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Improvement of the SWAT model for event-based flood forecasting on a sub-daily time scale

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Abstract. Flooding represents one of the most severe natural disasters threatening the development of human society. Flood forecasting systems imbedded with hydrological models are some of the most important non-engineering measures for flood defense. The Soil and Water Assessment Tool (SWAT) is a well-designed hydrological model that is widely applied for runoff and water quality modeling. The original SWAT model is a long-term yield model. However, a daily simulation time step and continuous time marching limit the use of the SWAT model for detailed, event-based flood forecasting. In addition, SWAT uses a uniform parameter set to parameterize the Unit Hydrograph (UH) for all sub-basins, thereby ignoring the heterogeneity among the sub-basins. This paper developed a method to perform event-based flood forecasting on a sub-daily time scale based on SWAT2005. First, model programs for surface runoff and water routing were modified for a sub-daily time scale. Subsequently, the entire loop structure was broken into discrete flood events in order to obtain a SWAT-EVENT model in which antecedent soil moisture and antecedent reach storage could be obtained from daily simulations of the original SWAT model. Finally, the original lumped UH parameters were refined into distributed parameters to reflect the spatial variability of the studied area. The modified SWAT-EVENT model was used in the Wangjiaba catchment located in the upper reaches of the Huaihe River in China. Daily calibration and validation procedures were first performed for the SWAT model with long-term flow data from 1990 to 2010, after which sub-daily ($\Delta t = 2$ h) calibration and validation in the SWAT-EVENT model were conducted with 24 flood events originating primarily during the flood seasons within the same time span. Daily simulation results demonstrated acceptable model performances with Nash-Sutcliffe efficiency coefficient (E_{NS}) values of 0.77 and 0.78 for the calibration and the validation, respectively. Event-based flood simulation results indicated reliable performances, with E_{NS} values varying from 0.66 to 0.95. The SWAT-EVENT model, compared to the SWAT model, also improved the simulation accuracies of the flood peaks. The application of distributed UH parameters within the SWAT-EVENT model can more effectively depict the spatial variability within the study area, resulting in higher qualification ratios of the relative peak discharge error (E_{RP}), relative peak time error (E_{RPT}) and relative runoff volume error (E_{RR}) relative to the application of lumped parameters.

Keywords: SWAT model; Event-based flood forecasting; Antecedent conditions; Unit Hydrograph

1 Introduction

A flood represents one of the most severe natural disasters in the world. It has been reported that nearly 40 % of losses originating from natural catastrophes are caused by floods (Adams Iii and Pagano, 2016). Numerous measures have been designed to defend against the threats of flooding. Of the many non-engineering measures, flood forecasting is one of the most important. A complete flood forecasting system consists of many different functional components, the most significant of which is the hydrological model.

Numerous hydrological models have been developed since their first appearance. According to the spatial discretization method, these existing hydrological models can be divided into two categories: lumped models and distributed models (Maidment, 1994). Although lumped models are commonly accepted for research and associated applications, they are not applicable to large catchments since they do not account for the heterogeneity of the catchments (Yao et al., 1998). Meanwhile, distributed models subdivide the entire catchment into a number of smaller heterogeneous sub-units with dissimilar attributes. The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Srinivasan et al., 1998; Arnold and Fohrer, 2005) is the most widely used of the prevailing distributed models.

The SWAT model was developed by the United States Department of Agriculture (USDA) in 1994 and represents a typical distributed hydrological model that can simulate long-term surface and subsurface discharge, sediment deposition, nutrient transport and transformation processes under varying land uses, soil types and management conditions. The SWAT model has been widely applied throughout the world (Gassman et al., 2010), with corresponding research involving runoff simulation, non-point source pollution, model parameters, hydrological responses to changed scenarios and so on.

SWAT is a continuous (i.e., long-term) model (Kiniry et al., 2005) with a limited applicability toward simulating instantaneous hydrologic responses. Therefore, Jeong et al. (2010) extended the capability of SWAT to simulate sub-daily or even sub-hourly hydrological processes, the modifications of which primarily focused on the model algorithms to enable the SWAT model to operate at a finer time scale with a continuous modeling loop. According to flood forecasting programs and technology in China (MWR, 2009), rainfall and discharge observations at a sub-daily time scale are usually only collected during flood periods, while daily data are measured otherwise. Hydrological models are usually applied at different time scales (i.e., a daily time scale for continuous simulations and a sub-daily time scale for event-based flood forecasting) according to the availability of observed rainfall and discharge data (Yao et al., 2014). Hence, a major constraint for the application of the SWAT model as modified by Jeong et al. (2010) is the conflict between a continuous simulation loop and the discontinuous observed sub-daily data in China.

To capture the sophisticated characteristics of flood events at a sub-daily time scale, a refinement of the spatial representation within the SWAT model is necessary. A dimensionless Unit Hydrograph (UH), which was distributed as a triangular shape and embedded within an overland flow routing process in the SWAT model, was applied to relate hydrologic responses to specific catchment characteristics, such as the dimensions of the main stream and basin area, through applications of Geographic Information System (GIS) or Remote Sensing (RS) software (Jena and Tiwari, 2006). In addition, the SWAT model provides a uniform parameter set with which to adjust the shape of the UH in each sub-basin. Given the spatial heterogeneity of the catchment, the application of this adjustment parameter seems to be rather unconvincing. Moreover, because a great deal of research has primarily focused on daily, monthly or yearly simulations using the SWAT model, little effort has actually been provided toward demonstrating the usage of the UH method in the SWAT model.

The objective of this paper is to modify the SWAT model in order to obtain the capability to forecast event-based floods at a sub-daily time scale and to improve the UH module in order to capture the spatial characteristics of flood events. SWAT is an open-source code model, which makes it possible to produce such a modification. SWAT2005 is employed in this study because the newer versions perform auto-calibration with external software (i.e., SWAT-CUP), and the Huaihe River basin in China is utilized for the case study in this paper.

2 Study area and data

2.1 Study area

The Huaihe River basin (30°55'–36°36' N, 111°55'–121°25' E) is situated in the eastern part of China. The Wangjiaba (WJB) catchment is situated within the upper reaches of the Huaihe River basin and was chosen as the study area for this paper (see Fig. 1). The WJB catchment has a drainage area of 30630 km^2, wherein the long channel reaches from the source region to the WJB outlet. The southwestern upstream catchment is characterized as a mountain range with a maximum elevation of 1110 m above sea level. The central and eastern downstream regions are dominated by plains. The study catchment is a subtropical zone with an annual average temperature of 15 °C. The long-term average annual rainfall varies from 800 mm in the north to 1200 mm in the south. Since the catchment is dominated by a monsoon climate, approximately 60 % of the annual rainfall is received during the flood season ranging from mid-May to mid-October. Severe rainfall events within the study area typically transpire during the summer, frequently resulting in severe floods (Zhao et al., 2011). Apart from the WJB stream gauging station at the catchment outlet, other stations at Bantai (BT), Xixian (XX) and Huangchuan (HC) are located upstream of the study catchment, all of which are illustrated in Fig. 1.

2.2 Model dataset

To construct and execute the SWAT model, a Digital Elevation Model (DEM), together with land use and soil type data, is required. Climate data, including that of rainfall, temperature, wind speed, etc., are also used.

The DEM data in this study were downloaded from the website of the U.S. Geological Survey (USGS) with a spatial resolution of 90 m. The study catchment was divided into four sub-basins with the four available stream gauges representing the corresponding outlets (i.e., of the sub-basins in Fig. 1). The geographic features of the four sub-basins are displayed in Table 1.

A land use map was produced from the Global Land Cover 2000 (GLC2000) data product with a grid size of 1 km (Bartholomé and Belward, 2005). Six categories of land use were identified for this catchment, as are shown in Fig.2 (a): agricultural land (80.51 %), forest-deciduous (6.76 %), forest-evergreen (2.26 %), range-brush (1.09 %), range-grasses (8.09 %) and water (1.29 %).

Soil data were obtained from the Harmonized World Soil Database (HWSD) with a spatial resolution of 30 arc-seconds. The HWSD also provides an attributed database that contains the physico-chemical characteristics of soil data worldwide (Nachtergaele et al., 2012). Since the built-in soil database within the SWAT model does not cover the study area, additional soil parameters were calculated using the method proposed by Jiang et al. (2014). Figure 2 (b) exhibits the distribution of soil types in the study area according to the FAO-90 soil classification. Consequently, Eutric Planosols and Cumulic Anthrosols are the two main soil types with area percentages of 24.71 % and 19.95 %, respectively.

