Response to Interactive comment Anonymous Referee #1

We heartily appreciate the reviewer's assessment on this study and the valuable suggestions provided to improve this manuscript. We hereby provide our point by point responses how the comments by referee #1 will be addressed in the revised manuscript.

1. Responses to major comments

Comment: The authors have to be more specific concerning the spatial resolution of the SWAT model. First, the SWAT model is a semi-distributed model consisting of subbasins and hydrological response units (HRU). Thus, please change from "distributed model" to "semi-distributed model".

Reply: Thanks for your correction. The "distributed hydrological model" is changed to "semi-distributed hydrological model" in the manuscript.

Comment: Since the manuscript is focused on spatial heterogeneity, a clear description of the three levels in the SWAT model, namely catchment, subbasin and HRU level, is required.

Reply: We appreciate the comment. It is really necessary to state the spatial discretization of the SWAT model. The following statement is added to the third paragraph in section 1:

"To spatially characterize the inhomogeneity, the SWAT model delineates a catchment into a number of sub-basins, which were subsequently divided into Hydrologic Response Units (HRUs). In SWAT model, HURs are basic simulation units of the land phase of the hydrological cycle that controls the total yield of streamflow, sediment, pesticide and nutrient to the main channel in corresponding sub-basin. Afterwards the routing phase converges the land phase results to the watershed outlet through the channel network."

Comment: Moreover, concerning the parameter heterogeneity and variability, it has to be clarified that some parameters (e.g. included in .bsn) are fixed for the whole catchment, others can be modified for each subbasins and a third group can be varied for each HRU. The authors should mention that the unit hydrograph is parameterized in the SWAT model version on the catchment level, which means that no spatial variation within a catchment is possible. In general, the SWAT model also allows a parameter variation on subbasin or HRU level. This has to be considered in the whole manuscript. In addition, the sentence in the abstract in L. 18 has to be more precise to avoid a misunderstanding.

Reply: Thank you very much for your advice. We've realized that the parameter heterogeneity and variability are important issues in distributed or semi-distributed hydrological model application.

The following description is added to the fifth paragraph in section 1:

"Due to the spatial discretization in the SWAT model, the model parameters are categorized into three levels: (1) basin level parameters are fixed for the whole catchment; (2) sub-basin level parameters are varied with sub-basins; (3) HRU level parameters are distributed in different HRUs."

The sentence "In addition, the SWAT model provides a uniform parameter set with which to adjust the shape of the UH in each sub-basin." in the fifth paragraph in section 1 is rephrased as follows:

"By default, the UH related parameters in the SWAT model are on the basin level, which indicates that no spatial variation within a catchment is possible when adjusting the shape of the UH in each sub-basin.".

The sentence in the abstract in L. 18 is changed as follows:

"SWAT uses a basin level parameter that is fixed for the whole catchment to parameterize the Unit Hydrograph (UH), thereby ignoring the spatial heterogeneity among the sub-basins when adjusting the shape of the UHs."

Comment: The SWAT model version 2005 is a very old one. SWAT2009 and SWAT2012 are available since several years. Thus, please justify the use of SWAT2005. This is in particular relevant since the SWAT model was continuously improved and bugs were removed. Thus, the newer versions are certainly better. Please give a statement on this.

The justification for the use of SWAT2005 (P.3, L. 13-15) cannot be accepted. Certainly it is possible to use SWAT-CUP for calibration, but it is certainly possible to use different calibration method for all SWAT version. There are lots of study using a different calibration approach for the SWAT model. Moreover a link between the use of SWAT2005 and the selected study catchment is not clear. Thus, please remove this part and provide a better explanation why SWAT2005 was selected instead of SWAT2009 or SWAT2012.

Reply: We propose to add the following for justification:

"The SWAT2005 version has an existing calibration module while the SWAT2009 and the SWAT2012 have removed the autocalibration routines. The integrated design of model simulation and autocalibration in the SWAT2005 is easily manageable and modified since there is no need to couple other algorithms. According to the revision history of the SWAT model, revisions after the SWAT2005 aimed mainly at the water quality simulation and have little effect on runoff simulation. Thus the SWAT2005 is employed in this study."

And the revision history will be provided as the attachments.

Comment: It is not acceptable to use only four sub-basins for 30630 km² catchment and claim at the same time limitations in spatial heterogeneity. According to my experience at least more than 100 subbasins can be expected for this catchment size. In particular, since the manuscript is focused on spatial heterogeneity, it is surprising that the subbasin number is very low.

