Hydrol. Earth Syst. Sci. Discuss., 12, 7437–7467, 2015
www.hydrol-earth-syst-sci-discuss.net/12/7437/2015/
doi:10.5194/hessd-12-7437-2015

Hydrology and Earth System Sciences
Discussions
Open Access

Sub-daily runoff simulations with parameters inferred at the daily time scale

J. E. Reynolds[1,2,3], S. Halldin[1,2], C. Y. Xu[1,4], J. Seibert[1,5,6], and A. Kauffeldt[1]

[1]Department of Earth Sciences, Uppsala University, Uppsala, Sweden
[2]Centre for Natural Disaster Science (CNDS), Uppsala, Sweden
[3]Instituto de Geociencias, Universidad de Panamá, Panamá, Panamá
[4]Department of Geosciences, University of Oslo, Oslo, Norway
[5]Department of Physical Geography, Stockholm University, Stockholm, Sweden
[6]Department of Geography, University of Zurich, Zurich, Switzerland

Received: 30 June 2015 – Accepted: 8 July 2015 – Published: 5 August 2015

Correspondence to: J. E. Reynolds (eduardo.reynolds@geo.uu.se)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Concentration times in small and medium-sized watersheds (~ 100–1000 km^2) are commonly less than 24 h. Flood-forecasting models then require data at sub-daily time scales, but time-series of input and runoff data with sufficient lengths are often only available at the daily time scale, especially in developing countries. This has led to a search for time-scale relationships to infer parameter values at the time scales where they are needed from the time scales where they are available. In this study, time-scale dependencies in the HBV-light conceptual hydrological model were assessed within the generalized likelihood uncertainty estimation (GLUE) approach. It was hypothesised that the existence of such dependencies is a result of the numerical method or time-stepping scheme used in the models rather than a real time-scale-data dependence. Parameter values inferred showed a clear dependence on time scale when the explicit Euler method was used for modelling at the same time steps as the time scale of the input data (1–24 h). However, the dependence almost fully disappeared when the explicit Euler method was used for modelling in 1 h time steps internally irrespectively of the time scale of the input data. In other words, it was found that when an adequate time-stepping scheme was implemented, parameter sets inferred at one time scale (e.g., daily) could be used directly for runoff simulations at other time scales (e.g., 3 or 6 h) without any time scaling and this approach only resulted in a small (if any) model performance decrease, in terms of Nash–Sutcliffe and volume-error efficiencies. The overall results of this study indicated that as soon as sub-daily driving data can be secured, flood forecasting in watersheds with sub-daily concentration times is possible with model-parameter values inferred from long time series of daily data, as long as an appropriate numerical method is used.

1 Introduction

In regions, such as Central America, where floods occur frequently and watersheds are usually small- or medium-sized with concentration times smaller than 24 h, there is a demand for flood-forecast models at sub-daily time scales. Applications of such hydrological models rely on the availability of good and sufficiently long time series of sub-daily observational data (e.g. rainfall and discharge) to infer model-parameter values. However, long time series at sub-daily time scales are commonly rare, especially in developing countries. If data are at all available, they are often available at a coarse time scale (e.g. daily or monthly). Depending on watershed size and the dominant runoff mechanism, watershed response can be slow or fast. The response time in a 100 km^2 watershed dominated by infiltration-excess overland flow can be around 2 h while in another watershed of the same size, dominated by saturation-excess overland flow, the response time can be around a day (cf. Fig. 2 in Blöschl and Sivapalan, 1995). Many watersheds globally, and especially in Central America, are characterised by sub-daily concentration times.

To bridge the gap between the daily to monthly observational scale and the sub-daily process scale, some scaling or regionalisation procedure is needed. One procedure is to use parameter sets inferred at daily or larger time scales to simulate runoff at sub-daily time scales. This procedure is applicable when a time series of sub-daily input data is or can be made available to drive the model, but this method has been criticised because of poor model performance (Bastola and Murphy, 2013). Some authors suggest that there are time-scale dependencies of model parameters, and if time-scale relationships of the most sensitive parameters can be found, model parameter inference at sub-daily time scales will not be necessary (Bastola and Murphy, 2013; Littlewood and Croke, 2008; Ostrowski et al., 2010; Wang et al., 2009, 2011). It is expected that model performance will improve with time scaling of the parameters, rather than using them without it, and many of these authors report strong time-scale relationships of model parameters. However, their models use simple numerical methods at any time step to solve the equations (e.g. explicit Euler). These relationships have been questioned because of erratic behaviour when these types of numerical methods are used (Kavetski and Clark, 2011; Kavetski et al., 2011; Michel et al., 2003), and because the strength of the time-scale dependencies of the parameters has been shown to depend on the numerical method used (Kavetski et al., 2011).

In this study, it was hypothesised that time-scale dependencies of the parameters of a conceptual hydrological model are caused by the numerical method or time-stepping scheme. The investigation was carried out within the generalized likelihood uncertainty estimation (GLUE) framework and intended to answer the following questions:

- Are time-scale dependencies of the parameters of a rainfall–runoff model found regardless of the time-stepping scheme?
- Does model performance change when parameter sets inferred at one time scale are used at other time scales without scaling?
- Can models simulate daily runoff more accurately with sub-daily rather than daily input data?

The motivation of this study was to explore the possibilities to simulate runoff at sub-daily time scales where data may not be available. It was considered that using data typically found in a developing country that frequently suffers the detrimental effects of floods would fit the purpose of this study.

2 Material and methods

2.1 Study site

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., 2011). This can be partly attributed to data limitations including limited measurements, poor data quality and difficulties accessing the available hydro-meteorological data (Reynolds, 2012).

In Panama, the Panama Canal watershed is an important contributor of the economy with the canal operations and related activities generating almost 10 % of the national gross domestic product (GDP) (Harmon, 2005). This watershed has a denser hydro-meteorological network than the rest of the country.

This study was performed on the tropical Boqueron River basin, which is located within the Panama Canal watershed (Fig. 1) and predominantly covered by forests. The 91 km^2 basin and its 17 km long main river drain to Lake Alajuela and elevation ranges from 100 to 980 m a.s.l. (USGS, 2015). The climate is characterised by a dry season (January–April) and a wet season (May–December). The mean annual rainfall and runoff are 3800 and 2728 $\text{mm}\,\text{y}^{-1}$ respectively (based on the period between 1997 and 2011).

2.2 Model forcing and runoff data

Hourly precipitation data were available from stations within and neighbouring the Boqueron River basin for the period 1997–2011. The areal precipitation was estimated based on Thiessen polygons. Precipitation datasets at different time scales were generated by aggregating the hourly data to 3-, 6-, 12- and 24-hourly time series.

Long-term daily mean values of potential evapotranspiration 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.

