptual rainfall-runoff models in design flood estimation. Hydrol. Res. 47, 701–717. http://dx.doi.org/10.2166/nh.2015.069.