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ORIGINAL ARTICLE

# Parameter Sensitivity Analysis of the WRF-Hydro Modeling System for Streamflow Simulation: a Case Study in Semi-Humid and Semi-Arid Catchments of Northern China

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**Abstract**
The WRF model is nowadays the most widely applied mesoscale numerical weather prediction model. Its land-surface hydrological modeling module, WRF-Hydro, which is designed to facilitate the land-surface modeling being coupled with WRF, draws more and more attentions from both the meteorological and the hydrological community. In this study, four sensitive and principle parameters of WRF-Hydro are tested in semi-humid and semi-arid areas of northern China. These parameters include the runoff infiltration parameter (REFKDT), the surface retention depth (RETDEPRT) controlled by a scaling parameter named RETDEPRTFAC, the channel Manning roughness parameter (MannN), and the overland flow roughness parameter (OVROUGHRT) controlled by the scaling parameter OVROUGHRTFAC. WRF-Hydro is designed with a 100-m horizontal grid spacing in two catchments of northern China. The performance of WRF-Hydro with different parameterisation combination schemes is tested for simulating a typical 24-h storm events with uniform rainfall evenness in space and time. The Nash-Sutcliffe efficiency and the root mean squared error of the simulated streamflow, together with the cumulative amount of the simulated rainfall is chosen as the evaluation statistics. It is found that REFKDT and MannN are the most sensitive parameter among the four parameters, and the case is especially evident with unsaturated soil conditions. In order to obtain the most reasonable value range, REFKDT and MannN are further verified by another three 24-h storm events with different spatial and temporal evenness. The range of REFKDT from 2.0 to 3.0, and the MannN scale factor from 1.5 to 1.8 is found to give the best results. The findings of this study can be used as references for calibration of the WRF-Hydro modeling system in semi-humid and semi-arid regions with similar rainfall-runoff response characteristics. The methodologies to design and test the combination schemes of parameterisations can also be regarded as a reference for evaluation of the WRF/WRF-Hydro coupled system for land-surface process modeling.

**Keywords** Streamflow simulation · WRF-hydro · Sensitivity analysis · Parameters · Northern China

## 1 Introduction

In traditional hydrological forecasting, the input of the hydrology model is principally the "throughfall" observed by the rain gauges. The forecast lead time depends on the confluence time of the river basin, and the accuracy of forecasting is limited by the layout of the rain gauge network. In order to further extend the forecast lead time and to improve the forecast accuracy, the mesoscale numerical weather prediction (NWP) model is increasingly used instead of the "throughfall". Nowadays it has become a promising method to couple the hydrological models with the fine-scale NWP models (1–10 km) for real-time forecasting of the streamflow. The coupling the hydrological model with the fine-scale atmospheric model has been shown to have possibility to sufficiently predict the streamflow at the catchment outlet (e.g.Yucel et al. 2015; Gochis et al. 2015; Arnault et al. 2015; Senatore et al. 2015). In recent years, the study of the coupled atmospheric-hydrological modeling system has been

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developing towards describing more detailed and complex land-surface hydrological processes.

The Weather Research & Forecasting (WRF) model is the most widely used mesoscale NWP model for the simulation and prediction of rainfall as well as the land-surface processes. Based on the study of the WRF model, the development of the WRF-Hydro modeling system enables WRF to be better used for hydrological forecasting (Gochis et al. 2015). It solves the problem that the resolution of the atmospheric model does not match that of the hydrological model. The WRF-Hydro modeling system has been developed by the National Center for Atmospheric Research (NCAR) and its research partners. WRF-Hydro is a fully distributed, multi-physical and multi-scale three-dimensional land-surface hydrological simulation system. It improves the one-dimensional vertical generalization of water transport by Noah, which is the original land surface module of WRF model. The WRF-Hydro modeling system takes into account the lateral redistribution process of surface, shallow groundwater and river water, and can better describe the relationship between water and energy fluxes at the atmospheric-terrestrial interface. It has now been serving as the core model for the new National Water Model of the United States.