Discharge data were available for the period 1997–2011 from the Peluca station, located at the outlet of the Boqueron River basin. The available 15-min discharge data were aggregated to 1-, 3-, 6-, 12- and 24-hourly time series and then converted to runoff.

Runoff observation uncertainty was estimated based on Westerberg et al. (2014), who use 35 stations in Honduras with good-quality rating curves and assume that other stations in the region have similar errors. As a conservative estimate, an additional 5 % stage error was added to the uncertainty bounds.

The data were quality controlled for possible inconsistencies. First, the long-term consistency of the data was evaluated by comparing the long-term runoff coefficient ($R_{\mathrm{C,LT}}$ = 72 %) to R_{C} of each individual year. A variation of less than ±10 % 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. It was assumed that no runoff responses were possible after the average response time of the basin (estimated to be $\sim$ 2–6 h by visual inspection). A threshold of 6 h of possible delay between rainfall and runoff responses was assumed. Runoff with longer response time than this threshold were removed and set as missing values. Additionally, observed runoff responses with larger volumes than their precedent rainfall pulses (within the delay threshold) were removed. Observed runoff responses without any observed rainfall were also removed and set as missing values.

2.3 Model scheme

The HBV model (Bergström, 1976) is a conceptual hydrological model which simulates river runoff through four different routines using precipitation, temperature and potential evapotranspiration as input data. This model has been used for many applications in the past, e.g., for hydrological forecasting, for estimation of design floods (e.g. Harlin and Kung, 1992), for climate-change studies (e.g. Bergström, 1992) and for regionalisation studies (e.g. Seibert, 1999).

The version HBV light (Seibert and Vis, 2012) with its standard model structure was used in this study (Fig. 2). Full details of the HBV model applied in this study are given elsewhere (Bergström, 1992; Seibert and Vis, 2012) and only a brief description is given here.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂◂ ▸▸
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

The standard model structure had eight parameters for inference (highlighted in bold in this paragraph). The model included a soil moisture reservoir (SM [mm]), an upper groundwater reservoir (SUZ [mm]) and a lower groundwater reservoir (SLZ [mm]). At every time step (t), rainfall (R_t) was separated into water filling the soil moisture reservoir and groundwater recharge based on the current water content of SM, the maximum soil moisture storage (**FC** [mm]) and a shape factor (**BETA** [–]). The actual evapotranspiration (AET) from the soil moisture reservoir equalled the potential evapotranspiration (PET) when SM was larger than **FC** times **LP** and was linearly reduced for lower SM values. Groundwater recharge was added to SUZ and an amount of up to **PERC** [mm Δ^{-1}] (Δ denotes the time scale being used) percolated to SLZ. Runoff from SUZ (Q_1) was computed by a non-linear function defined by the outflow coefficient $\boldsymbol{K_1}$ [mm Δ^{-1}] and the exponent **ALPHA** [–]. Runoff from SLZ (Q_2) was computed as a linear function of the storage and the outflow coefficient $\boldsymbol{K_2}$ [mm Δ^{-1}]. Finally, the total simulated runoff (the sum of Q_1 and Q_2) was transformed by an equilateral triangular weighting function defined by **MAXBAS** [Δ^{-1}] representing stream network routing.

2.4 Numerical method

Many widely-used hydrological models, such as the HBV model, use explicit Euler and operator-splitting schemes to solve the differential water-balance equations for the different storages. These numerical methods are attractive because of algorithmic simplicity and computational speed. However, these simple methods can lead to numerical problems and artefacts (Kavetski and Clark, 2011; Kavetski et al., 2011; Michel et al., 2003). For example, Kavetski and Clark (2011) compare explicit Euler (EE) and Implicit Euler (IE) numerical methods and show that storages can oscillate considerably when EE is used for modelling at large time steps, whereas this behaviour is not seen at small time steps. When the implicit Euler method is used, oscillations do not occur regardless of the time-step length. Another artefact seen when operator splitting schemes are used with non-linear storages is that a large input at a certain time step might result in a smaller storage than when a lesser (or no) input is added at that time step due to the overestimated outflow (e.g. Kavetski and Clark, 2011).

In the model version used in this study, the groundwater recharge was computed by adding the inputs to the soil moisture reservoir in steps of 1 mm. Actual evaporation was computed based on the average value of SM at the beginning respectively end of the simulation time step. Outflows from the response routine reservoirs (Q_1 and Q_2) were computed using the explicit Euler method by adding the input to SUZ (recharge) and to SLZ (percolation) first, before these two were computed at a certain time step.

In this study, to avoid results being affected by numerical artefacts due to using the explicit Euler or operator-splitting schemes for time steps of different length, runoff at time scales longer than one hour were modelled at 1 h time steps internally irrespectively of the time scale of the input data. The 3-, 6-, 12- and 24-hourly rainfall datasets were disaggregated to 1-hourly time series by assuming constant precipitation during each hour time step (e.g. a daily precipitation of 24 mm was disaggregated into 24 1 h steps of 1 mm). The 1-hourly runoff simulations were then aggregated to the respective time scale of the conditioning or runoff data to be simulated.

The robustness of this approach was evaluated in two numerical experiments. The first experiment, EXP_1, compared different numerical methods for simulating daily runoff using a single parameter set. This set was inferred by manual calibration, in terms of Nash–Sutcliffe efficiency, using the explicit Euler at daily steps. The numerical methods compared were the Explicit Euler (at daily time steps, $\mathrm{EE}_{24\,\mathrm{h}}$; at 1 h time steps driven by the disaggregated daily rainfall data, $\mathrm{EE}_{\mathrm{D},24\,\mathrm{h}}$; at 1 h time steps driven by the 1-hourly rainfall data, $\mathrm{EE}_{1\,\mathrm{h}}$) and the Implicit Euler (at daily time steps, $\mathrm{IE}_{24\,\mathrm{h}}$). The routing routine was excluded in EXP_1.

The second experiment, EXP_2, studied the effects of time scale on the distribution of behavioural parameters (i.e. existence of time-scale dependencies) and the effects in model performance when parameter sets inferred were used for simulating runoff at time scales different than those at which they were originally selected. Firstly,

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | I▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

parameter values inferred from three Monte Carlo (MC) simulations that used the explicit Euler method with different time-stepping schemes together with input and conditioning data at different time scales were compared. One MC simulation, $\mathrm{MC}_{\mathrm{EE}}$, simulated 1-, 3-, 6-, 12- and 24-hourly runoff with input data at the same time scale and time step as the runoff. A second MC simulation, $\mathrm{MC}_{\mathrm{EED}}$, simulated 1-, 3-, 6-, 12- and 24-hourly runoff with input data at the same time scale as the runoff, but modelled in 1 h time steps internally irrespectively of the time scale of the input data. The third MC simulation, $\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$, simulated daily runoff with input data at different time scales, but modelled in 1 h time steps internally irrespectively of the time scale of the input data.