Reply: We agree with the reviewer for this comment. Sub-basin is assumed homogeneous with parameters at the sub-basin level. Since this paper discussed the spatial differences in model parameter, we are going to redefine the sub-basins and do all the simulations again. We still need time to organize this part and will present the modification in revised manuscript.

Comment: Moreover, the SWAT model only provides spatially located outputs for each subbasin. In contrast, the authors stated that there are 138 gauges available. Thus, why do you not define a separate subbasin for each gauge or at least for the majority of the gauges? This would be even more a good approach to consider spatial heterogeneity.

Reply: Since we consider redefinition of the sub-basins, we will use the Taisen Polygon Method to calculate area rainfall in each sub-basin to consider the spatial heterogeneity of rainfall gages.

Comment: The evaluation of the model results with Nash-Sutcliffe efficiency coefficient (ENS) and coefficient of determination (R2) is redundant. Both indices are mathematically closely related. R2 did not provide any additional knowledge about process or parameter behaviour. Even though that I am aware that there are still publications using ENS and R2, it is not anymore state-of-the-art. At the same time, the use of three performance criteria is recommended. Thus, please select in addition to ENS and PBIAS, a contrasting performance criteria which provides additional information and replace R2.

Reply: We appreciate the comment. We would like to use the root mean square error (R_{MSE}) instead of R^2. R_{MSE} indicates a perfect match between observed and predicted values when it equals 0, with increasing R_{MSE} values indicating an increasingly poor match. The related descriptions will be modified in the revised manuscript.

Comment: I do not think that your approach really shows an example for flood forecasting. It is a sub-daily model studies, but I do not see that there is a forecasting. The model is calibrated and validated. Could you please provide more information on how your approach is related to flood forecasting? Or say

that this approach might be also beneficial for flood forecasting, but this was not considered here or will be part of future projects?

Reply: Thanks for your comment. We want to make some explanations here.

The hydrological model itself is not an example for flood forecasting, but a core part of the flood forecasting system. The quality of the hydrological model (in terms of its structure and parameter estimates) is one of the important factors for accurate flood forecasting (Noh et al., 2014). Thus this paper mainly focused on the modification of the structure of the original SWAT model to verify its suitability for flood simulation in study area, which is tightly related to the flood forecasting.

Meantime, model parameter estimation is an inevitable issue accompanied by the application of the hydrological model. Typically, calibration is performed by using multiple historical flood events data. Subsequently, the model validation consists in running the model under another group of historical flood events, with the input of parameter values thus being estimated in the calibration phase. This kind of calibration and validation is the common solution in many flood forecasting practices (Hapuarachchi and Wang, 2008). Thus the modified SWAT model was calibrated with 16 flood events from 1991 to 2004 and validated with 8 flood events from 2005 to 2010 in this paper.

In addition, Berthet et al. (2009) declared that the major drawback of the continuous simulation lies in its data requirements: long continuous precipitation time series up to the day of interest are difficult to obtain in an operational forecasting perspective. Yao et al. (2014) claimed that long continuous daily simulations are implemented to compute the soil moisture states that are used as antecedent conditions for the flood events in the operational use. Therefore the Figure 3 in this paper showed the operation at two time scales (i.e., continuous daily simulation and event-base sub-daily simulation).

In summary, this study addressed the model-based problems that related to flood forecasting. However we think it is still necessary to further clarify the relationship between the flood forecasting and our approaches.

The second paragraph in section 1: "A large number of distributed or semi-distributed hydrological models have been applied in flood forecasting (BEVEN and KIRKBY, 1979;Singh, 1997;Xiong and Guo, 2004;Mendes and Maia, 2017;Hapuarachchi et al., 2011)." replaces the "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." to emphasize the model-based approaches of flood forecasting.

We propose a paragraph explaining the approaches that have addressed the model structures and parameters issues in flood forecasting in the conclusions section:

"Flood forecasting is a synthetic system that integrates the data acquisition and processing, rainfall-runoff modeling and warning information release etc. Hydrological models are always the core part of the forecasting system. Model structures and model parameters are one of the most important issues for accurate flood forecasting (Noh et al., 2014). The original SWAT model is not competent to flood forecasting due to its initial design of long-term simulations with daily time-steps. This paper mainly focused on the modification of the structure of the original SWAT model to perform event-based simulation, which was applicable for the area without continuous long-term observations. The newly developed SWA-EVENT model was applied in the upper reaches of the Huaihe River. Model calibration and validation were made by the using of historical flood events, showing good simulation accuracy. To improve the spatial representation of the SWA-EVENT, the lumped UH parameters were then adjusted to the distributed ones. Calibration and validation results revealed the improvement of event-based simulation performances. This study expands the application of the original SWAT model in event-based flood simulation."

