Dear Editor and Reviewers,

The authors would like to thank the editor and reviewers for your time and constructive comments. Our point-to-point responses are listed below, where our responses are in blue color and the editor and reviewers' comments are in black color and italic.

Kind regards, all authors

Authors Response to Editor

Comment 1: *The paper received relatively positive comments, however there are some clarifications needed. Aside from the ones mentioned by the reviewers, a better clarification of the model calibration approach is needed.*

Response:

Thank you for your comments.

I) According to the comments of reviewer #1, we added the details of SUH determinations and described the routing method steps in more details. In addition, A picture for the flood event statistics used for model calibration and validation was inserted in the revised manuscript.

II) According to the comments of reviewer #2, we have revised the first and second paragraphs of the introduction.

III) The language of the revised manuscript has been improved by a native English speaker.

IV) A schematic of the calibration procedure was inserted in the revised manuscript, and clarifications of the calibration process have been added.

Comment 2: *It appears that (i) the hydrological model and the proposed flow routing models were calibrated separately ("the parameters of the XAJ model and the proposed distributed unit hydrograph were calibrated separately"), and (ii) the hydrological model + proposed flow routing model and the hydrological model + standard flow routing model have been calibrated in a different way ("The synthetic unit hydrograph, derived by historical rainfall-runoff data, was used for flow routing in the process of model calibration").*

Response:

(I) Regarding the first point, the hydrological model and the proposed flow routing models were calibrated separately.

(II) Regarding the second point, the hydrological model + proposed flow routing model and the hydrological model + standard flow routing model have been actually calibrated in the same way. The reasons can be summarized as follows:

First, the generation model (XAJ model) and the routing model were calibrated separately. The XAJ model were calibrated using the SCE-UA method. The parameters of the DUH methods were determined based on the physical characteristics and rainfall intensities of watershed. And SUH was derived according to the observed rainfall and runoff data.

Second, the parameters of the XAJ model remain unchanged, but different methods are used for runoff routing.

Third, the same calibration and validation periods were used for model comparison for the same flow event sets.

Comment 3: *Regarding the first point, it may be that by calibrating the two models separately, the flow routing model is correcting for some inconsistencies of the hydrological model, and in addition, since the observed variable is streamflow, I don't understand how this separate calibration can take place.*

Response:

Thank you for your comments.

First, the SUH and several distributed unit hydrographs were derived, respectively. Specifically, the SUH was derived from the observed rainfall and runoff. The parameters of three DUHs (DUH, TDUH and MC-TDUH) were calibrated according to the physical characteristics, rainfall intensities and soil moisture contents of watershed. Then DUHs can be derived according to Fig. 2 in section 2.2 of the revised manuscript.

Second, the SCE-UA method was used to optimize the parameters of the XAJ model. In this process, the SUH was selected as runoff routing approach. As the SUH was derived from observed rainfall and runoff, the flow routing model is correcting for some inconsistencies of the hydrological model. Therefore, the parameters of excess runoff can be calibrated.

Third, the accuracy of XAJ+ SUH and XAJ +DUHs (DUH, TDUH and MC-TDUH) were compared.

Comment 4: *Regarding the second point, two methods that are compared should be calibrated in exactly the same way. It would be unfair to use different methodologies for the "traditional" and the "proposed" model.*

Response:

The parameters of the traditional method and the proposed model were calibrated in essentially the same way, and the modes and parameters of runoff generation were absolutely unchanged.

Since the parameters of XAJ model were determined by combining with SUH, this calibration method would be more inclined to optimize the performance of XAJ+SUH model. When combined with other confluence models, the accuracy of the results may be affected to some extent.

Comment 5: *In any case, the way these models were calibrated, jointly or independently, and to which events, should be made much clearer, perhaps using some schematics.*

Response:

Thank you for your comments.

The schematic of the calibration procedure is given below.

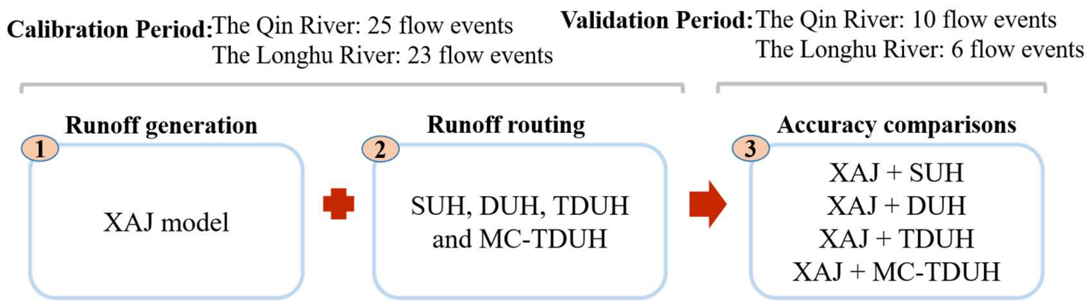

Figure 1 Schematic of the calibration procedure

Steps of the parameter calibration can be summarized as follows.