In short, the data used for model conditioning in EXP_2 are described as follows:

- $\mathrm{MC}_{\mathrm{EE}}$ and $\mathrm{MC}_{\mathrm{EED}}$ used observed 1-, 3-, 6-, 12- and 24-hourly runoff data.
- $\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$ used observed daily runoff data.

Secondly, behavioural parameter sets selected in EXP_2 were tested to evaluate their predictive ability to simulate runoff at other time scales than the ones in which they were inferred. These results helped to answer the question about whether model performance change when parameter sets inferred at one time scale are used without scaling at other time scales.

Thirdly, the model performance resulting from daily runoff simulations with input data at different time scales, $\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$, were compared to answer the question about whether models can simulate daily runoff more accurately with sub-daily rather than with daily input data.

2.5 Model conditioning and performance evaluation

Behavioural parameter sets depend on the objective function chosen for model conditioning. 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}). The first is an indicator of the ability of the model to reproduce the dynamic behaviour of watersheds, while 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):

$$X_1 = \begin{cases} 1, \text{ if } |V_E| \leq 0.10 \\ 0, \text{ otherwise} \end{cases} \tag{1}$$

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

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

where $R_{\text{eff, max}}$ is the maximum Nash–Sutcliffe efficiency value from each individual MC simulation. F varies between 0 and 1 with larger values indicating better fits. Behavioural parameter sets were considered those that gave an F score equal or higher than 0.90.

Ranges of parameter values from previous daily applications of the HBV model (e.g. Booij, 2005; Seibert, 1997) and the uniform probability distribution were used to generate 50 000 parameter sets for the three MC simulations. After initial exploratory MC simulations, the ranges of parameters values were adjusted (Table 1).

Runoff simulations were carried out from 1997 to 2011, where the first year was used as warming-up period, the following seven years were used for conditioning (1998–2004), and the last seven years for validation (2005–2011).

3 Results

3.1 Numerical experiment 1: comparison of numerical methods for daily runoff simulation

The manual calibration of the model rendered one parameter set with values within previously reported ranges for daily applications (e.g. Seibert, 1997) and a Nash–Sutcliffe efficiency of 0.8. All of the numerical methods gave similar results of SM (Fig. 3a) and SLZ, while the explicit Euler method at daily time steps ($\mathrm{EE}_{24\,\mathrm{h}}$) resulted in considerably lower SUZ storage (Fig. 3b) and higher runoff from SUZ (Q_1, Fig. 3c) than the other methods. Analysis of Q_1 for the different numerical methods revealed that $\mathrm{EE}_{24\,\mathrm{h}}$ showed a substantially better fit to observed runoff (Q_2 only had minor contributions to the total runoff and never more than 1.75 mm at any time step).

Assuming $\mathrm{EE}_{1\,\mathrm{h}}$ was the "exact solution" (this agreed almost perfectly with the implicit solution at 1-hourly steps), a comparison between the "exact solution" and $\mathrm{EE}_{24\,\mathrm{h}}$ revealed a large difference in the SUZ storage at time step 2515 (~ 47 %). This erratic behaviour by the $\mathrm{EE}_{24\,\mathrm{h}}$ solution was due to a large groundwater recharge added at the time step (254 mm), which resulted in a high Q_1 generation and thereby in a low SUZ storage.

The daily implicit method ($\mathrm{IE}_{24\,\mathrm{h}}$) and the explicit method driven by the disaggregated daily data ($\mathrm{EE}_{\mathrm{D},24\,\mathrm{h}}$) gave a fair agreement to the "exact solution" of SUZ (differences at time step 2515 were ~ 4.5 and 7.5 % respectively).

3.2 Numerical experiment 2: time scale dependencies of model parameters?

3.2.1 Effects of time scale on the distribution of behavioural parameters

The distribution of the behavioural parameter values for the explicit Euler method at 1-hourly time steps ($\mathrm{MC}_{\mathrm{EED}}$ and $\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$) seem relatively constant across the time scales (Fig. 4). Only a slight shift of ALPHA and K_1 at the 24 h time scale was seen in

$MC_{EED,Q=24\,h}$, and a large shift of the MAXBAS values was seen in MC_{EED} when moving from sub-daily to daily time scale. However, when the explicit Euler method was used for modelling at the same time steps as the time scale of the input data (MC_{EE}), some parameters (e.g. ALPHA and K_1) showed strong time-scale dependencies.

The K_2, FC, LP and BETA parameters for all three time-stepping schemes displayed similar behaviour as PERC in Fig. 4.

3.2.2 Maxima model performances after model conditioning

Higher Nash–Sutcliffe efficiencies (R_{eff}) were found when simulating runoff at daily than at sub-daily time scales in MC_{EE} and MC_{EED}, but performance was stable over the time scales for $MC_{EED,Q=24\,h}$ (Table 2).

3.2.3 Changes in model performance when simulating runoff at time scales different than those at which the parameter sets were inferred

The behavioural parameter sets inferred with daily runoff data and input data at different time scales ($MC_{EED,Q=24\,h}$) were used to simulate daily runoff with input data at other time scales than the ones at which the parameters were originally inferred. When those parameter sets were used with sub-daily input data, equal model performances were seen across the time scales (Fig. 5a–d). Model performance only slightly decreased when the parameter sets inferred with sub-daily input were used with daily input data (1st percentile model performance in Fig. 5e). This was presumably caused by the slight shift of ALPHA and K_1 at the daily time scale in this experiment, however relatively equal 50th and 99th percentile model performances were found across the time scales. The behaviours found in $MC_{EED,Q=24\,h}$ were similar in the validation period, though the Nash–Sutcliffe model efficiencies were higher (by ~ 0.1) assumingly related to differences in data quality between the two periods (volume errors were found to be approximately the same).

The behavioural parameter sets inferred with input and conditioning data at the same time scale (MC_{EED}) were also used to simulate runoff at other time scales than the ones at which they were originally inferred. When those were used to simulate daily runoff, equal model performances were appreciable (Fig. 6e). The largest decreases in model performance were seen when the behavioural parameter sets inferred at the daily time scale were used to simulate sub-daily runoff (1st percentile model performance at the 24 hourly time scale in Fig. 6a–d), however nearly equal 50th and 99th percentile model performances were found during this procedure as when parameter sets inferred at finer scales were used (Fig. 6a–d). Some decrease in model performance was also noticeable when the parameter sets inferred after conditioning the 3-, 6-, 12- and 24-hourly runoff were used to simulate 1-hourly runoff (1st percentile model performance in Fig. 6a), however relatively similar 50th and 99th percentile model performances were found across the time scales. When the behavioural parameter sets inferred at sub-daily time scales were used to simulate 3-, 6- and 12-hourly runoff, more or less equal model performances were appreciable (Fig. 6b–d). Similar behaviour in model performance was seen in both the conditioning and validation periods. Model performances were found to be higher in the validation than in conditioning period in MC_{EED}, as well as in $MC_{EED,Q=24\,h}$.