The SWAT model uses a “weather generator” to simulate the climatic characteristics of the catchment. Relative humidity, wind speed, solar radiation and the minimum and maximum air temperatures were obtained from the Climate Forecast System Reanalysis (CFSR), which was designed based on the forecast system of the National Centers for Atmospheric Prediction (NCEP) to provide an estimation for a set of climate variability from 1979 to the present day.

A dense rain gauge network consisting of 138 gauges is distributed throughout the study area, as illustrated in Fig. 1. Daily observed rainfall data were retrieved from 1991 to 2010 with coverage during the entire year, while sub-daily ($\Delta t = 2$ h) rainfall data are only available for flood periods from May to September during the years 1991 and 2010.

3 Methodologies

3.1 Development of a sub-daily event-based SWAT model

The original SWAT model was designed for continuous simulations using a daily time step. The SWAT model operates most effectively during the prediction of long-term catchment responses to land cover changes or soil management practices (Jeong et al., 2011). When faced with flood forecasting issues, a finer time scale is required to realistically capture the instantaneous changes representative of flood processes. Within the flood forecasting program and technology of China, discharges are observed daily during the dry seasons, which is intensified to sub-daily during flooding seasons in order to capture the details of flooding hydrographs and provide timely flood warnings (MWR, 2009).

Therefore, the original daily simulation-based SWAT model first needs to be modified in order to perform sub-daily simulations. This modification follows the method proposed by Jeong et al. (2010). Second, the sub-daily SWAT model must be applied in such a manner to achieve the simulation of individual flooding events rather than to simulate in a continuous way, as performed in the original SWAT model. Event-based flood modeling is necessary for these reasons: (1) to enable the modelers to acknowledge the detailed information of up-coming floods and (2) to potentially conduct flood forecasting within a watershed without possessing continuously recorded hydrologic data. To resolve this problem, a method was developed and it is illustrated in Fig. 3. A continuous rainfall sequence with a daily time-step was imported into the original SWAT model to perform long-term daily simulations in order to extract the antecedent conditions for the flood events, including the antecedent soil moisture and antecedent reach storage. To enable the SWAT model to simulate flood events, the original source codes were modified and compiled into a new version known as SWAT-EVENT. In the source code of SWAT2005, the subroutine "simulate" contains the loops governing the hydrological processes following the temporal marching for the entire simulation period. Here, this continuous loop design was broken into several discrete flood periods according to different starting and ending dates.

The initialization of variables for the land phase of the hydrologic cycle and channel routing are executed in the "varinit" and "rchinit" subroutines, respectively. Water stored within the soil profiles and reaches at the beginning of each flood event are set equal to the respective values extracted from the long-term daily simulations of the original SWAT model rather than the values of the previous day. This modification is described as follows:

$$\begin{aligned} s_0(i,j) &= s_{\text{ini}}(j) \quad \text{if } i=1 \\ s_0(i,j) &= s_{\text{t}}(i-1,j) \quad \text{if } i\neq 1 \end{aligned} \tag{1}$$

$$\begin{aligned} r_0(i,k) &= r_{\text{ini}}(k) \quad \text{if } i=1 \\ r_0(i,k) &= r_{\text{t}}(i-1,k) \quad \text{if } i\neq 1 \end{aligned} \tag{2}$$

where i is the current day being simulated for a specific flood event; j is the HRU number; $s_0(i,j)$ is the amount of water stored in the soil profile in the j_{th} HRU at the beginning of day i (mm); $s_{\text{ini}}(j)$ is a newly defined variable referring to the initial soil moisture in the j_{th} HRU for a specific flood event and is extracted from the daily simulation results in this study (mm); $s_{\text{t}}(i-1,j)$ is the final amount of water stored in the soil profile in the j_{th} HRU at the end of the day prior to day i (mm); k is the reach number; $r_0(i,k)$ is the water stored in the k_{th} reach at the beginning of day i (m^3); $r_{\text{ini}}(k)$ is a newly defined variable referring to the initial water stored in the k_{th} reach for a specific flood event and is extracted from the daily simulation results in this study (m^3); $r_{\text{t}}(i-1,k)$ is the final amount of water stored in the k_{th} reach at the end of the day prior to day i (m^3).

3.2 Application of Unit Hydrographs with distributed parameters in the SWAT model

The dimensionless UH method employed in the SWAT model exhibits a triangular shape (SCS, 1972), as shown in Fig. 4, wherein the time t (h) represents the X-axis, and the ratio of the discharge to peak discharge represents the Y-axis. This UH is defined as follows:

$$q_{\mathrm{uh}} = \frac{t}{t_{\mathrm{p}}} \quad \text{if } t \le t_{\mathrm{p}}$$
$$q_{\mathrm{uh}} = \frac{t_{\mathrm{b}} - t}{t_{\mathrm{b}} - t_{\mathrm{p}}} \quad \text{if } t > t_{\mathrm{p}} \tag{3}$$

where q_{uh} is the unit discharge at time t, t_{p} is the time to the peak (h), and t_{b} is the time base (h). Then, the dimensionless UH is expressed by dividing by the area enclosed by the triangle (Jeong et al., 2010). There are two time factors that determine the shape of the triangular UH, and they are defined by the following equations:

$$t_{\mathrm{b}} = 0.5 + 0.6 \bullet t_{\mathrm{c}} + t_{\mathrm{adj}} \tag{4}$$

$$t_{\mathrm{p}} = 0.375 \bullet t_{\mathrm{b}} \tag{5}$$

where t_{c} is the concentration time for the sub-basin (h), and t_{adj} is a shape adjustment factor for the UH (h) (Neitsch et al., 2011).

The time of concentration t_{c} can be calculated based upon the geographic characteristics of the sub-basin considered, for which t_{c} is denoted by the accumulation of the overland flow time t_{ov} (h) and the channel flow time t_{ch} (h):

$$t_{\mathrm{c}} = t_{\mathrm{ov}} + t_{\mathrm{ch}} \tag{6}$$

$$t_{\mathrm{ov}} = \frac{L_{\mathrm{slp}}{}^{0.6} \bullet n^{0.6}}{18 \bullet S_{\mathrm{sub}}{}^{0.3}} \tag{7}$$

$$t_{\mathrm{ch}} = \frac{0.62 \bullet L \bullet n^{0.75}}{A^{0.125} \bullet S_{\mathrm{ch}}{}^{0.375}} \tag{8}$$

where L_{slp} is the average slope length for the sub-basin under consideration (m); n is the Manning coefficient for the sub-basin; S_{sub} is the average slope steepness of the sub-basin (m m^{-1}); L is the longest tributary length in the sub-basin (km); A denotes the area of the sub-basin (km^2); and S_{ch} is the average slope of the tributary channels within the sub-basin (m m^{-1}).

The variable t_{adj} is a general basin level parameter possessing a uniform value for all of the sub-basins with the purpose of providing more tolerance to adjust the shape of the UH. However, the four sub-basins demonstrate obvious regional spatial heterogeneities. As seen in Table 1, the values of the average slope steepness (S_{sub}) of HC and XX are much higher than those of BT and WJB. Meanwhile, the average slope lengths (L_{slp}) for HC and XX are shorter than those for BT and WJB.

Thus, to highlight the differences representative of the UHs between each of the sub-basins, the parameter t_{adj} was modified from the basin level to the sub-basin level and renamed t_{subadj}.

3.3 Model calibration and validation

3.3.1 Sensitivity analysis

Sensitivity analysis is a process employed to identify the parameters that result in significant changes within a model output due to disturbances of the input (Holvoet et al., 2005). Generally, sensitivity analysis takes priority over the calibration process to reduce the complexity of the latter (Sudheer et al., 2011). Here, a combined Latin-Hypercube and One-factor-At-a-Time (LH-OAT) sampling method embedded within the SWAT model (Griensven et al., 2006) was used to conduct a sensitivity analysis. A total of 26 model parameters related to the flow simulation were involved in sensitivity analysis. Only the most sensitive parameters were used for the optimization procedure, while the values of the others parameters were set to their default values.