During the development of the WRF-Hydro system, worldwide relevant studies have been carried out for a wide range of research and operational problems, which have verified the practicability and the theoretical value of the system. Specific studies include flash flood prediction, regional water resources management, atmosphere-hydrology simulations and studies of atmospheric-terrestrial water balances. For example, Senatore et al. (2015) compared the rainfall-runoff simulation results from one-way and the two-way coupling of WRF/WRF-Hydro. The results showed that the fully coupled model can better capture the strong convective events. Kerandi et al. (2017) carried out 4-year continuous simulation in East Africa, which confirmed that the two-way coupling of WRF/WRF-Hydro can serve as a tool to quantify the atmospheric-land water balance for better water resources management. Arnault et al. (2015) carried out a 1-year continuous simulation in West Africa. The results showed that WRF-Hydro can reflect the role of runoff-infiltration partitioning and resolve the overland flow on land atmosphere feedbacks, particularly precipitation. Ryu et al. (2017) applied WRF-Hydro in a coupled atmospheric-hydrological system for flash flood forecasting in Korea, and the results showed that the fully coupled model can successfully help predict flash floods over the Korean Peninsula. Outputs from the two-way coupling of WRF/WRF-Hydro were compared with the observed runoff in the arid and semi-arid areas of Israel and Jordan by Silver et al. (2017), and the forecast results basically reflected the actual runoff changes. Naabil et al. (2017) carried out a 3-year continuous simulation using the WRF-Hydro in West Africa, the outputs from which were then served as the inputs of a water balance model to simulate the dam levels. However, the results were not satisfactory, and it was suggested the calibration of the WRF-Hydro parameters needed further improvement.

The stand-alone WRF-Hydro modeling system consists of many parameters, which can cause great uncertainties. Four of them are considered as the most important ones for rainfall and streamflow simulation in WRF-Hydro by Ryu et al. (2017): the runoff infiltration parameter (REFKDT), the surface retention depth scaling parameter (RETDEPRTFAC), the overland flow roughness scaling parameter (OVROUGHRTFAC) and the channel Manning roughness (MannN). Besides, Naabil et al. (2017) think the parameter governing the deep drainage (SLOPE), bucket model exponent (Expon) and lateral saturated conductivity (LKSATFAC) as also correlative parameters to the rainfall-runoff simulation. According to Gochis et al. (2015), SLOPE parameter is linear scaling of “openness” of bottom drainage boundary and influences groundwater flow and causes a secondary effect on surface flow, LKSATFAC parameter is multiplier on lateral hydraulic conductivity controlling anisotropy between vertical and lateral conductivity, and Expon as a function of governing deep drainage depth controls rate of bucket drainage. Yucel et al. (2015) also considers that REFKDT parameter and MannN parameter can adjust the model to make it most suitable for the observations of streamflow amount and timing.

The calibration of the key parameters of WRF-Hydro is of great significance for accurately reproducing the observed runoff process, including those controlling the total water volume in the channel (e.g. REFKDT, RETDEPRTFAC and SLOPE) and the temporal distribution of discharge (e.g. OVROUGHRTFAC, LKSATFAC, Expon and MannN). This is a generally accepted approach, Senatore et al. (2015), Ryu et al. (2017), Naabil et al. (2017) and Kerandi et al. (2017) calibrated the parameters by taking into account the volume of discharge as well as the overall shape of the hydrograph. In practice, there are different ways to calibrate parameters mentioned above. Yucel et al. (2015) recommended a stepwise approach to minimize the number of model runs and reduce excessive computational time. Lahmers et al. (2019) followed the method proposed by Pokhrel et al. (2012) to calibrate the WRF-Hydro parameters, which was a simple form of spatial regularization. The calibration process was addressed by Senatore et al. (2015) in two steps: the first step was manual calibration, which aimed to identify the most relevant parameters and roughly calibrating them. The second step adopted an automated calibration procedure based on the PEST software (Doherty 2002) with the aim of calibrating the most influential parameters again. Details of the parameters that may have some effect on the generation of runoff are shown in Table 1.

**Table 1** WRF-Hydro parameters considered for calibration from the WRF-Hydro model technical description and user's guide, version 3.0. (Gochis et al. 2015). Classifications are based on findings of Senatore et al. (2015), Naabil et al. (2017) and Lahmers et al. (2019)

| Classifications | Description | Parameter | Use for Calibration | Units |
|---|---|---|---|---|
| controlling the total water volume | runoff infiltration parameter | REFKDT | REFKDT is a tunable parameter, which determines the input flow in the channel confluence calculation, that is, inflow to stream channels = rainfall - the soil infiltration capacity. | unitless |
| | surface retention depth scaling parameter | RETDEPRTFAC | Multiplier on retention depth limit. | unitless |
| | coefficient governing deep drainage | SLOPE | Linear scaling of "openness" of bottom drainage boundary. | unitless; 0–1 |
| controlling the shape of the hydrograph | overland flow roughness scaling parameter | OVROUGHRTFAC | Multiplier on overland flow roughness. The overland flow roughness depends on the land use type, and also influences the amount of water that is transferred to the channel network as streamflow. | unitless |
| | saturated soil lateral conductivity | LKSATFAC | Multiplier on lateral hydraulic conductivity (controls anisotropy between vertical and lateral conductivity) | m/s |
| | bucket model exponent | Expon. | Exponent controlling rate of bucket drainage as a function of depth. The WRF-Hydro bucket model is a poor representation of baseflow in semi-arid environments, where groundwater recharge is unlikely to reach the local channel network. | dimensionless |
| | channel Manning roughness parameter | MannN | Manning roughness coefficient based on scaling factor corresponding. MannN reflects the influence of the channel roughness on the streamflow. | $s/m^{1/3}$ |