3.2.4 Changes in the uncertainty of the simulated Runoff

Uncertainty ranges of the simulated runoff was found to decrease when the behavioural parameter sets inferred in $MC_{EED,Q=24\,h}$ were used with input data at coarser time scales than the 1-hourly used during conditioning (Fig. 7). In other cases, there was not a clear pattern of the changes in uncertainty ranges of the simulated runoff (MC_{EED} example in Fig. 8).

4 Discussion

In literature it has been reported that time-scale dependencies of hydrological model parameters are common. However, the causes of these dependencies are not clear. Numerical errors due to using the explicit Euler or operator-splitting schemes have not been sufficiently addressed by hydrologists compared to extensive studies on other sources of uncertainty involved in rainfall–runoff modelling. Two numerical experiments were carried out in this study to address this issue. First, several daily runoff simulations generated using a single parameter set but different numerical methods were compared (EXP$_1$). Secondly, the effects of time scale on the distribution of behavioural parameters and on model performance were analysed by implementing different time-stepping schemes together with input and conditioning data at different time scales (EXP$_2$).

4.1 Numerical experiment 1: comparison of numerical methods for daily runoff simulation.

Numerical errors are dependant on the numerical method implemented to solve the model equations and on the time scale of model runs (Kavetski et al., 2003). The first experiment showed that large numerical errors occur when the explicit Euler and operator-splitting schemes are used to simulate runoff at daily time steps. From the numerical methods implemented in EXP$_1$, the Explict Euler method at daily time steps (EE$_{24\,\mathrm{h}}$) gave the best fit to the observed runoff, but this good fit was misleading since this behaviour was not seen in the more robust numerical methods. This spurious behaviour was mainly caused by the numerical method implemented rather than by the ability of the parameter set to represent the physical processes of the watershed.

In this study, the possible large numerical errors when using the explicit Euler method were dealt by disaggregating the input data in 1 h steps, irrespectively of its time scale, to run the model internally at this time step, and then aggregating the 1-hourly simulations to the respective time scale of the conditioning or runoff data to be simulated. This approach resulted in solutions similar to the more robust implicit Euler method, but at a much lower computational cost. If unsuitable time-stepping schemes are used to solve model equations, false or erroneous conclusions might be made in model sensitivity analyses, parameter inference, result interpretation and model uncertainty analyses (e.g. inferring that some parameter sets are representative of the system when in reality they are not) (Kavetski and Clark, 2011).

4.2 Numerical experiment 2: time-scale dependencies of model parameters?

4.2.1 Effects of time scale on the distribution of behavioural parameters

The second experiment showed a clear time-scale dependence of the parameter values inferred when the explicit Euler method was used without considering the possible large numerical errors due to the time-step length (i.e. $\mathrm{MC}_{\mathrm{EE}}$). This dependence almost fully disappeared, when the same numerical method was run at 1 h time steps using disaggregated input if necessary (i.e. $\mathrm{MC}_{\mathrm{EED}}$ and $\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$).

These results contradict what has been stated in many previous studies (e.g. Bastola and Murphy, 2013; Littlewood and Croke, 2008; Littlewood, 2007; Ostrowski et al., 2010; Wang et al., 2009), and support the arguments by Kavetski et al. (2011), that parameter values representative of the system are relatively constant over different time scales when robust numerical methods are used. Since numerical errors are small when robust numerical methods are used, parameter sets inferred from models that use those schemes are more reliable than those inferred from models that use simple numerical methods with no error controls.

The large shift of the MAXBAS values seen when moving from sub-daily to daily time scale in $\mathrm{MC}_{\mathrm{EED}}$ may be due to identifiability problems (i.e., parameter equifinality; Beven, 2009). MAXBAS is a representation of the concentration time and since this is short for the study area, MAXBAS became insensitive at coarser time scales. The MAXBAS values inferred at the daily time scale were therefore those that combined with the rest of the model-parameter values gave the highest model performances, but were not necessarily more representative than other values. There was no obvious explanation for the slight changes in ALPHA and K_1 towards the daily time scale in $\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$. However, the overall results suggest that parameter sets inferred at one time scale can be used at other time scales without any time scaling.

4.2.2 Maxima model performances after model conditioning

Relatively equal maximum Nash–Sutcliffe model efficiencies were found when simulating daily runoff with daily and sub-daily input data. This may be related to the information content of the daily conditioning data, rather than to the information content of the input data. These results are contrary to that of Wang et al. (2009) who report better predictions of daily discharge, in terms of a relative error function, using hourly rather than daily input data.

In $\mathrm{MC}_{\mathrm{EE}}$ and $\mathrm{MC}_{\mathrm{EED}}$, it was shown that better model performances were found for simulating daily than sub-daily runoff, which was likely caused to the increase of information at the sub-daily time scales (e.g. more time steps to evaluate the model-run performance). Even if one might expect higher model efficiencies when modelling at a finer time scale this might often not be the case as simulations become more sensitive to random errors.

4.2.3 Changes in model performance when simulating runoff at time scales different than those at which the parameter sets were inferred

It was shown that when the behavioural parameter sets inferred in $\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$ were used to simulate daily runoff with input data at other time scales than the ones at which they were inferred, relatively equal model performances were obtained for most cases. This suggested that if parameter sets inferred at a certain time scale are intended to be used for modelling at the same time scale but with input data at finer scales, no changes in model performance should occur.

When parameter sets inferred at the daily time scale were used to simulate runoff at sub-daily time scales ($\mathrm{MC_{EED}}$), performance only slightly decreased compared to when parameter sets inferred at those time scales were used. A loss in performance is to be expected since many of the physical processes that characterize the modelled watershed (e.g. quick flow) are hidden by the aggregation of the input and conditioning data at the daily time scale, resulting in a loss of information in the parameter sets inferred at daily time scale compared to those inferred at finer time scales.

Model performance decreased somewhat when parameter sets inferred at coarser time scales than 1-hourly were used for modelling at this time scale. This decrease in performance was likely due to the relatively simple model structure used in this study and the lesser information content in the parameter sets inferred at time scales larger than 1 h. However, a more complex model structure may not have been meaningful at coarse time scales since the model would have been overparameterized.

The decrease in model performance when simulating runoff at time scales different than those at which the parameter sets were inferred was considerably smaller than what has been reported in other studies (e.g. Bastola and Murphy, 2013). Some of those studies have used the explicit Euler method at large time steps (e.g. daily) to infer model parameters, possibly causing the large decrease in performance when those parameters were used to simulate runoff at finer time scales. In this study the time-stepping scheme of the previous numerical method was adjusted to 1-hourly time steps to avoid large numerical errors and to limit the possibility for erroneous conclusions.