3.3.2 Daily model calibration and validation

Due to the high spatial heterogeneity within the hydrological processes simulated by the SWAT model, the values of numerous parameters will be difficult to determine by manual calibration alone. Therefore, the application of an automatic calibration process to estimate the model parameters that minimize the errors between the observed and simulated results is necessary. The Shuffled Complex Evolution (SCE-UA) algorithm (Duan et al., 1992) is a global optimization technique that is incorporated as a module into the SWAT model. In this study, the SWAT-EVENT model employed the same built-in automatic calibration subroutine. The SCE-UA algorithm has been applied to multiple physically based hydrological models (Sorooshian et al., 1993; Luce and Cundy, 1994; Gan and Biftu, 1996) and has exhibited good performance similar to other global search procedures (Cooper et al., 1997; Thyer et al., 1999; Kuczera, 1997; Jeon et al., 2014).

Daily simulations were performed within the time span, from 1990 to 2010, using observed data at the outlet of WJB. One year (1990) was selected as the model warm-up period, the period from 1991 to 2000 was used for the model calibration, and the remaining data from 2001 to 2010 were employed for validation.

Multiple statistical values, including the Nash-Sutcliffe efficiency coefficient (E_{NS}) (Nash and Sutcliffe, 1970), the coefficient of determination (R^2) and the percent bias (P_{BIAS}) (Gupta et al., 1999), were selected in this study to evaluate the daily model performances. The E_{NS} provides a normalized statistic indicating how closely the observed and simulated data match with each other, wherein a value equal to 1 implies an optimal model performance insomuch that the simulated flow perfectly matches the observed flow. The R^2 coefficient expresses the portion of the variance in the observed discharge explained by simulated values varying from 0 to 1. An approximation of the maximum value (R^2=1) represents the most efficient and well-matched results. The P_{BIAS} detects the degree that the simulated data deviates from the observed data.

3.3.3 Event-based sub-daily model calibration and validation

Sub-daily simulations in the SWAT-EVENT model were conducted within the same time span as the daily simulation, with a primary focus on the flood season with a series consisting of 24 flood events, two-thirds of which were utilized for the calibration while the rest were used for validation. Preferential implementation was applied to daily calibration from which the antecedent conditions were extracted.

Additional parameters associated with the UH method were added for the sub-daily calibration. To analyze the influence of the UH parameters on the SWAT-EVENT model performances, two sets of calibration scenarios were implemented separately using t_{adj} and t_{subadj}. For the basin level calibration, t_{adj} was consistently updated with uniform values for all of the sub-basins in each iteration; for the sub-basin level calibration, t_{subadj} was updated with the 4 distributed values for each of the sub-basins in each iteration.

E_{NS}, relative peak discharge error (E_{RP}), relative peak time error (E_{RPT}) and relative runoff volume error (E_{RR}) were selected as the performance evaluation statistics for the flood event simulations to comply with the Accuracy Standard for Hydrological Forecasting in China (MWR, 2008). E_{RP}, E_{RPT}, and E_{RR} are specific indicators used to indicate whether the accuracies of the simulations reach the national standard (MWR, 2008). They are considered to be sufficiently qualified when the absolute values are less than 20 %, 20 % and 30 %, respectively.

4 Results

4.1 Daily simulation results

The model performances for the daily streamflow simulations at outlet WJB are summarized in Table 2. The E_{NS} value is 0.77 for the calibration period and 0.78 for the validation period. These two values of the daily E_{NS} both exceed 0.65, which is considered to be acceptable or good according to performance ratings for evaluation statistics recommended by Moriasi et al. (2007). The daily R^2 values are 0.88 and 0.89 for the calibration and validation, respectively, indicating that the simulated streamflow is in good agreement with the observed data. The SWAT model overestimates the streamflow during calibration with a P_{BIAS} of 14.46 %, and underestimates the streamflow during validation with a corresponding value of -21.90 %. Visual comparisons between the observed and simulated streamflows for both of the calibration and validation periods are shown in Fig. 5, from which it can be observed that the SWAT model misses several flood peaks both during calibration and validation. In general, the daily simulation results obtained from the SWAT model at WJB demonstrate decent applicability and can consequently represent a preliminary basis for further flood event simulation.

4.2 Event-based simulation results

Table 3 displays the model performances of the daily simulations using the SWAT model for specific flood events, as well as the sub-daily flood simulations obtained using the SWAT-EVENT model. The simulation results for the 24 flood events, as shown in Table 3, exhibit reliable performances of the SWAT-EVENT model, with E_{NS} values varying from 0.66 to 0.95. Compared to the daily simulation results, most of the E_{NS} values, aside from flood event 20060722, are significantly increased in the simulations obtained using the SWAT-EVENT model.

The peak flows simulated by the SWAT-EVENT model at a sub-daily time scale are much closer to the observed flows relative to the predictions obtained from the SWAT model at a daily time scale, especially for flood events with high peak flows. There are eight flood events (19910610, 19910629, 19960628, 20020622, 20030622, 20050707, 20050822 and 20070701) that exhibit peak flows greater than 5000 $m^3\ s^{-1}$. The sub-daily simulation results of these eight floods were aggregated into daily averages and then compared with those of the daily simulations, the results of which are illustrated in Fig. 6. It can be concluded that the daily simulations are likely to miss the high flood peaks. The more effective performances of the SWAT-EVENT model are due to rainfall data with a higher temporal resolution, which can capture the instantaneous changes representative of hydrological processes.

The aforementioned simulation results indicate that the SWAT-EVENT model can accurately reproduce the dynamics of observed flood events based upon antecedent conditions extracted from SWAT daily simulations.

4.3 Effects of the application of the distributed parameters of the Unit Hydrographs

To analyze the spatial variability of the UH parameters and their influences on the event-based flood simulation results, the time characteristics of the sub-basins as well as two sets of optimized UH parameters are displayed in Table 4. From Eq. (7) and Eq. (8), in addition to the geographic features of the sub-basins depicted in Table 1, the overland flow time t_{ov} and the channel flow time t_{ch} were calculated. For each of the four sub-basins in the studied catchment, the values of t_{ch} are always much greater than those of t_{ov}, indicating that the channel flow time t_{ch} is the key factor that influences the total time of concentration t_c in Eq. (6). Sub-basins 1 and 3 have longer channel flow times (t_{ch}) than sub-basins 2 and 4. This result can be explained according to Eq. (8), wherein sub-basins with relatively longer tributary lengths demonstrate longer durations of the channel flow concentration time, thereby leading to a greater sub-basin concentration time t_c.

The sub-basin level UH parameters (t_{subadj}) vary from 81.56 h to 137.39 h, while the basin level parameters (t_{adj}) display a uniform value of 75.8 h for each sub-basin. As a result, the time bases (t_b) of the UHs at the sub-basin level are 79 h, 49 h, 92 h and 59 h for sub-basins 1, 2, 3 and 4, respectively, whereas those values at the basin level are very similar to one another. Figure 7 illustrates these two situations regarding the UHs within the sub-basins. It can be observed that the UHs in sub-basins 1 and 3 are relatively flat, while those in sub-basins 2 and 4 have higher peaks and shorter durations, as is illustrated in Fig. 7 (b). However, as shown in Fig. 7 (a), only minor differences exist between the UHs at the basin level.

The UH can be regarded as the direct flow response to excess rainfall and should exhibit regional characteristics (Tung et al., 1997; Yeh et al., 1997). The UHs derived from the sub-basin level parameters can more effectively represent the spatial variability of the study area, as is illustrated in Fig.7 (b), than the UHs derived from the basin level parameters displayed in Fig. 7 (a).

The SWAT-EVENT simulation results using the sub-basin level UH parameters are also presented in Table 3. Compared with the basin level situation, the sub-basin level situation induces an increase in the qualified ratio of E_{RP} from 81.25 % to 93.75 % during the calibration period, and from 87.50 % to 100 % during the validation period. This finding indicates that the application of sub-basin level UH parameters in the SWAT-EVENT model can improve the simulation accuracies of flood peaks.

The overall distributions of E_{NS} statistics for the 24 flood events for the two calibration scenarios (i.e., the basin level UH parameters vs. the sub-basin level UH parameters) are plotted in Fig. 8. The box plots therein exhibit rectangle heights equal to the interquartile range (IQR), the upper and lower ends of which are separately marked with the upper and lower quartile values, respectively. The median is represented by a line transecting either of the two rectangles. The extended whiskers denote the range of the batch data (Massart et al., 2005; Cox, 2009). According to Table 3 and Fig. 8, the SWAT-EVENT model simulated using sub-basin level UH parameters demonstrates significant improvements for flood simulation. For the sub-basin level case in Fig. 8, almost all of the events (except 20070701) exhibit E_{NS} values exceeding 0.85. In addition, half of the E_{NS} values range from 0.89 to 0.95, with a median of 0.91, which can potentially represent the highest flood forecasting accuracy standard (A) according to MWR (MWR, 2008). However, the basin level case performs comparatively poorly with regard to reproducing the flood hydrograph, wherein the majority of E_{NS} values vary between 0.8 and 0.9.