Comment: I have one general major comment: The authors suggest to improve the SWAT model in two ways. At first, at the spatial level, the model parameter t_adj is moved from the catchment level to the subbasin level to allow an individual parameterizsation for each subbasin and thus to consider spatial heterogeneity. Secondly, at the temporal scale, a sub-daily modeling is suggested to improve the representation of flood peaks. Both aspects, spatial and temporal improvements, are not clearly enough separated. It would interesting to know why aspect improves the model more and in which part of the hydrograph. The study would benefit from a four-step comparison instead of a two-step comparison. To be more precise: I recommend to add two cases: (1) Sub-daily calculation with t_adj at catchment level (without t_subadj) and the opposite case (2) daily calculation with t_adj at subbasin level (with t_subadj).

Reply: Thanks for your comment. We assume the referee is here referring the four-step comparison:

daily calculation with catchment level parameter (t_adj);

daily calculation with sub-basin level parameter (t_subdadj);

sub-daily calculation with catchment level parameter (t_adj);

sub-daily calculation with sub-basin level parameter (t_subdadj).

If so, we want to respectfully clarify some confusions. In SWAT model, the Unit Hydrograph (UH) method is only used for sub-daily simulation, rather than a daily simulation. The main reason of this situation is that the flood hydrograph resulting from a known storm often vary significantly within sub-daily time-scales, while the daily calculation may exceed the time of concentration for most of the sub-basins. Even for large sub-basins with a time of concentration greater than 1 day, SWAT incorporates a lag equation to store a portion of the surface runoff release to the main channel. Thus we think there are no such cases: daily calculation with catchment level parameter (t_adj) and daily calculation with sub-basin level parameter (t_subdadj).

The other argument is that modification at the temporal level was the first step, and modification at the spatial level was the second step.

At the temporal level, there are two drawbacks in the application of the original SWAT model for event-based flood simulation: (1) algorithms with daily time step for some hydrological processes are implicitly assumed (2) the continuous long-term simulation loop of its initial design. This paper referenced the methodologies in a previous study (Jeong et al., 2010) to solve the aforementioned problem (1). Then this paper broke down the continuous cycle of the model structure to solve the problem (2). Finally the SWAT-EVENT model was developed to simulate the event-based floods. At the spatial level, the UH parameter was modified from basin level to sub-basin level to represent the spatial heterogeneity of studied catchment, expecting an improvement for event-based flood simulation with the SWAT-EVENT model.

This paper used a two-step comparison to prove that: (1) temporal modification enabled the original SWAT model to simulate flood events and the improvements of the aggregated daily performances of the SWAT-EVENT model in Figure 6 were due to the higher temporal resolutions for input rainfall and the simulation time step; (2) spatial modification improved the simulation accuracy for even-based floods (Table 3 and Figure 8).

Comment: The model modification of Jeong et al. (2010) to simulate on sub-daily resolution needs to be explained and not only mentioned (P.5, L.4). This is a core point of the manuscript. The readers need to understand this modification without reading the paper of Jeong et al. (2010).

Reply: Thank you for your valuable suggestion. We will explain specifically the model modification of Jeong et al. (2010) in the revised manuscript. I still need time to organize this part.

Comment: You have mentioned that the SWAT is in its default version not adapted to sub-daily flood peak simulations. Keeping in mind that a large number of models is available: Why do you have selected

the SWAT model and not a model which is focused on the hydrograph simulation. The major points of the SWAT model such as nutrient simulation, detailed land managements operation etc. are not relevant for your study.

Reply: The perceptive comment shows the reviewer's knowledge in the field, and we have to admit that the SWAT model is not the first choice of flood simulation because there are so many other models have good applicability in this field. Here we respectfully argue that this study still has certain scientific significance. Though the highlights of the model of the SWAT model are the predictions of the impact of land management practices on water, sediment and agricultural chemical yields, runoff simulation is always a fundamental. Moreover, we have noticed that the study on the event-based water quality assessment has been a hot topic (He et al., 2010;Nguyen and Meon, 2013;He et al., 2011). Therefore the improvement of the SWAT model for event-based flood simulation will lay the lay the foundation for event-based water quality modeling. To emphasize our points, the following statement is added to the conclusion section:

"Event-based runoff quantity and quality modeling has become a challenge task since the impact of hydrological extremes on the water quality is particularly important. The improvement of the SWAT model for event-based flood simulation will lay the foundation for dealing with the event-based water quality issues."