1) The XAJ model was used to calculate the excess rainfall, in which, the SUH derived from observed runoff was selected as the runoff routing method. The SCE-UA method was used to optimize the XAJ model parameters in this study. 25 and 23 flow events in the Qin River basin and Longhu River basin were used for the calibration of the XAJ + SUH model.

2) The SUH was derived using 25 and 23 flow events in the Qin River basin and Longhu River basin, respectively. The DUH, TDUH and MC-TDUH were derived, based on physical characteristics and rainfall intensities of the watersheds. The parameters determination method is given in Section 5.1.3.

3) Since the objective of this study was to propose a new flow routing method, the runoff production model with its parameters were not changed in order to discuss the performance of flow routing models. The XAJ model with calibrated parameters in Step 1) and DUH, TDUH as well as MC-TDUH determined in Step 2) were used for the validation

period. 10 and 6 flow events of the two basins were then used for the validation of the XAJ + (SUH, DUH, TDUH and MC-TDUH) model.

Authors Response to Reviewer #1

Comment #1: *The paper speaks about a very interesting study of UH concepts of runoff generation in river basins. The authors have successfully compared the performances of four types of UHs e.g SUH, DUH, TDUH (DUH with time-varying rainfall intensity); and TDUH (DUH with time-varying rainfall intensity & soil moisture). The approach has practical application if soil moisture conditions and the observed rainfall intensity are known and a set of IUHs are already developed using the past rainfall and flood events. The accuracy of the methodology is well established, hence acceptable. However, the reviewer raises the following points for clarification and, if incorporated into the manuscript, the quality of the paper will improve a lot.*

Response:

We appreciate you for taking the time to review our paper and provide some insightful discussion points to improve the transparency and clarity of our work. We make the following adjustments to the manuscript based on your suggestions.

Comment #2: *Section 1 (Line 100). IA? Explain.*

Response:

This is a typo. And “*IA*” has been corrected as “*A*” in the revised version.

Comment #3: *The Author uses equations (1), (2) & (3) for velocity computation from grid cells in the case of DUH, TDUH (DUH with rainfall intensity) and the present method considering both the rainfall intensity and soil moisture content (may be referred as TDUH-MC) respectively. Subsequently, all computations for the UH or flood hydrographs have been attempted. The paper also speaks about the traditional SUH of the two test catchments about which the author has not spoken. Please explain. Or is it Clark's approach of determining the IUH considering the time-area histogram and the attenuation of this time-area hydrograph using a linear reservoir that represents channel storage effects?*

Response:

Thank you for your comments.

I) This is a good suggestion and the TDUH method considering both the rainfall intensity and soil moisture content has been expressed as TDUH-MC method in the revised manuscript.

II) The details of SUH determinations have been added to the revised manuscript in Section 3. The Nash instantaneous unit hydrograph model (Nash, 1957) was used to derive the synthetic IUH in this study. In the Nash IUH model, a catchment is assumed to be made up of a series of n identical linear reservoirs, each with the same storage constant K, which is given by

$$h(t)=\frac{e^{-\frac{t}{k}}}{k\Gamma(n)}\left[\frac{t}{k}\right]^{n-1}$$

where $h(t)$ is the IUH of the Nash model, $\Gamma(n)$ is the Gamma function. Using the method of moments, the model parameters n and k can be determined by (Singh, 1988; Chow et al., 1988)

$$M_1(Q)-M_1(I)=nk$$

$$M_2(Q)-2M_1(I)M_1(Q)+M_2(I)=nk^2(n-1)$$

where M_1 and M_2 are the first and the second moments of the quantities within parentheses. For some watersheds without observed rainfall and runoff data, Nash established experimental relations between watershed physical properties and the IUH parameters and presented a synthetic IUH (Singh, 1988).

The added sentences are as follows:

"*Finally, the SUH was selected as runoff routing approach in the XAJ model. Specifically, the Nash instantaneous unit hydrograph model (Nash, 1957) was used to derive the SUH in this study. For the Nash IUH model, a catchment was assumed to be made up of a series of n identical linear reservoirs, each with the same storage constant K. The magnitudes of n and K were estimated based on the observed excess rainfall hyetograph and corresponding direct runoff hydrograph using the method of moments. Details can be found in Singh (1988) and Chow et al. (1988). The parameters n of the Qin River basin and Longhu River basin are 4 and 3, and the parameters k are 3.4 and 2.1, respectively.*"

References:

Nash, J. E.: The form of the instantaneous unit hydrograph. International Association of Science and Hydrology, 45(3):114-121, 1957.