In conclusion, the spatial variability of UH parameters have a significant impact on the simulation results using the SWAT-EVENT model. More precisely, the application of spatially distributed UH parameters allows the SWAT-EVENT model to simulate the flood events more accurately.

5 Discussion

Rainstorms during the flooding seasons typically produce intense and instantaneous flood events. To adequately resolve the processes that influence the timing and magnitude of rapidly changing flood events, hydrological models are required to operate at a sub-daily time scale for flood simulation (Hapuarachchi et al., 2012). The SWAT (SWAT2005) model has limited capabilities for the simulation of hydrological processes on sub-daily time scales (Jeong et al., 2010). To solve this issue, new sub-hourly model components were developed by Jeong et al. (2010) to allow the original SWAT model to simulate streamflow on any sub-daily time scale. The application of such sub-daily hydrological models relies heavily on the availability of historical continuous data observed at a sub-daily time scale (e.g., rainfall and discharge) to calibrate the model parameters. However, such intensive observations at a sub-daily time scale are only available during the flooding seasons in the study area. Thus, the question then becomes whether continuous simulations in the SWAT model will still conflict with the event-based observed data in practice. In this regard, further model modifications were made in this study to compile a new SWAT-EVENT model, which disrupted the continuous loop within the SWAT model to overcome its inherent insufficiency with respect to event-based flood simulations at a sub-daily time scale.

Antecedent moisture conditions of a coming flood event can influence the flood volume and its duration. The advantage of continuous simulation models (e.g., the SWAT model) is that the initial values of the model states are implicitly incorporated within the modeling framework (Pathiraja et al., 2012). In contrast, event-based models require a separate method to obtain the antecedent conditions (Berthet et al., 2009), including the SWAT-EVENT model. The combination of continuous simulation (i.e., SWAT model) and event-based simulation (i.e., SWAT-EVENT model) used in this study (Fig. 3) can represent a common solution to this issue (Nalbantis, 1995). Take flood event 20030622 as an example, for which the impact of the antecedent conditions on the performance of the event-based flood simulation result is presented in Fig. 9. The flood hydrograph simulated by using the calibrated SWAT-EVENT model is comparatively lower when the antecedent conditions are initialized to zero relative to when they are extracted directly from the daily SWAT model. However, this combination approach still has deficiencies. On the one hand, the SWAT model suffers from poor simulation and prediction performance for low streamflows (Zhang et al., 2015), resulting in an inaccurate estimation of the antecedent moisture conditions. On the other hand, inevitable uncertainty regarding the estimated antecedent conditions exists because a model-based approach is used. Field measurements are highly beneficial, ideally, for initializing the SWAT-EVENT model in this study. Bronstert et al. (2012) compared different soil moisture measurement technologies, and subsequently concluded that only Spatial-Time Domain Reflectometry (STDR) was capable of acquiring continuous data. Massari et al. (2014) used soil moisture observations to improve hydrological modeling at the Valescure experimental catchment in France. Thus, for improving event-based flood forecasting results, applying antecedent model states based on field measurements may be promising.

Rainfall is the main driving force for the hydrological cycle. Hence, the temporal resolution of rainfall data could also have substantial impact on the simulation of flood processes. The decent performance of the SWAT-EVENT model at peak flows as shown in Fig. 6 could be due to the high temporal resolution of the input rainfall. Rainstorms may significantly vary over the course of a day, and thus, the use of daily rainfall data might not adequately represent the temporal profile. For example, a rainfall event (2 July 2003) prior to the peak of flood event 20030622 (Fig. 6) was characterized by an average daily rainfall of 80.6 mm for sub-basin 4, 85.24 % of which occurred during the first four time intervals ($\Delta t = 2$ h) between 0 and 8 am. The daily surface runoff was calculated using the SCS curve number method, and the sub-daily surface runoff was calculated using the Green & Ampt infiltration method in the SWAT model. On a daily basis, the Green & Ampt method will perform more effectively due to rainfall intensity and duration considerations. Similar results were analyzed through the comparison of the aforementioned two methods on the Goodwin Creek Watershed (Vol., 1999).

The UH represents the most widely practiced technique for determining flood hydrographs. Sherman (1932) first proposed the UH concept in 1932. However, because the UH proposed by Sherman is based on observed rainfall-runoff data at gauging sites for hydrograph derivations, it is only applicable for gauged basins (Jena and Tiwari, 2006). A prominent lack of observed data promoted the appearance of the Synthetic Unit Hydrograph (SUH), which extended the application of the UH technique to ungauged catchments. The triangular dimensionless UH used in the SWAT and SWAT-EVENT models denotes the simplest of SUHs, which relates hydrologic responses to the catchment geographic characteristics. There was a definite positive effect from the application of the distributed parameters of the UHs on the simulation of flood peaks as indicated in Table 3, resulting in a significant improvement of E_{NS} values (Fig. 8), which has been known to be sensitive to high values within a given dataset. Simply applying different parameters of UHs for different sub-basins has improved flood forecasting accuracies greatly, as seen in this research and in other studies (Luxon et al., 2013). This implies that improving the application of UHs in the SWAT model may be attractive for further model improvement. This result has similarly been reported by Bhunya (2011) and Aron and White (1982), wherein it was suggested that the application of probability distribution function-based SUHs would also improve model performances.

6 Conclusions

The original SWAT model was initially designed to perform well for long-term simulations with daily time-steps. This paper developed a SWAT-EVENT model to improve upon the original SWAT model in two aspects: (1) to enable the SWAT model to conduct flood forecasting on a flood event basis (i.e., not continuously), as well as on a sub-daily time scale; and (2) each sub-basin's dimensionless triangular UH parameters were assigned with different values, whereas the original SWAT models assigned each sub-basin with the same value.

An application of the SWAT-EVENT model in the upper reaches of the Huaihe River exhibited high accuracies of flood forecasting, wherein the E_{NS} values varied from 0.66 to 0.95.

Assigning each sub-basin with dimensionless triangular UH parameters with different values further improved the model performances, following which the qualification ratios of the E_{RP} , E_{RPT} and E_{RR} values for the calibration period increased from 81.25 %, 87.50 % and 87.50 % to 93.75 %, 87.50 % and 93.75 %, respectively, and those of the validation period increased from 87.5 %, 100 % and 100 % to 100 %, 100% and 100 %, respectively.

These results indicated that the SWAT-EVENT model developed herein can be successfully applied for flood event forecasting and that assigning sub-basin model parameters with distributed values is necessary for further model performance improvement.

Data availability

The DEM data were downloaded from the website http://srtm.csi.cgiar.org/.

The land use data (GLC2000) were downloaded from the website http://www.landcover.org/.

The soil data (HWSD) were downloaded from the website http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/.

The global weather data were downloaded from the website https://globalweather.tamu.edu/.

The rainfall observations at 138 stations and the discharge observations at the outlet (WJB) were provided by Hydrologic Bureau of Huaihe River Commission.

The source codes of SWAT model are available at the website http://swat.tamu.edu/.

Competing interests

The authors declare that they have no conflict of interest.

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References

Adams Iii, T. E., and Pagano, T. C.: Flood Forecasting: A Global Perspective, in: Flood Forecasting, Academic Press, Boston, xxiii-xlix, 2016.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R.: LARGE AREA HYDROLOGIC MODELING AND ASSESSMENT PART I: MODEL DEVELOPMENT 1, JAWRA Journal of the American Water Resources Association, 34, 73–89, 1998.

Arnold, J. G., and Fohrer, N.: SWAT2000: Current Capabilities and Research Opportunities in Applied Watershed Modeling, Hydrol. Process., 19, 563-572, 2005.

Aron, G., and White, E. L.: Fitting a Gamma Distribution Over a Synthetic Unit Hydrograph, JAWRA Journal of the American Water Resources Association, 18, 95-98, 1982.

Bartholomé, E., and Belward, A. S.: GLC2000: a new approach to global land cover mapping from Earth observation data, International Journal of Remote Sensing, 26, 1959-1977, 2005.

Berthet, L., Andréassian, V., Perrin, C., and Javelle, P.: How crucial is it to account for the antecedent moisture conditions in flood forecasting? Comparison of event-based and continuous approaches on 178 catchments, Hydrology & Earth System Sciences, 13, 819-831, 2009.