The initial calibration attempt was based on sensitivity studies of the runoff infiltration parameter (REFKDT) and the channel Manning roughness parameter (MannN) in the Korean Peninsula (Ryu et al. 2017), which have similarities as the study area in northern China, such as the catchment sizes and the precipitation characteristics due to the Eastern Asian monsoon climate. In this study, sensitivity studies are carried out for four key parameters in the WRF-Hydro modeling system: the runoff infiltration parameter (REFKDT), the surface retention depth scaling parameter (RETDEPRTFAC), the overland flow roughness scaling parameter (OVROUGHRTFAC) and the channel Manning roughness (MannN). The small-scale catchments in the Daqinghe basin, located in semi-humid and semi-arid area of northern China, are chosen as the study area. Floods in the study area are mainly caused by intense and short-duration summer rainstorms, and the distributions of storms are highly uneven in both space and time. The simulation and prediction of the streamflow has always been a tricky issue in the study area. Therefore, exploring the sensitivity of the key parameters seems to be rather important and necessary before applying the WRF-Hydro modeling system in practice. Four storm events with different spatial and temporal distribution characteristics are selected to carry out the sensitivity tests. Appropriate ranges of the four key parameters are finally given. The outcomes from this study could be referenced in areas with similar climatic conditions and rainfall-runoff generation characteristics, and the methodology adopted in this study could provide a guideline for WRF-Hydro parameter sensitivity analysis.

## 2 Study Area and Storm Events

Fuping and Zijingguan catchments, which respectively belong to the south and the north branch of the Daqinghe basin are chosen as the study area for streamflow simulation using the WRF-Hydro modeling system. The Daqinghe basin, located in northern China, has a warm temperate continental monsoon climate. Figure 1 shows the locations of the study area together with the rain gauges and the catchment outlets. Fuping catchment is located at 39°22′ N ~ 38°47′ N and 113°40′ E ~ 114°18′ E with a drainage area of 2210 $km^2$ and Zijingguan catchment is located at 39°13′ ~ 39°40′ N and 114°28′ ~ 115°11′ E with a drainage area of 1760 $km^2$. The average annual rainfall in the study catchments is approximately 600 mm, with the majority of rain occuring between the late May and early September. The two catchments are located in the Taihang mountain section and the upper reaches of the Daqinghe basin, with the maximum and the minimum elevation being 2286 m and 200 m above the sea level. The elevation decreases from northwest to southeast and changes greatly. The steep terrain leads to a short confluence time of the flood, which together with high-intensity, short-duration precipitation is prone to cause severe flood disasters. They are concentrated in areas with thin soil layer and low vegetation coverage especially. Soil vadose zones are often in a state of water shortage. Runoff generation process is accompanied by a mixed mechanism of infiltration capacity excess and storage capacity excess. The "63.8″ flood was the largest in history, which occurred in August 1963. The levees in the middle and lower reaches of the basin broke successively, causing