4.2.4 Changes in the uncertainty of the simulated runoff

Uncertainty ranges of the simulated runoff tended to change when parameter sets inferred at the daily time scale were used to simulate daily runoff with input data at other time scales than the ones used during conditioning. The larger the difference in time scale between the input data used during conditioning and the input data used afterwards to simulate runoff, the lesser the uncertainty of the simulated daily runoff was. This was assumed to be related to the information content of the parameter sets inferred, which was determined by the time scale of the input data.

Changes in the uncertainty of the simulated runoff were also noticed in $\mathrm{MC_{EED}}$ when the parameter sets inferred at a certain time scale were used to simulate runoff at other time scales. However, there was no clear pattern of this behaviour.

5 Conclusions

The main motivation of this study was the need of flood forecasting models at sub-daily time scales in regions where data availability at these scales is limited. The main findings were:

1. Time-scale dependencies were found to be an artefact of the numerical method or time stepping used rather than a real time-scale-data dependence.
2. Given an appropriate numerical method, parameters inferred at one time scale can be used directly (without any time scaling) to simulate runoff at other time scales with small (if any) decreases in model performance (in terms of Nash–Sutcliffe and volume-error efficiencies).
3. The findings imply that as soon as sub-daily driving data can be secured, flood forecasting in watersheds with sub-daily concentration times is possible with model parameter values inferred from long time series of daily data, as long as an appropriate numerical method is used.
4. Daily runoff simulations are as accurate when sub-daily input data is used as when daily input data is used.

The results of this study can contribute to forecast floods in watersheds with concentration times smaller than 24 h and can help minimize the detrimental effects of floods to society in areas where data at sub-daily time scales may not be available.

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.

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 would like to thank the staff at the Panama Canal Authority (ACP) and the Department of Hydrometeorology at ETESA (Empresa de Transmisión Eléctrica, S.A.) for their kind assistance in providing data for the study.

References

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

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

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

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

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

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

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

Harmon, R. S.: An introduction to the Panama Canal watershed, in: The Río Chagres: A Multidisciplinary Profile of a Tropical Watershed, Springer, Netherlands, 19–28, 2005.

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

Kavetski, D., Kuczera, G., and Stewart, W., F.: Semidistributed hydrological modeling: a “saturation path” perspective on TOPMODEL and VIC, Water Resour. Res., 39, 1246, doi:10.1029/2003WR002122, 2003.

Kavetski, D., Fenicia, F., and Clark, M. P.: 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, doi:10.1029/2010WR009525, 2011.

Littlewood, I. G.: 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, 149–155, 2007.

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

Michel, C., Perrin, C., and Andreassian, V.: The exponential store: a correct formulation for rainfall – runoff modelling, Hydrolog. Sci. J., 48, 109–124, doi:10.1623/hysj.48.1.109.43484, 2003.

Ostrowski, M., Bach, M., Desimone, S. V and Gamerith, V.: Analysis of the time-step dependency of parameters in conceptual hydrological models, Technische Universität Darmstadt, Darmstadt, Germany, 31 pp., 2010.

Reynolds, J. E.: Usability of Standard Monitored Rainfall–Runoff Data in Panama, Juan Diaz River Basin, M. S. thesis, Uppsala University, Uppsala, Sweden, 62 pp., 2012.

Seibert, J.: Estimation of parameter uncertainty in the HBV model, Nord. Hydrol., 28, 247–262, doi:10.2166/nh.1997.015, 1997.

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

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

USGS: U. S. Geological Survey, http://hydrosheds.cr.usgs.gov/datadownload.php?reqdata=3demg, last access: 05 June 2015.

Wang, Y., He, B., and Takase, K.: 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, Hydrolog. Sci. J., 54, 886–898, doi:10.1623/hysj.54.5.886, 2009.

Wang, Y., He, B., and Takase, K.: Reply to the discussion of "Effects of temporal resolution on hydrological model parameters and its impact on prediction of river discharge" by Littlewood et al., Hydrolog. Sci. J., 56, 525–528, doi:10.1080/02626667.2011.565770, 2011.

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

Westerberg, I. K., Gong, L., Beven, K. J., Seibert, J., Semedo, A., Xu, C.-Y., and Halldin, S.: Regional water balance modelling using flow-duration curves with observational uncertainties, Hydrol. Earth Syst. Sci., 18, 2993–3013, doi:10.5194/hess-18-2993-2014, 2014.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. Final ranges of the parameters values used for the MC simulations.

Parameter	Description	Minimum	Maximum	Unit
	Soil Moisture Routine			
FC	Maximum soil moisture storage	200.00	600.00	mm
LP	Soil moisture value above which actual evapotranspiration reaches potential evapotranspiration.	0.70	1.00	–
BETA	Determines the relative contribution to runoff from rainfall or snowmelt	1.00	2.50	–
	Response Routine			
PERC	Threshold parameter	2.40	9.60	$\mathrm{mm\,d^{-1}}$
ALPHA	Non-linearity coefficient	0.50	1.00	–
K_1	Storage coefficient 1	0.0024	0.12	$\mathrm{d^{-1}}$
K_2	Storage coefficient 2	0.005	0.01	$\mathrm{d^{-1}}$
	Routing Routine			
MAXBAS	Length of equilateral triangular weighting function	1.00	6.00	h

Table 2. Nash–Sutcliffe efficiency maxima obtained and *F* threshold values for selecting the behavioral parameter sets at each time scale from the Monte Carlo (MC) simulations in numerical experiment 2, EXP_2. Maxima values are those outside the parenthesis and the *F* threshold values are those inside of them. The three MC simulations used the explicit Euler method (EE) with different time-stepping schemes together with input and conditioning data at different time scales. EED stands for using EE but disaggregating the input data to 1-hourly time steps to model internally at this time step irrespectively of the time scale of the input data.

Time scale of runoff data for model conditioning	Time scale of the input data				
	1 h	3 h	6 h	12 h	24 h
Same as input data ($\mathrm{MC}_{\mathrm{EE}}$)	0.71 (0.64)	0.71 (0.64)	0.70 (0.63)	0.78 (0.70)	0.81 (0.73)
Same as input data ($\mathrm{MC}_{\mathrm{EED}}$)	0.71 (0.64)	0.72 (0.65)	0.71 (0.64)	0.75 (0.68)	0.81 (0.73)
Daily ($\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$)	0.82 (0.74)	0.82 (0.74)	0.82 (0.74)	0.80 (0.72)	0.81 (0.73)