Bhunya, P. K.: Synthetic Unit Hydrograph Methods: A Critical Review, Open Hydrology Journal, 5, 1-8, 2011.

Bronstert, A., Creutzfeldt, B., Graeff, T., Hajnsek, I., Heistermann, M., Itzerott, S., Jagdhuber, T., Kneis, D., Lück, E., and Reusser, D.: Potentials and constraints of different types of soil moisture observations for flood simulations in headwater catchments, Natural Hazards, 60, 879-914, 2012.

Cooper, V. A., Nguyen, V. T. V., and Nicell, J. A.: Evaluation of global optimization methods for conceptual rainfall-runoff model calibration, Water Science & Technology, 36, 53-60, 1997.

Cox, N. J.: Speaking Stata: Creating and varying box plots, Stata Journal, 9, 478-496, 2009.

Duan, Q., Soroosh, S., and Vijai, G.: Effective and efficient global optimization for conceptual rainfall-runoff models, Water Resources Research, 28, 1015-1031, 1992.

Gan, T. Y., and Biftu, G. F.: Automatic Calibration of Conceptual Rainfall-Runoff Models: Optimization Algorithms, Catchment Conditions, and Model Structure, Water Resources Research, 32, 3513-3524, 1996.

Gassman, P. W., Arnold, J. J., Srinivasan, R., and Reyes, M.: The Worldwide Use of the SWAT Model: Technological Drivers, Networking Impacts, and Simulation Trends, Century Watershed Technology: Improving Water Quality and Environment Conference Proceedings, 21-24 February 2010, Universidad Earth, Costa Rica, 2010,

Griensven, A. V., Meixner, T., Grunwald, S., Bishop, T., Diluzio, M., and Srinivasan, R.: A global sensitivity analysis tool for the parameters of multi-variable catchment models, J. Hydrol., 324, 10-23, 2006.

Gupta, H. V., Sorooshian, S., and Yapo, P. O.: Status of Automatic Calibration for Hydrologic Models: Comparison With Multilevel Expert Calibration, Journal of hydrologic Engineering, 4, 135-143, 1999.

Hapuarachchi, H. A. P., Robertson, D., and Wang, Q. J.: Validity of high temporal resolution conceptual hydrological model parameters calibrated using low resolution data, Hydrology & Water Resources Symposium, 10, 16-23, 2012.

Holvoet, K., Griensven, A. V., Seuntjens, P., and Vanrolleghem, P. A.: Sensitivity analysis for hydrology and pesticide supply towards the river in SWAT, Physics & Chemistry of the Earth Parts A/b/c, 30, 518-526, 2005.

Jena, S. K., and Tiwari, K. N.: Modeling synthetic unit hydrograph parameters with geomorphologic parameters of watersheds, J. Hydrol., 319, 1-14, 2006.

Jeon, J. H., Park, C. G., and Engel, B. A.: Comparison of Performance between Genetic Algorithm and SCE-UA for Calibration of SCS-CN Surface Runoff Simulation, Water, 6, 3433-3456, 2014.

Jeong, J., Kannan, N., Arnold, J., Glick, R., Gosselink, L., and Srinivasan, R.: Development and Integration of Sub-hourly RainfallRunoff Modeling Capability Within a Watershed Model, General Information, 24, 4505-4527, 2010.

Jeong, J., Kannan, N., Arnold, J. G., Glick, R., Gosselink, L., Srinivasan, R., and Harmel, R. D.: DEVELOPMENT OF SUB - DAILY EROSION AND SEDIMENT TRANSPORT ALGORITHMS FOR SWAT, Transactions of the Asabe, 54, 1685-1691, 2011.

Jiang, X. F., Wang, L., Fang, M. A., Hai-Qiang, L. I., Zhang, S. J., and Liang, X. W.: Localization Method for SWAT Model Soil Database Based on HWSD, China Water & Wastewater, 30, 135-138, 2014.

Kiniry, J. R., Williams, J. R., and King, K. W.: Soil and Water Assessment Tool Theoretical Documentation (Version 2005), Computer Speech & Language, 24, 289-306, 2005.

Kuczera, G.: Efficient subspace probabilistic parameter optimization for catchment models, Water Resources Research, 33, 177–185, 1997.

Luce, C. H., and Cundy, T. W.: Parameter Identification for a Runoff Model for Forest Roads, Water Resources Research, 30, 1057-1070, 1994.

Maidment, D. R.: handbook of hydrology, Earth-Science Reviews, 24, 227–229, 1994.

Massari, C., Brocca, L., Moramarco, T., Tramblay, Y., and Didon Lescot, J.-F.: Potential of soil moisture observations in flood modelling: Estimating initial conditions and correcting rainfall, Advances in Water Resources, 74, 44-53, http://dx.doi.org/10.1016/j.advwatres.2014.08.004, 2014.

Massart, D. L., Smeyers-Verbeke, J., Capron, X., and Schlesier, K.: Visual presentation of data by means of box plots, Lc Gc Europe, 18, 215-218, 2005.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Transactions of the Asabe, 50, 885-900, 2007.

Nachtergaele, F. O., Velthuizen, Verelst, L., Batjes, N. H., Dijkshoorn, J. A., Engelen, V., W. P., Fischer, G., Jones, A., and Montanarella, L.: Harmonized World Soil Database (Version 1.2), Laxenburg, Austria : Food and Agriculture Organization of the UN, International Institute for Applied Systems Analysis, ISRIC - World Soil Information, Institute of Soil Science - Chinese Academy of Sciences, Joint Research Centre of the EC, 2012 - p, 2012.

Nalbantis, I.: Use of multiple-time-step information in rainfall-runoff modelling, J. Hydrol., 165, 135-159, 1995.

Nash, J. E., and Sutcliffe, J. V.: River flow forecasting through conceptual models part I — A discussion of principles J. Hydrol., 10, 282-290, 1970.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R., and Williams, J. R.: Soil and Water Assessment Tool Input/output File Documentation: Version 2009. Texas Water Resources Institute Technical Report 365, Journal of Information Processing and Management, 33, 2011.

Pathiraja, S., Westra, S., and Sharma, A.: Why continuous simulation? The role of antecedent moisture in design flood estimation, Water Resources Research, 48, 6534, 2012.

SCS: National engineering handbook, section 4, hydrology., in, US Department of Agriculture,SCS, Washington, DC, 1972.

Sherman, L.: Stream Flow from Rainfall by the Unit-Graph Method, 1932.

Sorooshian, S., Duan, Q., and Gupta, V. K.: Calibration of rainfall-runoff models: Application of global optimization to the Sacramento Soil Moisture Accounting Model, Water Resources Research, 29, 1185-1194, 1993.

Srinivasan, R., Ramanarayanan, T. S., Arnold, J. G., and Bednarz, S. T.: Large Area Hydrologic Modeling and Assessment: Part II – Model Application, JAWRA Journal of the American Water Resources Association, 34, 91-101, 1998.

Sudheer, K. P., Lakshmi, G., and Chaubey, I.: Application of a pseudo simulator to evaluate the sensitivity of parameters in complex watershed models, Environ. Modell. Softw., 26, 135-143, http://dx.doi.org/10.1016/j.envsoft.2010.07.007, 2011.

Thyer, M., Kuczera, G., and Bates, B. C.: Probabilistic optimization for conceptual rainfall-runoff models: A comparison of the shuffled complex evolution and simulated annealing algorithms, Water Resources Research, 35, 767–773, 1999.

Tung, Y. K., Yeh, K. C., and Yang, J. C.: Regionalization of unit hydrograph parameters: 1. Comparison of regression analysis techniques, Stochastic Hydrology & Hydraulics, 11, 145-171, 1997.

Vol., N.: COMPARISON OF GREEN-AMPT AND CURVE NUMBER METHODS ON GOODWIN CREEK WATERSHED USING SWAT, Transactions of the ASAE, 42, 919-926, 1999.

Yao, C., Zhang, K., Yu, Z., Li, Z., and Li, Q.: Improving the flood prediction capability of the Xinanjiang model in ungauged nested catchments by coupling it with the geomorphologic instantaneous unit hydrograph, J. Hydrol., 517, 1035-1048, http://dx.doi.org/10.1016/j.jhydrol.2014.06.037, 2014.

Yao, H., Hashino, M., Terakawa, A., and Suzuki, T.: COMPARISON OF DISTRIBUTED AND LUMPED HYDROLOGICAL MODELS, Doboku Gakkai Ronbunshuu B, 42, 163-168, 1998.