Comment: The model results from SWAT2005 are used as input for SWAT-EVENT to simulation the flood peak. Is the model output of SWAT-EVENT then transfered back to SWAT2005? This point might be relevant since the first two flood events occured with a time lag of 19 days (P.9, L. 11). Thus, I expect a difference in the model states at the end of the first flood between SWAT and SWAT-EVENT. In this context, I like to mention that SWAT-EVENT does not impact the amount of water available in the system, but the water redistribution.

Reply: The answer to the question "Is the model output of SWAT-EVENT then transfered back to SWAT2005" is no. In fact, the daily SWAT model and the sub-daily SWAT-EVENT model were executed independently. According to Figure 3, the continuous daily SWAT model ran first to calculate the antecedent conditions for each flood events. After this, the SWAT-EVENT model began to run. This approach has been commonly used in other researches when no measurements of antecedent moisture conditions are available (Tramblay et al., 2012).

Comment: P.5, L.16-29: This part needs to be reformulated to present the idea in a better way. In the

current version, it is difficult to understand.

Reply: We agree that better reformulation about the modification of the SWAT model should be presented. Reorganization of this part will be completed in the revised manuscript. We still need time to organize this part.

Comment: P. 7, L. 1-2: This is a major point of the manuscript and has to be emphasised. A new model parameter is introduced at the subbasin level to include spatial heterogeneity. This is really important that it becomes clear.

Reply: Thank you for the suggestion. We think it is really necessary to add more descriptions for this major point. The last paragraph in section 3.2 is changed to:

"According to Eq. (4) the time base of the UH (t_b) is determined by both concentration time for the sub-basin (t_c) and shape adjustment factor (t_{adj}) concurrently. Though the t_c can present the spatial differences among sub-basins based on the geographical characters including slope length, slope steepness and sub-basin area and et al. The variable t_{adj} in Eq. (4) is a basin level parameter possessing the same value for the whole catchment, meaning that the spatial heterogeneities may be homogenized. 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}."

Comment: P. 11, L. 18-19: This statement is not right. The SWAT model is not limited in representing low flows. It is more that there is a trade-off between high and low flow simulations at the same time. At it is true that it is difficult to represent high and low flows in a very good quality with the same model run. This is by the way an often occurring problem in hydrological modelling. The major point here is that the selection of the performance measures is at the same time a decision on the study focus. By selecting the NashSutcliffe Efficiency high flows are more weighted than low flows. Thus, it would not be a surprise if the high flows are well represented while low flows perform poorly. This results could be different if using ENSlog or a different performance measure related to low flows. Please improve this statement.

Reply: Thank you very much for pointing out my mistake. The following statement is going to correct the mistake:

"On the one hand, the SWAT model was calibrated using the sum of squares of the residuals as the objective function, which was more sensitive to high flows than low flows. Thus the calibration results ensured the simulation accuracy at the expense of the low flow performances"

Comment: The aspect of flood forecasting is strongly emphasised in the conclusion. I still do not see that the strength of the manuscript is related to flood forecasting. Please rework the conclusion accordingly.

Reply: We will rework the whole conclusion section as follows:

"Flood forecasting is a synthetic system that integrates the data acquisition and processing, rainfall-runoff modeling and warning information release etc. Hydrological models are always the core part of the forecasting system. Model structures and model parameters are one of the most important issues for accurate flood forecasting (Noh et al., 2014). The original SWAT model was not competent to flood forecasting due to its initial design of long-term simulations with daily time-steps. This paper mainly focused on the modification of the structure of the original SWAT model to perform event-based simulation, which was applicable for the area without continuous long-term observations. The newly developed SWA-EVENT model was applied in the upper reaches of the Huaihe River. Model calibration and validation were made by the using of historical flood events, showing good simulation accuracy. To improve the spatial representation of the SWA-EVENT, the lumped UH parameters were then adjusted to the distributed ones. Calibration and validation results revealed the improvement of event-based simulation performances. This study expands the application of the original SWAT model in event-based flood simulation.

The determination of hydrological model parameters is an inevitable process before flood forecasting. Parameter estimations of distributed or semi-distributed hydrological models commonly depend on automated calibration procedure due to overparametrization. The optimal parameters of the SWAT-EVENT model were obtained by the automatic parameter calibration module that integrated SCE-UA algorithm in this study. However, serveral factors such as interactions among model parameters, complexities of spatio-temporal scales and statistical features of model residuals may lead to the parameter non-uniqueness, which is the source of the uncertainty in the estimated parameters. Uncertainty of model parameters will be finally passed to the model results, hence leading to certain risks in flood forecasting. In the future, emphasis will be placed on the quantification of the parameter uncertainty to provide better supports for flood operations.