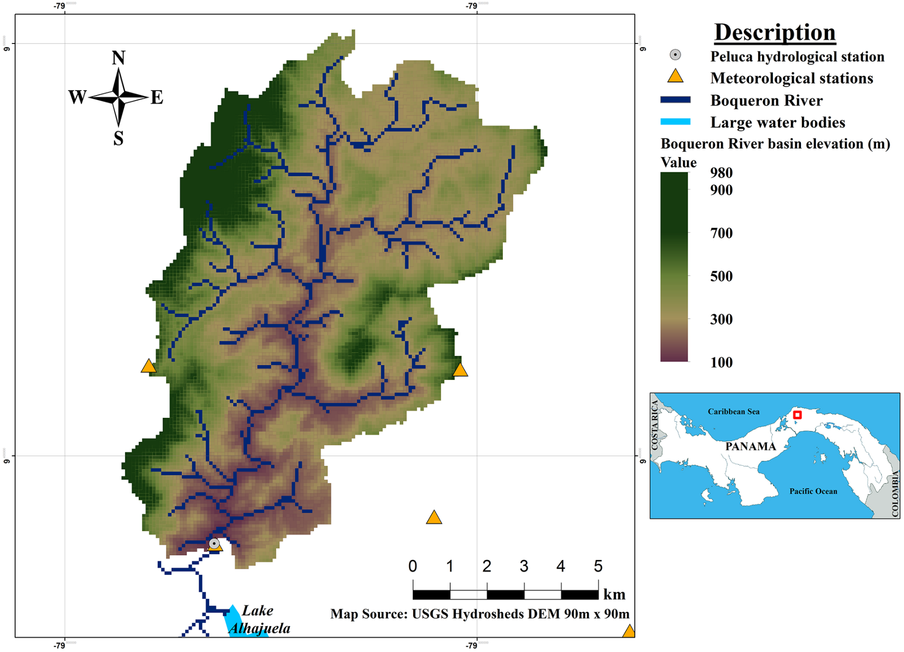

Figure 1. Location of Boqueron River Basin in Panama.

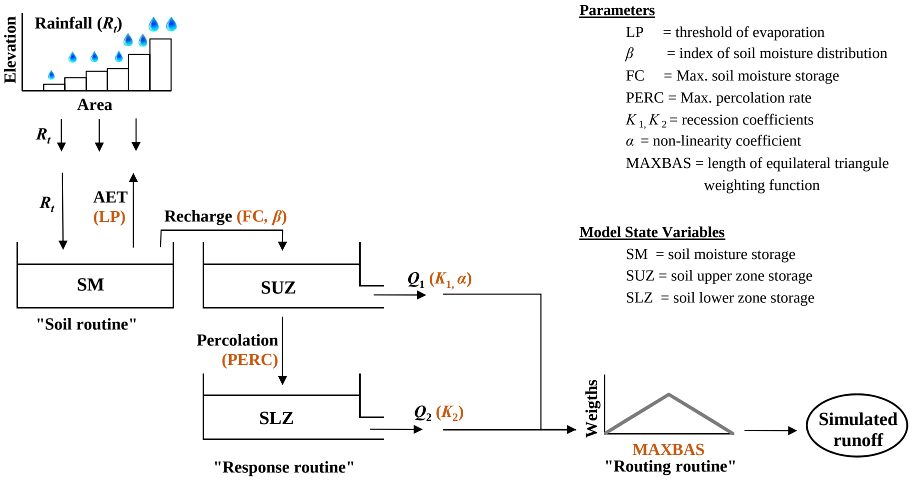

Figure 2. Standard model structure of the HBV-model.

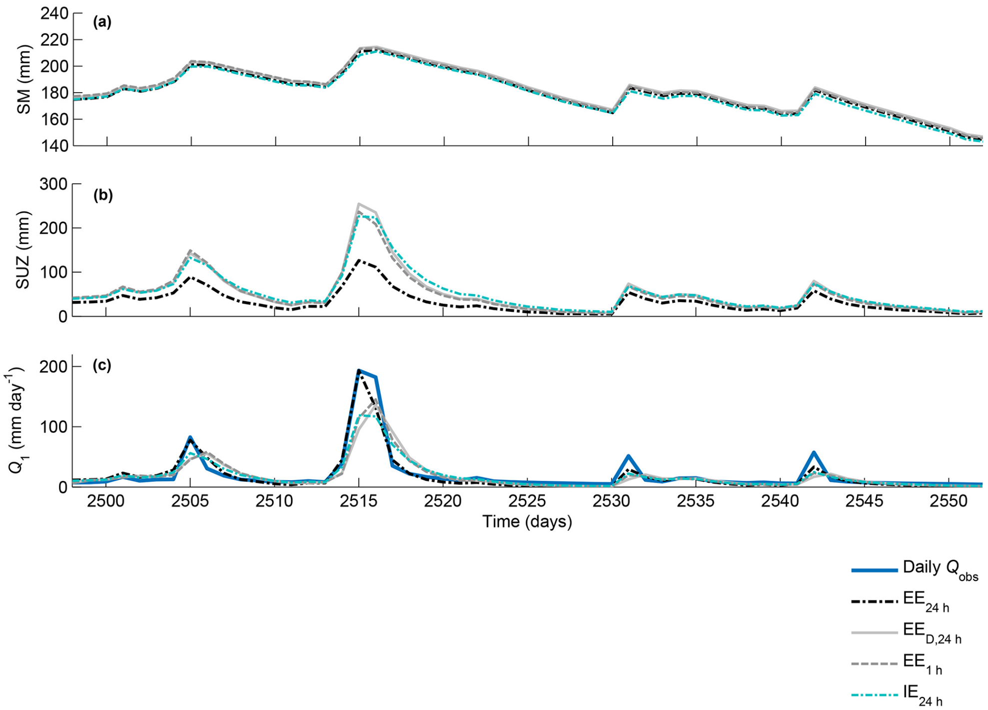

Figure 3. Daily simulated soil moisture storage, SM **(a)**; upper groundwater storage, SUZ **(b)**; and runoff from SUZ, Q_1 **(c)** using different numerical methods. The numerical methods compared were the explicit Euler at daily time steps, $\mathrm{EE}_{24\,\mathrm{h}}$; the explicit Euler at 1 h time steps driven by the disaggregated daily rainfall data, $\mathrm{EE}_{\mathrm{D},24\,\mathrm{h}}$; the explicit Euler at 1 h time steps driven by the hourly rainfall data, $\mathrm{EE}_{1\,\mathrm{h}}$; and the implicit Euler method at daily time steps, $\mathrm{IE}_{24\,\mathrm{h}}$. Daily Q_{OBS} stands for observed runoff. The simulation period shown is towards the end of the rainy season (between the beginning of November 2004 until the first third of December 2004).