Singh V.P.: Hydrologic Systems, Rainfall–Runoff Modeling, vol. I, Prentice-Hall, Englewood Cliffs, 1988.

Chow V. T., Maidment D. R., Mays L. W.: Applied Hydrology, McGraw-Hill, New York, 1988.

Comment #4: *The author has commented on the assumptions of Bunster et al. (2019) regarding the watershed equilibrium condition prior to the end of excess rainfall pulse (Line 138-148). Under saturated conditions and the routing velocity-at-maximum condition,* *the time to peak becomes shorter, peak is higher. How the slower travel time (line 145-146) will ensure shorter time to peak and higher peak may be justified/corrected?*

Response:

Thank you for your comments. This sentence has been corrected.

Change from

"This assumption of equilibrium globally or in grid cells yields slower travel times, shorter times to peak and higher peak discharges."

to

"This assumption of equilibrium globally or in grid cells yields faster travel flow velocities, smaller travel time, and higher peak discharge."

Comment #5: *Section 3. Several approaches can be adopted to compute the runoff at the basin outlet. The author has used the Muskingum method of runoff routing. Since any natural river is multiple inflows-single outflow runoff systems with different travel times from the sub-basins to reach the outlet, the author may describe the routing method steps in more detail.*

Response:

Thank you for your comments. The details about the parameters determination of the Muskingum method has been added in Section 3 of the revised manuscript. In the conventional Muskingum method, these parameters are determined by calibration using measured inflow and outflow hydrographs. In recent decades, the artificial intelligence-based optimization methods have been widely utilized in the parameter estimation of the Muskingum model (Chu et al., 2009; Moghaddam et al., 2016). In addition, the physical-based methods were also widely used for parameters estimation, such as Muskingum-Cunge method (Ponce et al., 1996).

1) For the SUH, the basin was taken as a whole. The parameters of the Muskingum methods were calibrated with those of the Xinanjinag model. The SCE-UA algorithm was used to calibrate the parameters of XAJ model. The parameters (*XE* and *KE*) of the Muskingum method have been given in Section 5.1.2.

2) For the DUH, the basin was divided into several sub-basins. Since natural rivers are multiple inflows-single outflow runoff systems with different travel times from the sub-basins to the outlet, we adopted the physical-numerical principles established by Cunge to calculate the routing parameters of the Muskingum method, which is suitable to be applied to ungauged watersheds (Ponce et al., 1996). The parameters of the Muskingum method for each sub-basin were determined based on flow and channel characteristics, such as the

top width of the river, wave celerity, reach length and reach slop, which can be found in Chow (1959) and Wilson and Ruffin (1988).

$$KE = \frac{\Delta L}{V_w}$$

$$XE = \frac{1}{2} - \frac{Q_0}{2SWV_w\Delta L}$$

where Q_0 is the reference discharge; S is dimensionless channel bottom slope; V_w is kinematic wave celerity; ΔL is routing reach length; W is water surface width.

The parameters (*KE* and *XE*) for each sub-basins have been added in the revised paper as follows.

Table 1. Information on sub-basins

Sub-basins	Drainage area/km^2	Number of grids	Average slope	*KE*	*XE*
Sub-basin 1	175.64	176	13.29	10.7	0.13
Sub-basin 2	195.86	197	9.27	10.7	0.13
Sub-basin 3	154.97	156	12.50	8.3	0.12
Sub-basin 4	153.08	151	9.57	5.9	0.15
Sub-basin 5	147.79	147	12.49	5.9	0.15
Sub-basin 6	249.36	253	11.74	4.7	0.11
Sub-basin 7	213.34	211	10.56	2.1	0.11
Sub-basin 8	122.28	129	10.77	2.1	0.11
Sub-basin 9	166.51	161	9.74	/	/

References:

Chow, V. T.: Open Channel Hydraulics, McGraw-Hill, New York, USA, 1959.

Wilson, B. N., Ruffini, J. R.: Comparison of physically based Muskingum methods. Transactions of ASAE, 31(1): 91-97, 1988.

Chu, H. J., Chang, L. C.: Applying Particle Swarm Optimization to Parameter Estimation of the Nonlinear Muskingum Model. Journal of Hydrologic Engineering, 14(9):1024-1027, 2009.

Dooge J. Linear theory of hydrologic systems. Agricultural Research Service, US Department of Agriculture, 1973.