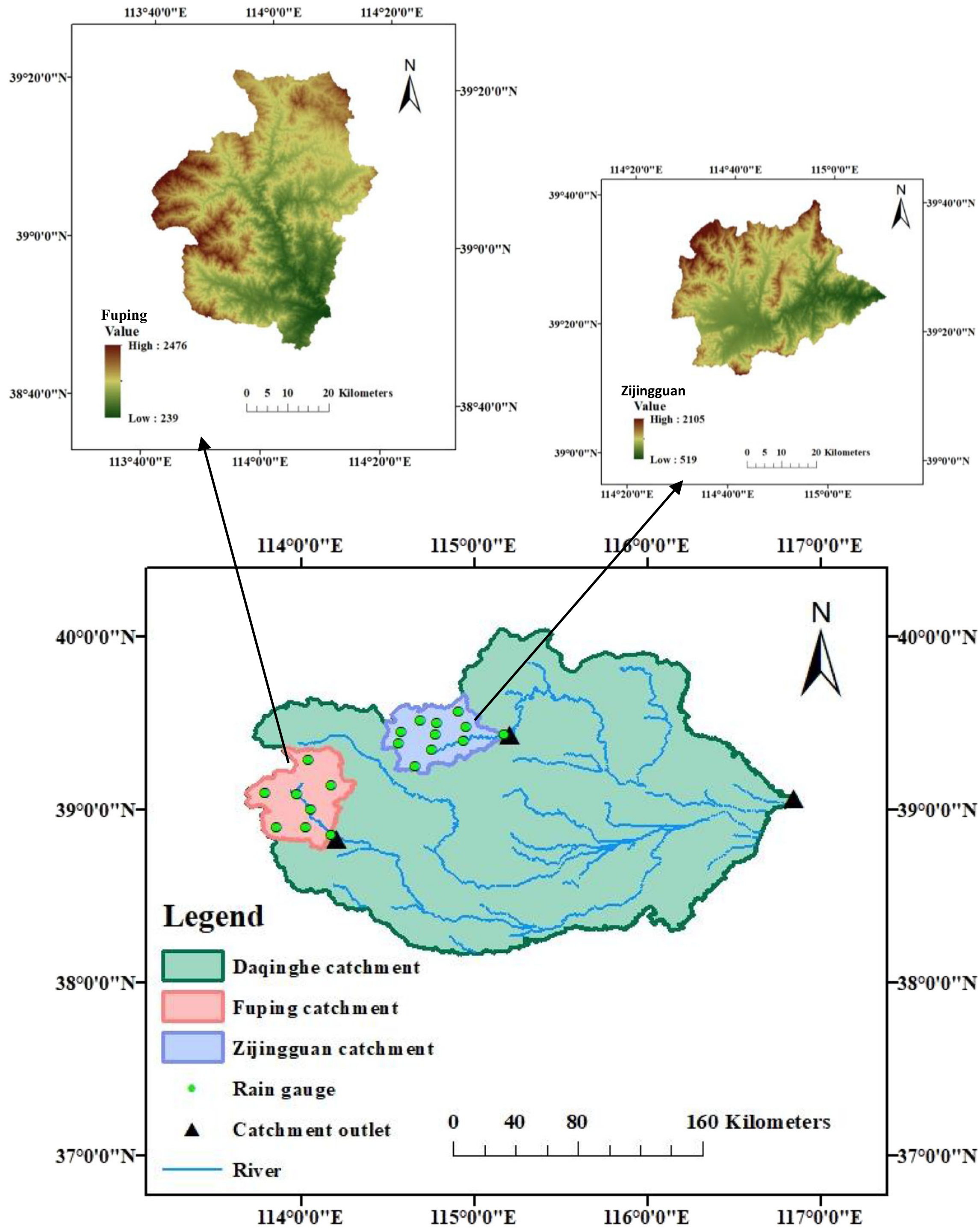


**Fig. 1** Location map and two study sites in the Daqinghe catchment

significant economic losses in the region. For three consecutive days, the rainfall accumulation was close to 1130 mm. The total volume of floods in the south branch of the Daqinghe basin was 5.7 billion $m^3$, while that in the north branch was 1.89 billion $m^3$.

Figure 1 shows 8 gauges locations in the Fuping catchment and 11 in the Zijingguan catchment respectively. In consideration of the representativeness of the storm and flood characteristics, four 24-h rainstorm events are selected from the last 10 years (2006 to 2015). The evenness of the spatial and temporal rainfall distributions of the four storm events are quite different. The duration of the four storm events and the accumulative rainfall amounts are shown in Table 2.

**Table 2** Duration, accumulated rainfall and maximum stream flow of the four selected 24-h storm events

| Event ID | Catchment | Storm start time | Storm end time | Accumulated rainfall (mm) |
|---|---|---|---|---|
| I | Fuping | 29/07/2007 20:00 | 30/07/2007 20:00 | 63.38 |
| II | Fuping | 11/08/2013 07:00 | 12/08/2013 07:00 | 30.82 |
| III | Zijingguan | 10/08/2008 00:00 | 10/08/2008 24:00 | 45.53 |
| IV | Zijingguan | 06/06/2013 22:00 | 07/06/2013 22:00 | 52.06 |

The 24-h rainfall accumulation is computed by Thiessen polygon method, which averages the observations from the rain gauges.