Yeh, K. C., Yang, J. C., and Tung, Y. K.: Regionalization of unit hydrograph Parameters: 2. Uncertainty analysis, Stochastic Hydrology & Hydraulics, 11, 173-192, 1997.

Zhang, D., Chen, X., Yao, H., and Lin, B.: Improved calibration scheme of SWAT by separating wet and dry seasons, Ecological Modelling, 301, 54-61, https://doi.org/10.1016/j.ecolmodel.2015.01.018, 2015.

Zhao, L. N., Tian, F. Y., Wu, H., Qi, D., Di, J. Y., and Wang, Z.: Verification and comparison of probabilistic precipitation forecasts using the TIGGE data in the upriver of Huaihe Basin, Advances in Geosciences, 29, 95-102, 2011.

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Table 1 Geographic features of each of the sub-basins

Stream gauge	Sub-basin No.	Drainage area (km^2)	Mean elevation (m)	Average slope steepness (m m^{-1})	Average slope length (m)	Longest tributary length (km)	Average slope of the tributary (m m^{-1})
Bantai (BT)	1	11826.35	51	0.002	121.95	240.93	0.002
Wangjiaba (WJB)	2	6628.62	44	0.003	121.95	167.15	0.002
Xixian (XX)	3	10220.41	119	0.071	60.97	216.47	0.001
Huangchuan (HC)	4	1954.62	149	0.073	60.97	101.59	0.008

Table 2 SWAT model performance statistics for the calibration and validation periods

	E_{NS}	R^2	P_{BIAS} (%)
Calibration	0.77	0.88	14.46
Validation	0.78	0.89	-21.90

Table 3 Performance evaluations for the daily and sub-daily simulations for specific flood events

	Flood event	Start date	End date	Observed peak flow	Daily simulation		Basin level UH parameter					Sub-basin level UH parameter				
					Simulated peak flow	E_{NS}	Simulated peak flow	E_{RP}	E_{RPT}	E_{RR}	E_{NS}	Simulated peak flow	E_{RP}	E_{RPT}	E_{RR}	E_{NS}
				($m^3 s^{-1}$)	($m^3 s^{-1}$)		($m^3 s^{-1}$)	(%)	(%)	(%)		($m^3 s^{-1}$)	(%)	(%)	(%)	
Calibration	19910521	21 May	10 Jun	2935	1310	0.54	3130	6.64	-1.34	1.91	0.91	2730	-6.98	-0.67	-2.46	0.95
	19910610	10 Jun	29 Jun	7577	3720	0.62	6850	-9.59	-5.41	-23.18	0.86	6270	-17.25	-1.35	-24.20	0.96
	19910629	29 Jun	21 Jul	5931	3710	0.70	6010	1.33	1.75	-11.24	0.90	5190	-12.49	4.39	-12.76	0.94
	19910804	04 Aug	17 Aug	4824	2830	0.60	4590	-4.85	-1.59	-10.27	0.93	4190	-13.14	-1.59	-9.59	0.97
	19950707	07 Jul	18 Jul	2613	1690	0.55	3170	21.32	7.32	29.73	0.95	2560	-2.03	0.00	19.73	0.97
	19950803	03 Aug	06 Sept	922.1	958	0.57	905	-1.85	68.32	17.39	0.79	900	-2.40	68.32	13.78	0.90
	19960628	28 Jun	25 Jul	5298	3070	0.28	5590	5.51	-1.53	4.37	0.84	4830	-8.83	-2.67	0.93	0.87
	19960917	17 Sept	26 Sept	1239	1140	0.69	1170	-5.57	7.32	-8.09	0.80	1430	15.42	0.00	10.53	0.96
	19970629	29 Jun	30 Jul	2171	1210	0.75	2230	2.72	-0.45	19.12	0.87	1980	-8.80	-2.23	8.39	0.90
	19980630	30 Jun	13 Jul	4504	2460	0.63	4830	7.24	-1.64	-14.38	0.80	4340	-3.64	-4.92	-14.51	0.91
	19980725	25 Jul	02 Sept	3698	3360	0.73	4010	8.44	24.35	5.57	0.83	3760	1.68	24.78	3.94	0.91
	20020622	22 Jun	11 Jul	5715	3830	0.63	7270	27.21	-10.20	19.56	0.88	6190	8.31	-12.24	15.71	0.95
	20020722	22 Jul	04 Aug	4088	2570	0.58	3350	-18.05	51.02	-13.58	0.85	3400	-16.83	48.98	-13.65	0.89
	20030622	22 Jun	29 Jul	8740	4160	0.59	6840	-21.74	-6.72	-0.94	0.90	6920	-20.82	0.00	-2.72	0.89
	20040717	17 Jul	29 Jul	2229	1850	0.60	1900	-14.76	-6.12	-1.49	0.90	1970	-11.62	-14.29	5.60	0.94
	20040804	04 Aug	13 Aug	2641	2400	0.51	2420	-8.37	-2.04	-5.68	0.72	2580	-2.31	-6.12	8.25	0.90
Qualified (%)								81.25	87.50	87.50			93.75	87.50	93.75	
Validation	20050707	07 Jul	12 Aug	7331	4300	0.52	7660	4.49	-21.05	3.87	0.73	7660	4.49	-5.26	2.38	0.93
	20050822	22 Aug	10 Sept	5650	3470	0.33	5660	0.18	0.00	-18.22	0.82	4950	-12.39	1.65	-17.71	0.88
	20060722	22 Jul	16 Aug	1770	1430	0.78	1810	2.26	2.73	0.96	0.66	1890	6.78	1.82	5.80	0.86
	20070701	01 Jul	01 Aug	7926	5570	0.62	7980	0.68	-3.25	-7.74	0.75	7510	-5.25	-5.69	-9.24	0.75

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Hydrology and Earth System Sciences Discussions
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	20080722	22 Jul	09 Aug	4264	3000	0.58	5580	30.86	-4.08	15.21	0.89	5110	19.84	0.00	15.25	0.93
	20080814	14 Aug	27 Aug	4219	2620	0.55	3820	-9.46	-3.23	2.01	0.91	3630	-13.96	-8.06	5.53	0.93
	20090826	26 Aug	13 Sept	2221	1870	0.73	2340	5.36	4.17	14.49	0.86	2480	11.66	2.78	19.32	0.89
	20100712	12 Jul	05 Aug	4314	2910	0.77	4490	4.08	-0.88	-5.57	0.88	4070	-5.66	-0.88	-10.78	0.91
Qualified (%)								87.50	100	100			100	100	100	

Table 4 Time characteristics of the sub-basins (t_c, t_b, t_p) and the optimized UH parameters for each sub-basin

Sub-basin	Stream gauge	t_{ov} (h)	t_{ch} (h)	t_c (h)	Basin level UH parameters			Sub-basin level UH parameters		
					t_{adj} (h)	t_b (h)	t_p (h)	t_{subadj} (h)	t_b (h)	t_p (h)
1	Bantai (BT)	1.97	30.2	32.17	75.8	48	17	137.39	79	29
2	Wangjiaba (WJB)	1.74	22.18	23.92		46	16	81.56	49	18
3	Xixian (XX)	0.36	35.49	35.86		49	18	161.67	92	34
4	Huangchuan (HC)	0.36	9.34	9.7		42	15	110.36	59	21