Nash, J. E.: The form of the instantaneous unit hydrograph. International Association of Science and Hydrology, 45(3):114-121, 1957.

Moghaddam, A., Behmanesh, J., Farsijani, A.: Parameters estimation for the new four-parameter nonlinear Muskingum model using the particle swarm optimization, Water Resour. Manage., 30 (7), pp. 2143-2160, 2016.

Ponce, V. M., Lohani, A. K., Scheyhing, C.: Analytical verification of Muskingum-Cunge routing. Journal of Hydrology, 174(3-4): 235-241, 1996.

Comment #6: *Section 5.1.1 (Line 377-382). In the model calibration process, SUH derived from historical rainfall-runoff data was used for flow routing in the model calibration process. But different rainfall-runoff events associated with different soil moisture conditions will give rise to various shapes of UH. The author may throw some more light on the suggested routing model calibration in this Section.*

Response:

Thank you for your comments. We realized that the initial condition is crucial for the UH derivation, and the shapes of the UH depend on the spatial and temporal distribution of rainfall and antecedent soil moisture.

The traditional UH method has little flexibility to different storm events, i.e. the unit hydrographs computed by it vary considerably from storm to storm (Rao and Delleur, 1971). This is partially because the UH methods ignore the influence of initial soil moisture conditions or antecedent soil moisture conditions (evapotranspiration and rainfall) on runoff generating processes. Several studies have shown that UH which is derived by considering antecedent soil moisture are more consistent than UH which is ignoring that (Yue and Hashino, 2000; Nourani et al., 2009). Therefore, the antecedent precipitation was calculated and was considered in this study. In order to obtain the UH, we defined excess rainfall and separated direct runoff and baseflow hydrographs in advance. The SUH used for calibration of the two case studies are average values deduced by 25 and 23 historical flood events respectively.

The added sentences are as follows:

"Several studies have shown that UH which is derived by considering antecedent soil moisture is more consistent than UH which ignores that (Yue and Hashino, 2000; Nourani et al., 2009). Therefore, the antecedent precipitation was calculated and considered in this study. In order to obtain the SUH, we defined excess rainfall and separated direct runoff and baseflow hydrographs in advance. The final SUH used for calibration is the average value deduced by multiple historical flow events."

References:

Rao R. A., Delleur, J. W. The instantaneous unit hydrograph. Its calculation by the transform method and noise control by digital filtering. Technical Report No. 20, Purdue University, Water Resources Research Center, West Lafayette, IN. 1971.

Yue S, Hashino M. Unit hydrographs to model quick and slow runoff components of streamflow. Journal of Hydrology, 227(1-4): 195-206, 2000.

Nourani V, Singh V P, Delafrouz H. Three geomorphological rainfall–runoff models based on the linear reservoir concept. Catena, 76(3): 206-214, 2009.

Comment #7: *Section 5.1.2. A Table for the flood event statistics used for model calibration and validation may be inserted in this section.*

Response:

Thank you for your comments. The flood events statistics used for model calibration and validation has been added to Section 5.1.2. The average peak flow of the two basins are 1311 m^3/s and 118 m^3/s, and the average flood durations are about 50 h and 13 h, respectively.