The evenness of the rainstorm events is quantitatively evaluated in spatial and temporal dimensions by variation coefficient Cv in this study.

$$\mathrm{Cv} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{X_i}{\overline{X}}-1\right)} \quad (1)$$

In the spatial dimension, $X_i$ is the accumulated 24-h rainfall at the rain gauge $i$, and $\overline{X}$ is the average of $X_i$. $N$ is the number of rain gauges. In the temporal dimension, $X_i$ is average hourly rainfall from all the rain gauges at time $i$, and $N$ is the number of hours. The higher Cv is, the more uneven the rainfall distribution is.

Table 3 shows the Cv values of the four storm events in both spatial and temporal dimensions. It can be found that the rainfall is more uneven in time than in space.

## 3 Model Description and Experimental Design

In order to study the variation law and applicable scope of the WRF-Hydro parameters in the study catchment, the WRF (Skamarock and Klemp 2008) and its hydrological extension package WRF-Hydro (Gochis et al. 2015) are adopted in this study. The WRF model is a fully compressible, non-hydrostatic, mesoscale NWP and atmospheric simulation system. In addition, the WRF-Hydro modeling system was developed as a community-based, open source, model coupling framework designed to link multi-scale atmospheric models and watershed hydrological models. One of the main features of WRF-Hydro is the approach of dealing with the surface runoff. WRF-hydro can be used to distribute runoff infiltration. Part of the excess runoff will accumulate in the subgrid, part will flow into the next grid cell, generating runoff, and part will permeate in the next step (Arnault et al. 2015). A brief overview of the basic model settings and the experiment design can be found in the following sections.

**Table 3** Rainfall evenness of the four selected 24-h storm events in space and time

| Event ID | I | II | III | IV |
|---|---|---|---|---|
| Spatial Cv | 0.3975 | 0.7400 | 0.4588 | 0.4258 |
| Temporal Cv | 0.6011 | 2.3925 | 1.3779 | 1.8865 |

### 3.1 Weather Research and Forecasting Model (WRF)

In this study, WRF version 3.7 is used for all experiments. WRF has different options for physical parameterization. The model performance is highly dependent on the parameterisation schemes which might be applicable to one storm event but not to others (Liu et al. 2012). Since it is difficult to determine the best choice for future storm events, the parameterisation schemes are normally pre-determined in operational applications (Liu et al. 2015). In this study, the most widely used physical parameterizations in northern China are adopted. Details of the parameterizations that have major impacts on the generation of precipitation are shown in Table 4 and explained in more details by Tian et al. (2017).

In this study, a three nested domain is set-up over the Fuping and Zijingguan catchments, respectively. For hydrological models, the high-resolution rainfall products based on the WRF model downscaling are more suitable for their input (Cardoso et al. 2013; Chambon et al. 2014). Therefore, the innermost domain of the WRF is set at 1 km horizontal resolution, and the downscaling radio is set to be 1:3 (Givati et al. 2012; Yang et al. 2012). For the Fuping catchment, the center of the domain is at 39°04′15″N and 113°59′26″E, and the nested domain sizes from the outermost to the innermost are $252 \times 234$ km$^2$, $144 \times 126$ km$^2$ and $96 \times 84$ km$^2$. For the Zijingguan catchment, the center of the domain is at 39° 25′ 59″N and 114° 46′01″E, and from the outermost to the innermost the nested domain sizes are $216 \times 198$ km$^2$, $108 \times 90$ km$^2$ and $72 \times 42$ km$^2$. The locations of the nested domains for the two catchment are shown in Fig. 2. Forty vertical levels are considered for the three nested domains in the vertical structure, up to a 50 hPa pressure top (Aligo et al. 2009; Qie et al. 2014). The $1° \times 1°$ grids of FNL six-hourly global analysis data provides the initial and transverse boundary conditions for the simulations. Owing to assimilating a certain amount of available observational data, the boundary conditions provided by the FNL data are closer to actual atmospheric conditions, and which is the final analysis supplied by National Centers for Environmental Prediction (NCEP). Therefore, many studies employed FNL to simulate the historical storm events (Dasari and Salgado 2015; Kim et al.

**Table 4** Major Physical parameterizations of the WRF model used in this study

| Parameterisation | Chosen option | Reference |
|---|---|---|
| Microphysics scheme | Lin | (Lin et al. 1983) |
| Longwave radiation | Rapid Radiative Transfer Model (RRTM) | (Mlawer et al. 1997) |
| Shortwave radiation | Dudhia | (Dudhia 1989) |
| Land surface scheme | Noah | (Chen and Dudhia 2001) |
| Planetary boundary layer | Yonsei University (YSU) | (Hong et al. 2006) |
| Cumulus convection | Kain-Fritsch (KF) | (Kain 2004) |

2013). The integration time-step is 6 s and the time step of the WRF model output is set to be 1 h. The precipitation data downscaled by the WRF model is then used to drive WRF-Hydro.