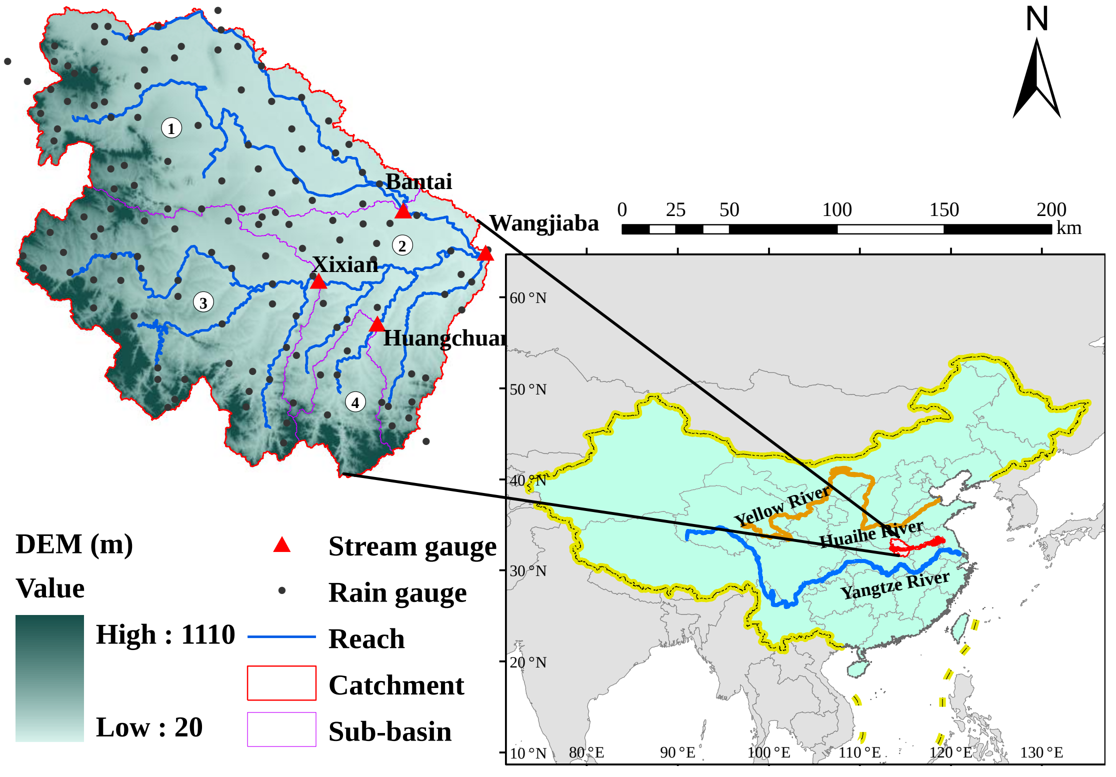

Figure 1 The Wangjiaba (WJB) catchment

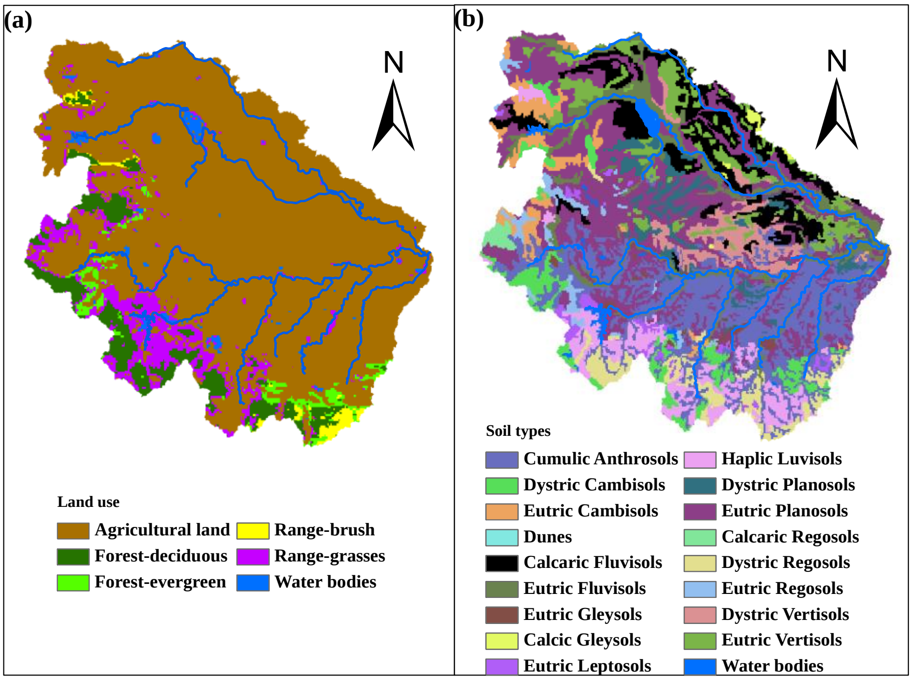

Figure 2 (a) Land use and (b) soil types throughout the study area

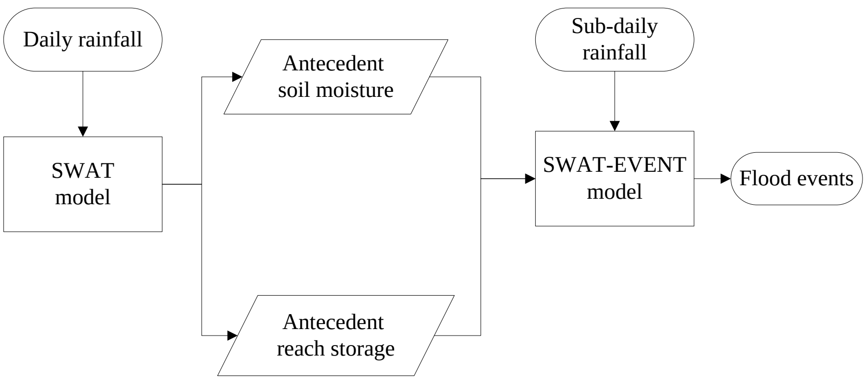

Figure 3 SWAT-EVENT model for the simulation of event-based flood data based on the initial conditions extracted from daily simulation results produced by the original SWAT model

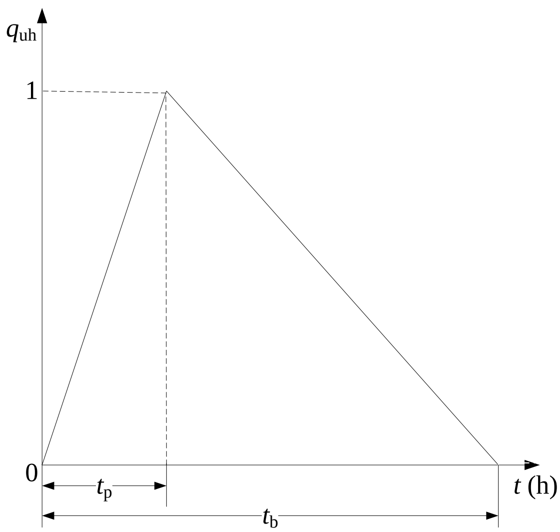

Figure 4 Shape of the dimensionless triangular UH

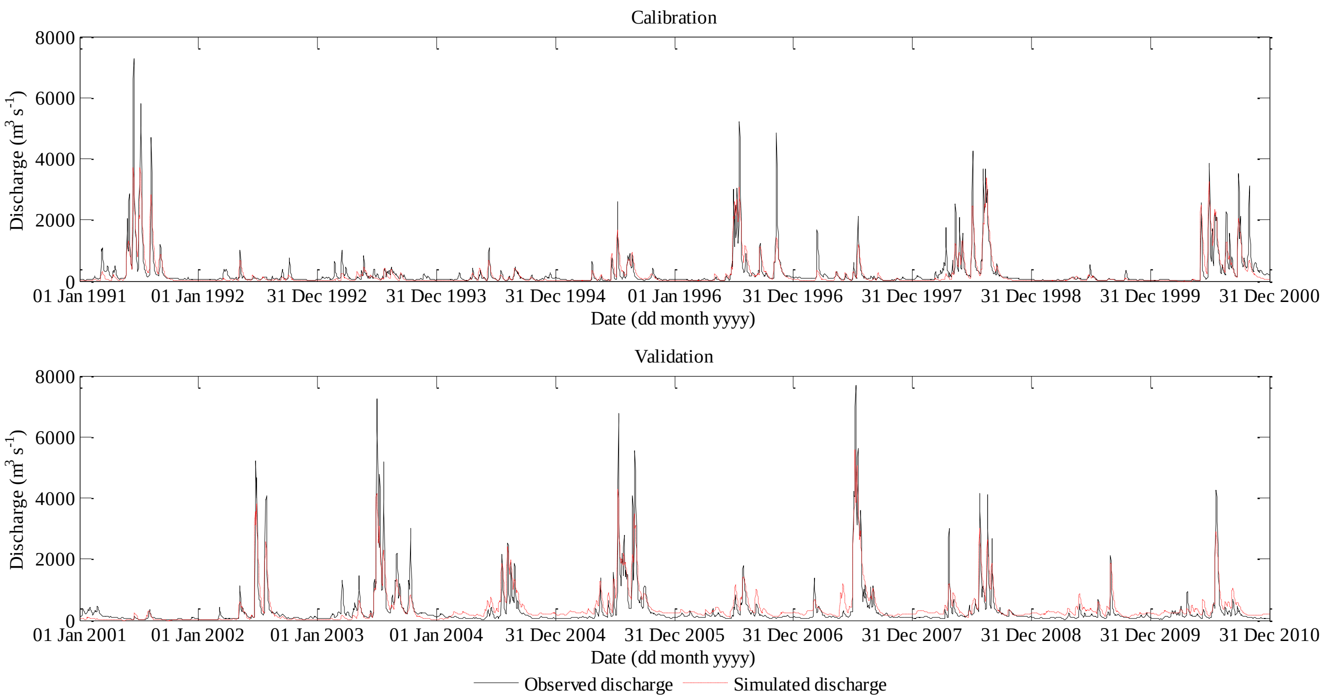

Figure 5 Comparisons between the observed and simulated daily discharges for the calibration and validation periods at WJB