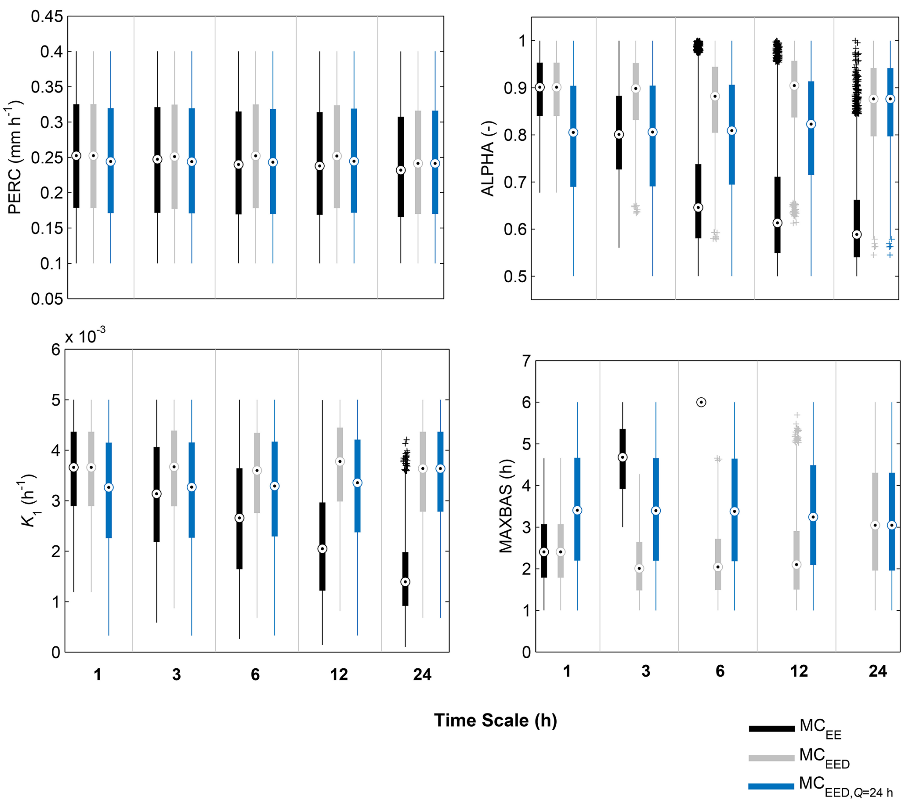

Figure 4. Boxplots of behavioural parameter values inferred at different time scales from each individual Monte Carlo (MC) simulation using the explicit Euler (EE) method: when the time scale of the input data was used as the time step (MC$_{\mathrm{EE}}$), when hourly time steps were used and input data was disaggregated when needed (MC$_{\mathrm{EED}}$), and when hourly time steps were used and input data was disaggregated when needed but always inferred against daily runoff (MC$_{\mathrm{EED},Q=24\,\mathrm{h}}$).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
|◀
▶|
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

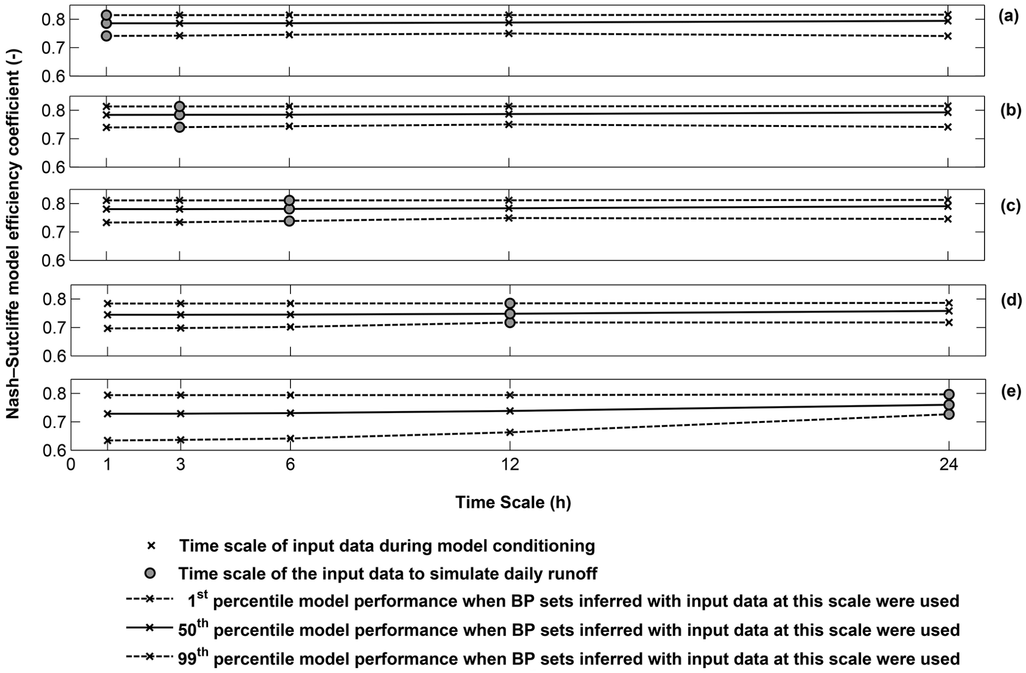

Figure 5. Nash–Sutcliffe model efficiencies when simulating daily runoff with the behavioural parameter (BP) sets inferred against daily runoff ($\mathrm{MC}_{\mathrm{EED},Q=24\,\mathrm{h}}$), with input data at finer **(a–d)** or the same time scale **(e)** as the runoff data.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀|
|▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

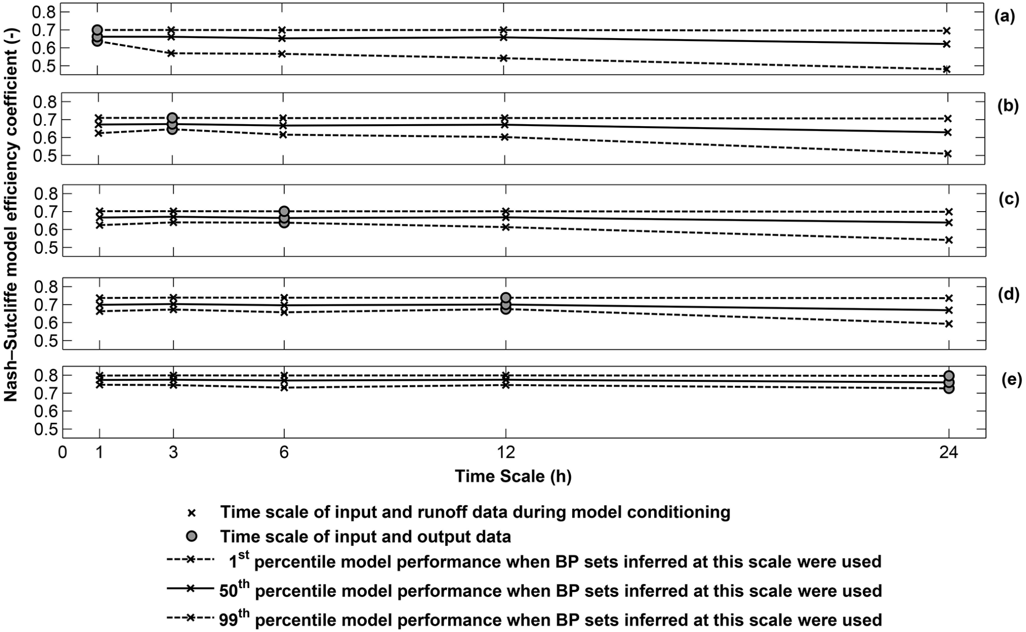

Figure 6. Nash–Sutcliffe model efficiencies when simulating runoff at time scales different than those at which the behavioural parameter (BP) sets were inferred (MC_{EED}).