## 3.2 The WRF-Hydro Modeling System

The fundamental objective of the WRF-Hydro exploitation is to improve the prediction kill of hydrometeorological forecasts basing on science-based numerical prediction tools. Therefore, WRF-Hydro is not only a stand-alone hydrological modeling architecture but also a coupling component for integrating hydrological models with atmospheric models. Like the WRF model it does not attempt to formulate a special or singular suite of physics but, instead, is designed to be extensible to new hydrological parameterizations. The WRF-Hydro modeling system version 3.0 is used for this study (Gochis et al. 2015) for an one-way run with the WRF model. Specific details relevant to the WRF-Hydro settings are provided in Table 5. In this study, the WRF-Hydro horizontal resolution is defined by dividing the WRF inner domain at 100 m horizontal gird spacing. Experience-based bucket model, used to represent the baseflow of the stream network, is switched off due to insufficient information about the channel characteristics.

It should be noted that the LSM configuration is very important in the partitioning of the surface energy and water. The default Noah configurations in WRF-Hydro are adopted in this study, rather than site specific ones. Therefore, the results presented here should be viewed as a reference for the basic model performance of WRF-Hydro, with a hope to benefit future model users working in specific basins of northern China and similar areas, and to guide further model improvement activities in the future.

## 3.3 Experimental Design for the WRF-Hydro Sensitivity Tests

The WRF-Hydro modeling system provides various predefined hydrological parameters, which may be adjusted or calibrated depending on the study region and hydrologic behavior of interest. Due to the particularity of regional orography and climatology in each study area, the default values of parameters are often not universally applicable, especially the key parameters that have a great impact on the simulation results. Therefore, the parameter settings in the appropriate range (including the default parameters)are compared to

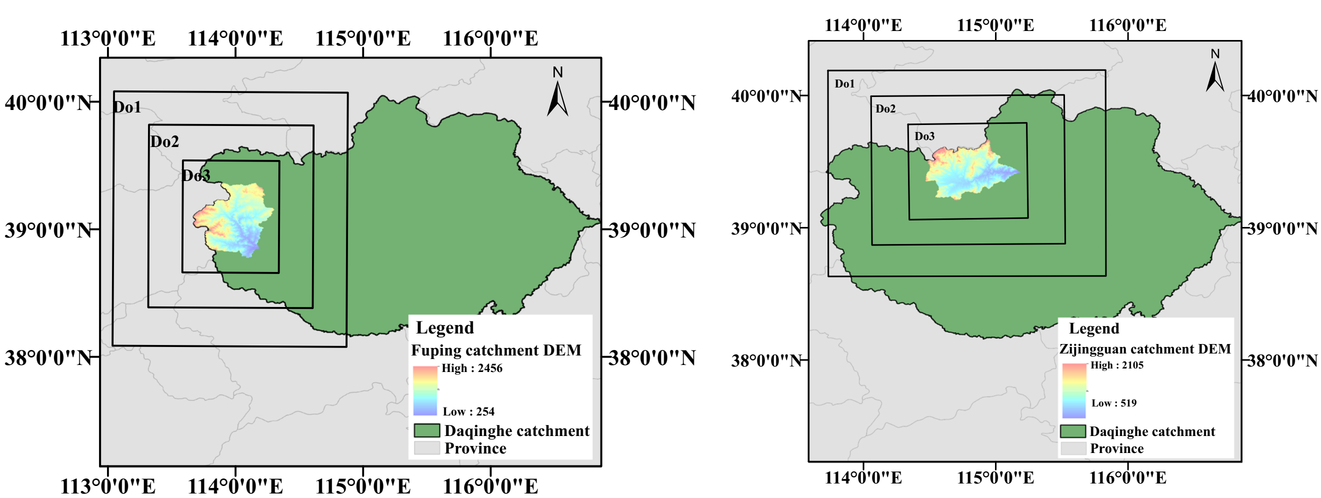


**Fig. 2** The study area with nested configuration of WRF domains at 9-km, 3-km and 1-km resolution

**Table 5** Basic settings of the uncoupled WRF-Hydro modeling system

| Subject | Chosen option |
|---|---|
| Nest identifier | 3 |
| Hydro output interval | 1 h |
| Land surface scheme | Noah |
| Regrinding (nest) Factor | 10 |
| soil column | 2 m |
| Four soil layer thickness | 10 cm, 30 cm, 60 cm, 100 cm |
| Physics options/parameterizations | |
| Subsurface routing | Yes |
| Overland flow routing | Yes |
| Channel routing | Yes with diffusive wave |
| Baseflow bucket model | No |