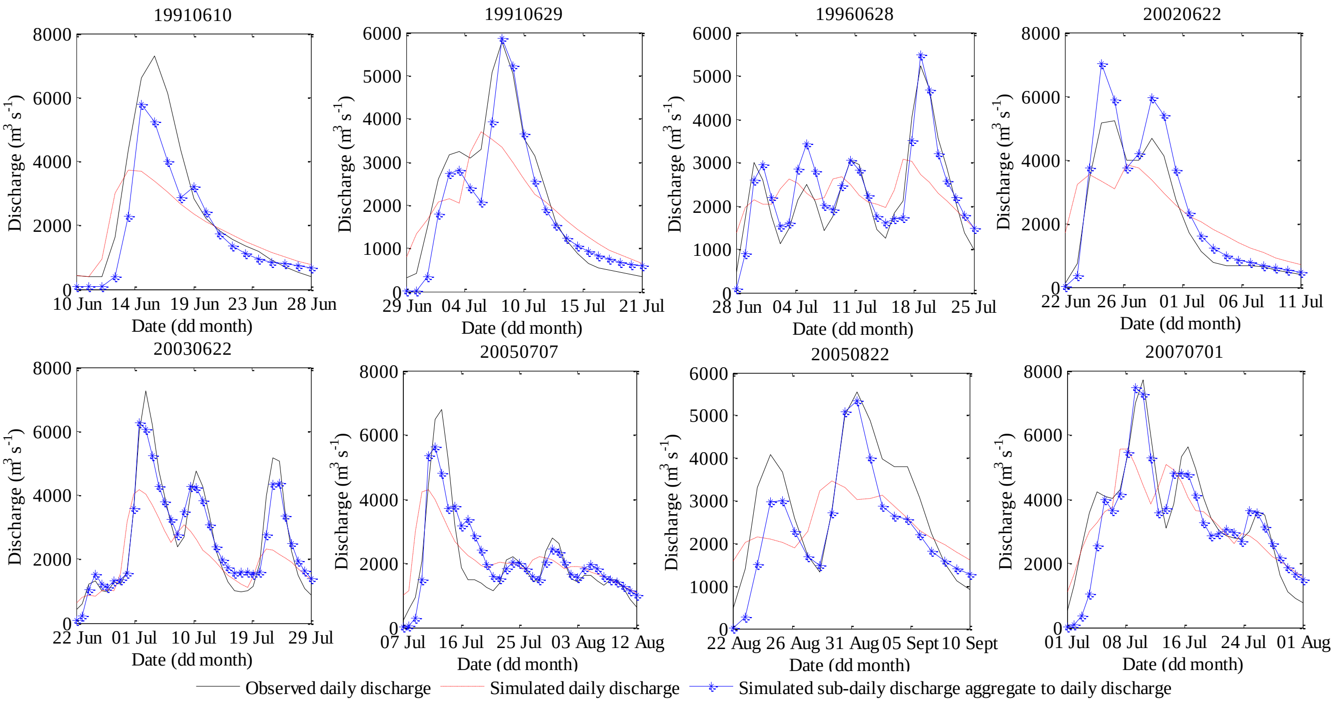

Figure 6 Comparisons of the daily simulations conducted using the SWAT model and the aggregated sub-daily simulations conducted using the SWAT-EVENT model

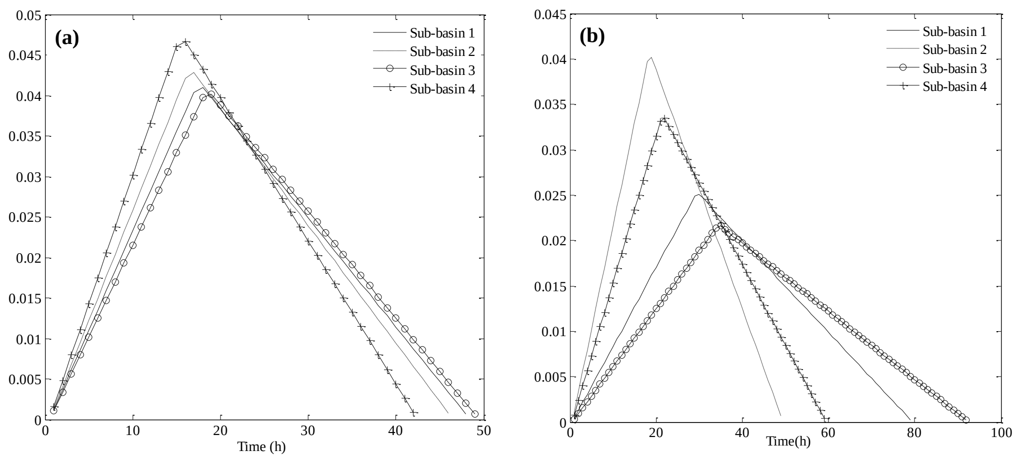

Figure 7 Plotted dimensionless UHs for each sub-basin with (a) basin level parameters and (b) sub-basin level parameters

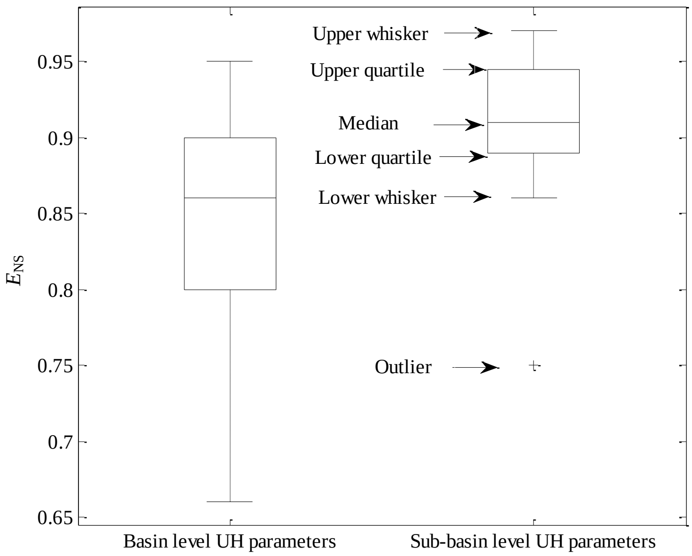

Figure 8 Box plots of E_{NS} values for the SWAT-EVENT model results for sub-basin level UH parameters and basin level UH parameters

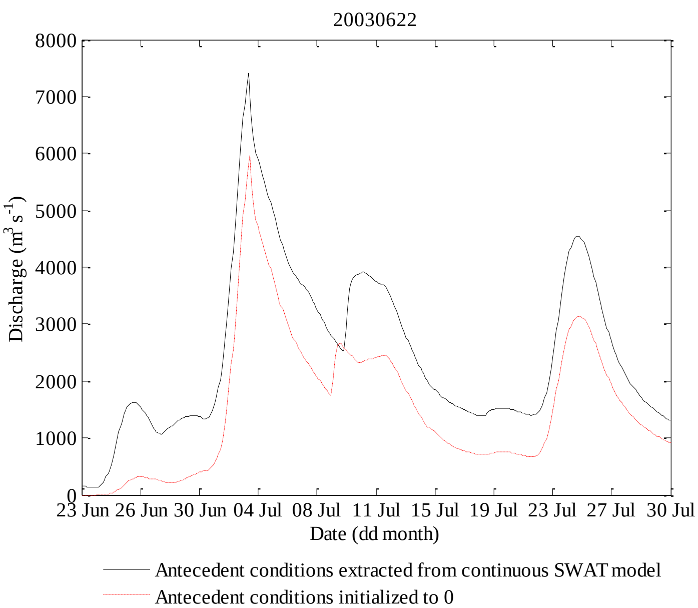

Figure 9 Impact of the antecedent conditions on the performance of the event-based flood simulation results