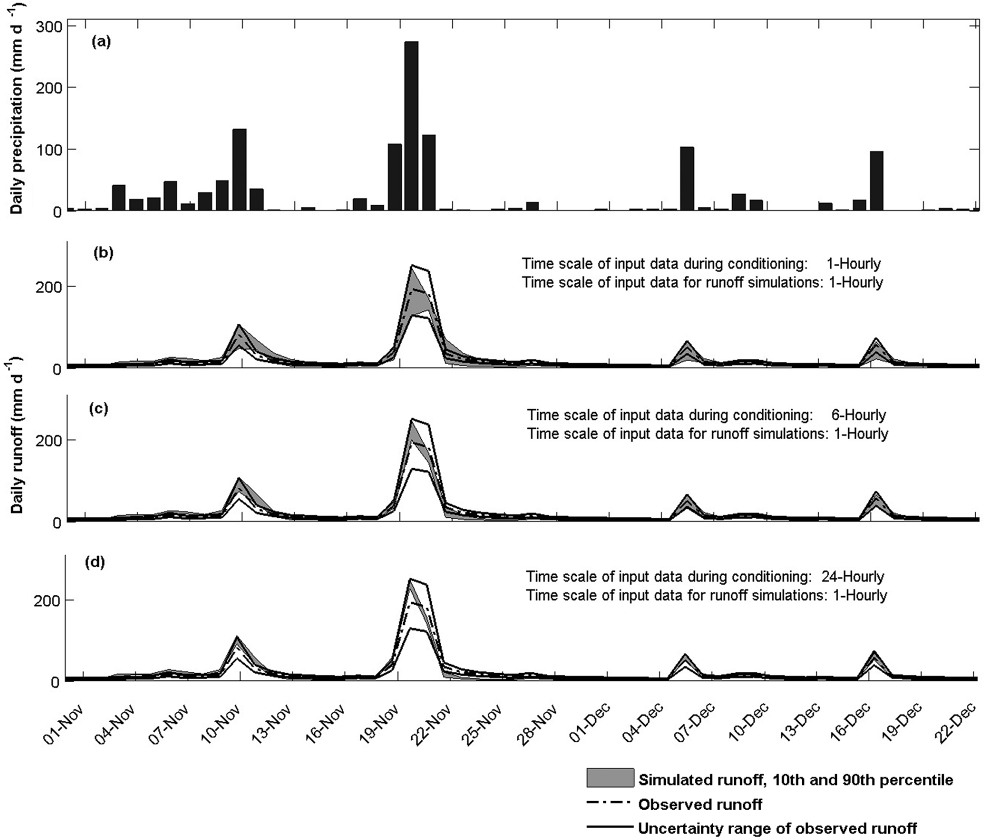

Figure 7. Daily precipitation **(a)** and uncertainty limits (10th and 90th percentile) of observed and predicted daily runoff **(b–d)** in the conditioning period using parameter sets inferred against daily observed runoff ($MC_{EED,Q=24\,h}$). The period shown is towards the end of 2004.

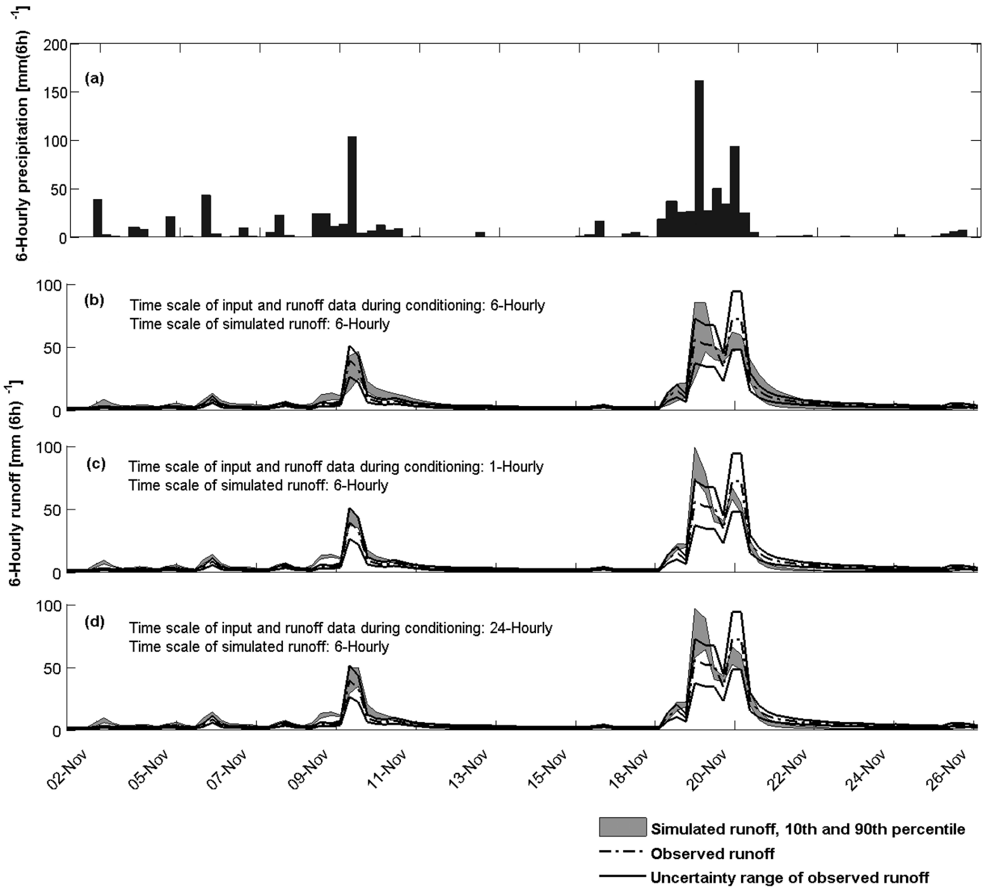

Figure 8. 6-hourly precipitation **(a)** and uncertainty limits (10th and 90th percentile) of observed and predicted 6-hourly runoff **(b–d)** in the conditioning period using parameter sets inferred at the 6-, 1- and 24-hourly time scales (MC_{EED}). The period shown is towards the end of 2004.