obtain an optimal parameter set to be applied for a better regional simulation. It has been reported that the calibration of a number of major parameters, including those controlling the total water volume in the channel (Yucel et al. 2015). Therefore, two major aspects are considered in the calibration process for testing the sensitivity of the WRF-Hydro model parameters. On the one hand, it is to consider the parameters controlling the total water volume in the channel, which include the runoff infiltration parameter (REFKDT), and the surface retention depth (RETDEPRT) controlled by a scaling parameter named RETDEPRTFAC. The REFKDT determines the input flow in the channel confluence calculation, that is, the difference between the rainfall and the soil infiltration capacity. Increasing in the RETDEPRT scaling factor on channel pixels can encourage more local infiltration near the river channel, resulting in wetter soils and better emulate riparian conditions. For calibration purposes gridded values of a scaling factor for RETDEPRT, i.e., RETDEPRTFAC can be specified in the main routing grid. One the other hand, it is to look at the parameters controlling the shape of the hydrograph, which include the channel Manning roughness parameter (MannN), and the overland flow roughness parameter (OVROUGHRT) controlled by the scaling parameter OVROUGHRTFAC. OVROUGHRT is determined by the type of land use and affects the speed of the overland transmitters downstream, and MannN reflects the influence of the channel roughness on the streamflow. The same as RETDEPRTFAC, the scaling parameter OVROUGHRTFAC is used for an easy calibration of OVROUGHRT.

In this study, sensitivity tests are firstly carried out to determine the appropriate range of REFKDT, and then MannN is calibrated by fixing appropriate values of REFKDT. This approach is to adjust the model to get the best fit of the runoff amount and timing (Yucel et al. 2015). The best values obtained at the two first steps are fixed in the subsequent calibration of the parameter RETDEPRTFAC. After that, calibrated values for REFKDT, MannN, and RETDEPRTFAC are fixed before the sensitivity tests of OVROUGHRTFAC are carried out. Except for the four main parameters which have major influence on the total water volume in the channel and the shape of the hydrograph, the other parameters are set to their default values owing to the lack of observational data. This is also to see whether the calibration of the 4 key parameters is sufficient and necessary in leading to satisfactory performance of the WRF-Hydro modeling system.

## 4 Results

### 4.1 Parameter Sensitivity Tests for event I

(1) REFKDT

In the WRF-Hydro modeling system, the single column Noah LSM is used to compute the change in the surface water depth $h$ (m) as the rate of the infiltration excess (Chen and Dudhia 2001):

$$\frac{\partial \mathrm{h}}{\partial \mathrm{t}}=\frac{\partial \mathrm{P_d}}{\partial \mathrm{t}}\left\{1-\frac{\left[\sum_{i=1}^{4}\Delta Z_i(\theta_s-\theta_i)\right]\left[1-exp\left(-k\frac{K_s}{K_{ref}}\frac{\delta_t}{86400}\right)\right]}{P_d+\left[\sum_{i=1}^{4}\Delta Z_i(\theta_s-\theta_i)\right]\left[1-exp\left(-k\frac{\mathrm{K_s}}{K_{ref}}\frac{\delta_t}{86400}\right)\right]}\right\} \tag{2}$$

where $P_d$ (m) is the precipitation not intercepted by the canopy; $\Delta Z_i$(m) is the depth of the soil layer i; $\theta_i$ is the volumetric water content (soil moisture) of the soil layer; $\theta s$ is the saturated soil moisture (porosity), which depends on soil texture; $K_s$ (m s$^{-1}$) is the saturated hydraulic conductivity, which also depends on soil texture; $K_{ref} = 2 \times 10^{-6}$ (m s$^{-1}$) indicates the saturated hydraulic conductivity of the silty-clay-loam soil texture chosen as a reference for the area; $\delta_t$ (s) is the model time step; and $k$ is the runoff-infiltration partitioning parameter ($k$ is equivalent to the parameter REFKDT in WRF-Hydro). Time integrating Eq. (2) gives a measure of the modeled surface runoff.

In Eq. (2), $k$ regulates the rate of surface infiltration at each time step, taking into account the volume of rainfall water at the surface and the potential volume of water that can still be contained in the 2 m soil layer until saturation, so that the surface runoff or the infiltration can be decreased or increased by changing the value of $k$, respectively (Schaake et al. 1996). Based on field experiments (Wood et al. 1998), the default value of k, i.e., REFKDT is 3.0. However, some studies (Chen and Dudhia 2001) suggest that REFKDT should be calibrated for basins with differing precipitation climatology and runoff generation mechanism.