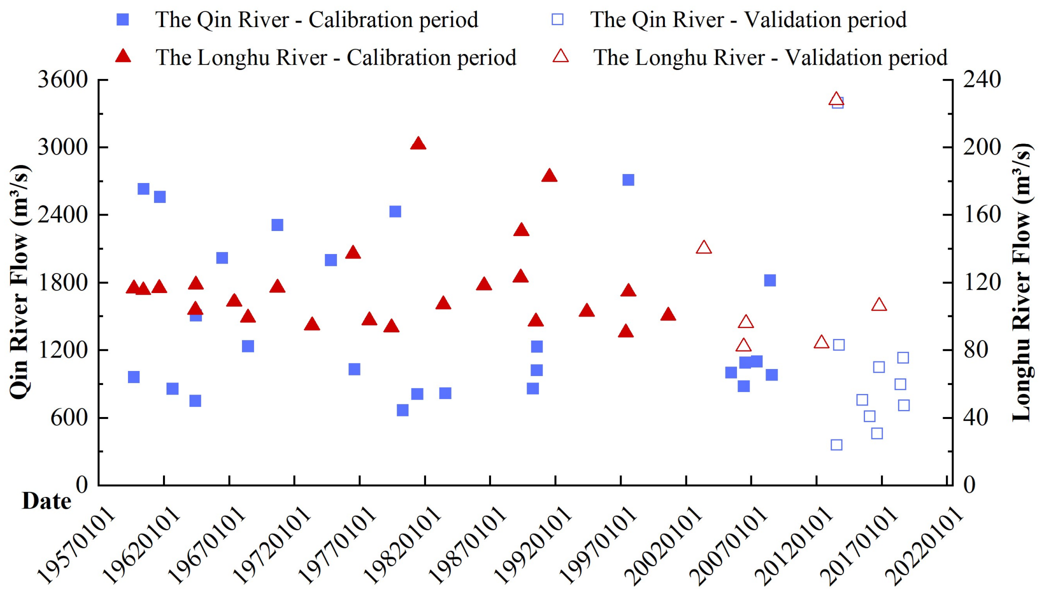

Figure 6. Flow event statistics used for model calibration and validation

Comment #8: *Section 5.2 (Line 443). Sub-basin 6 may be corrected as sub-basin 9.*

Response:

Thank you for your comments. *Sub-basin 6* has been corrected to *sub-basin 9* in the revised paper.

Comment #9: *Section 5.4 (Line 535). Is it Fig 10 or Fig 11. May be corrected accordingly.*

Response:

Thank you for your comments. *Fig 10* has been corrected to *Fig 11* in the revised paper.

Comment #10: *The paper suffers from improper sentence formation (at few places sentences are not completed), poorly written. Sentences are not properly formed. Hence needs improvement.*

Response:

Thank you for your comments. The language of the revised manuscript has been improved by a native speaker.

Authors Response to Reviewer #2

Comment #1: *The article is well prepared and I personally believe that the result of the study is valuable for hydrological modeling related engagements, particularly in countries with poor gauging stations. In this regard, the paper can be accepted for publication. However, the authors are supposed to take care of the following points.*

Response:

We appreciate the reviewer for taking the time to review our paper and for the positive comments. We have improved the manuscript based on your suggestions.

Comment #2: *Polish the document in terms of the English language use. For instance, in the abstract, replace "the objective of this study is…. " with " the objective of this study was.. ". In Line 149, too.*

Response:

Thank you for your comments. The language of the revised manuscript has been improved by a native speaker.

Comment #3: *Please, add the implications of the result of the study in terms of future uses and hydrological modelling in a sentence or two in the abstract if there are no limitations of words*

Response:

Thank you for your comments. The added sentences are given below.

"The proposed method can be used for the watersheds with sparse gauging stations and limited observed rainfall and runoff data."

Comment #4: *I do not see the need for Paragraph 1 in the introduction part. You could justify your study in terms of the absence of observed unit hydrographs of gauging stations and the non-reliability of existing UH development methods.*

Response:

Thank you for your comments. Paragraphs 1and 2 have been substituted by

Flow routing is an essential component of a hydrological model, whose accuracy directly affects runoff prediction and forecasting. Different types of flow routing techniques are available, such as hydraulic and hydrologic methods (Akram et al., 2014). Since hydraulic methods are usually computationally intensive, hydrologic methods are widely used all over the world. The unit hydrograph, proposed by Sherman (1932), is one of the methods most widely used in the development of flood prediction and warning systems for *gauged basins with observed rainfall and runoff data (Singh et al., 2014). However, the UH method has inherent problems, such as areal lumping of catchment and rainfall characteristics as well as the utilization of linear system theory (Singh, 1988; James and Johanson, 1999). Moreover, current routing methods usually require numerous rainfall and runoff data. For watersheds with sparse gauging stations, it is difficult to develop an adequate relationship between physical watershed characteristics and unit hydrograph shape. The unit hydrograph estimation in small and ungauged basins is still a challenge in hydrological studies (Petroselli and Grimaldi, 2015).*

References:

Akram F, Rasul M G, Khan M M K, et al. Comparison of different hydrograph routing techniques in XPSTORM modelling software: A case study. International Journal of Environmental and Ecological Engineering, 8(3): 213-223, 2014.

James W, Johanson R C. A Note on an Inherent Difficulty with the Unit Hydrograph Method[J]. Journal of Water Management Modeling, 1999.

Petroselli A, Grimaldi S. Design hydrograph estimation in small and fully ungauged basins: a preliminary assessment of the EBA4SUB framework. Journal of Flood Risk Management, 11: S197-S210, 2015.

Sherman, L. K.: Streamflow from rainfall by the unit-graph method. Engineering News Record, 108:501-505, 1932.

Singh, P. K., Mishra, S. K. and Jain, M. K.: A review of the synthetic unit hydrograph: from the empirical UH to advanced geomorphological methods. International Association of Scientific Hydrology Bulletin, 59(2):239-261, https://doi.org/10.1080/02626667.2013.870664, 2014.