Event-based runoff quantity and quality modeling has become a challenge task since the impact of hydrological extremes on the water quality is particularly important. The improvement of the SWAT model for event-based flood simulation will lay the foundation for dealing with the event-based water quality issues.”

2. Responses to specific comments

Comment: P.3, L.3: How do you "relate hydrologic response to specific catchment characteristics“? By parameter settings?

Reply: The dimensionless UH used in the SWAT model is just one form of the Synthetic Unit Hydrograph (SUH), which can be used to the ungauged catchments. The SUH was derived from catchment characteristics rather than rainfall-runoff data (Bhunya, 2011). According to Equation (3), the UH was defined based on the hydrologic property of the catchment. To be clear, detail descriptions of this kind of UH will be added in the revised manuscript.

Comment: P.4, L. 18: The weather generator is only used in the case of missing climate data. Please improve this statement.

Reply: We suggest the following statement to be a replacement:

“The SWAT model has developed a weather generator (WXGEN) to fill the missing climate data by the use of monthly statistics.”

Comment: P. 5, L. 21: It was not mentioned before that the SWAT model includes HRUs. Please improve the description of the SWAT model.

Reply: We suggest the following description to be added to the third paragraph in section 1:

“To spatially characterize the inhomogeneity, the SWAT model delineates a catchment into a number of sub-basins, which were subsequently divided into Hydrologic Response Units (HRUs). In SWAT model, HURs are basic simulation units of the land phase of the hydrological cycle that controls the total yield of streamflow, sediment, pesticide and nutrient to the main channel in corresponding sub-basin. Afterwards the routing phase converges the land phase results to the watershed outlet through the channel network.”

Comment: P. 7, L. 9: Please denote the 26 parameters, maybe in the attachments.

Reply: Thanks for the good suggestion. The following table is added to introduce the 26 parameters in the SWAT model:

Parameters	Definition	lower bound	upper bound
ALPHA_BF	Baseflow alpha factor (days).	0	1
BIOMIX	Biological mixing efficiency.	0	1
BLAI	Maximum potential leaf area index.	0	1
CANMX	Maximum canopy storage (mm H2O).	0	10
CH_K(2)	Effective hydraulic conductivity in main channel alluvium (mm/hr).	0	150
CH_N	Manning's "n" value for the main channel.	0	1
CN2	Initial SCS runoff curve number for moisture condition II.	-25	25
EPCO	Plant uptake compensation factor.	0	1
ESCO	Soil evaporation compensation factor	0	1
GW_DELAY	Groundwater delay time (days).	-10	10
GW_REVAP	Groundwater "revap" coefficient.	-0.036	0.036
GWQMN	Threshold depth of water inthe shallow aquifer required for return flow to occur (mm H2O).	-1000	1000
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H2O).	-100	100
SMTMP	Snow melt base temperature (ºC).	0	5
SLOPE	Average slope	-25	25
SLSUBBSN	Average slope length (m).	-25	25
SMFMN	Melt factor for snow on December 21 (mm H2O/ºC-day).	0	10
SMFMX	Melt factor for snow on June 21 (mm H2O/ºC-day).	0	10
SMTMP	Snow melt base temperature (ºC).	-25	25
SOL_ALB	Moist soil albedo.	-25	25
SOL_AWC	Available water capacity of the soil layer (mm H2O/mm soil).	-25	25
SOL_K	Saturated hydraulic conductivity (mm/hr).	-25	25
SOL_Z	Depth from soil surface to bottom of layer (mm).	-25	25
SURLAG	Surface runoff lag coefficient.	0	10
TIMP	Snow pack temperature lag factor.	0	1
TLAPS	Temperature lapse rate (ºC/km).	0	50

Comment: P. 8, L.13: Please explain the three indices, at best with equations.

Reply: We agree to the comment and will add the following equations for the three indices in the revised manuscript:

$$E_{\mathrm{NS}} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Q_{obs}(i) - Q_{sim}(i) \right)^2}{\sum_{i=1}^{n} \left(Q_{obs}(i) \text{-} \overline{Q}_{obs} \right)^2} \right]$$

$$P_{\mathrm{BIAS}} = \left[\frac{\sum_{i=1}^{n} \left(Q_{obs}(i) - Q_{sim}(i) \right) \bullet 100}{\sum_{i=1}^{n} Q_{obs}(i)} \right]$$

$$R_{\mathrm{MSE}} = \sqrt{\frac{\sum_{i=1}^{n}\left(Q_{obs}(i) - Q_{sim}(i)\right)^2}{n}}$$

where Q_{obs} is the observed values; Q_{sim} is the simulated values; n is the number of the value points.

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