The tunable range of the REFKDT parameter is from 0.1 to 10, which controls the hydrograph volume. For storm event I, a rational range of 1.0–4.0 is considered. The Fig. 3 shows the

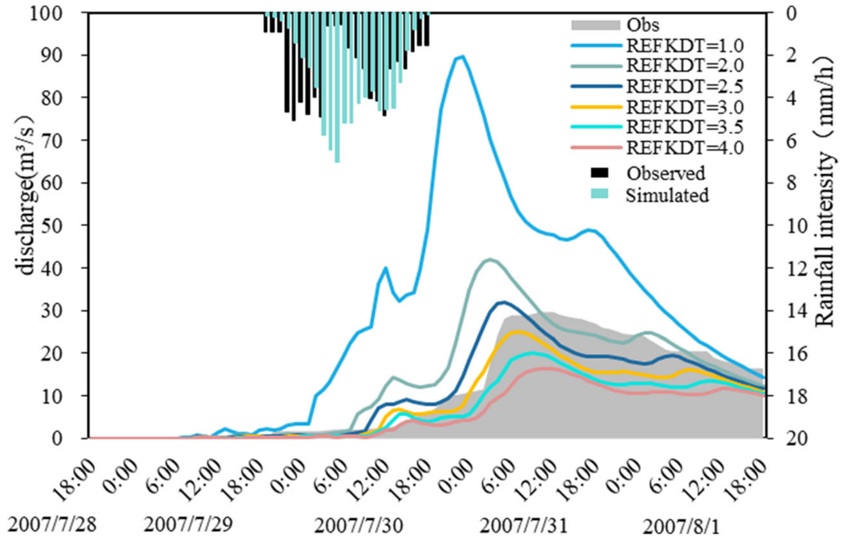


**Fig. 3** Simulated hydrographs of event I with the sensitivity tests of REFKDT (1.0, 2.0, 2.5, 3.0, 3.5, 4.0)

simulated discharge of event I after running the one-way WRF-Hydro model with REFKDT being 1.0, 2.0, 2.5, 3.0, 3.5 and 4.0. As expected, REFKDT has a considerable impact on the surface runoff in the study site. In the WRF-Hydro modeling system, the available streamflow input water is derived mainly from the amount of precipitation in infiltration capacity excess in each model grid (Ryu et al. 2017). It can be seen that when the soil condition is unsaturated, the higher is the REFKDT value, the smaller is the simulated volume of the hydrograph. However, this decrease is clearly nonlinear. With the increase of REFKDT, the decrease of the surface runoff slows down, and the hydrograph becomes smoother. When REFKDT decreases from 2.0 to 1.0, the discharge of the peak flow is decreased by 112.29%. Meanwhile, when REFKDT decreases from 2.5 to 2.0, from 3.0 to 2.5, from 3.5 to 3.0, and from 4.0 to 3.5, the discharge of the peak flow is decreased by 32.11%, 26.97%, 24.70% and 21.94%, respectively. At the same time, the increase of REFKDT also affects the occurrence of the peak. When the value of REFKDT is increased by 0.5, the peak time is delayed by approximate two hours. Through the sensitivity tests of the parameters affecting the total water volume in the channel, it is found that REFKDT is the most sensitive parameter especially with unsaturated soil conditions.

(2) RETDEPRTFAC

The surface retention depth scaling parameter (RETDEPRTFAC) whose default value is 1.0 has a similar function as REFKDT. Inflow to stream channels occurs when the surface head exceeds a pre-defined retention depth that is RETDEPRT. The depth of surface head is a combination of the local infiltration capacity excess, the amount of water flowing onto the grid cell from over land flow and exfiltration from groundwater flow. Similarly, REFKDT plays a decisive role in calculating the inflow of river confluence. The RETDEPRTFAC parameter is adjusted depending on the surface slope, which is a scaling parameter controlling RETDEPRT. Sensitivity tests of RETDEPRTFAC, the reasonable range of which is 0.0–10.0, are carried out with the testing values being 0.1, 0.5 and 1.0. The corresponding hydrographs of event I can by seen in Fig. 4. The results show that the influence of this parameter on the total flow in the channel is not obvious, or we can say it does not affect the runoff basically. In the WRF-Hydro modeling system, the discharge increases slightly with the decrease of the parameter value, and it seems that the sensitivity of RETDEPRFAC has the weakest sensitivity to the change of the total flow in the channel among the parameters tested in this study. This may be due to the large variation of the altitude and the steep terrain in the study area, in which case there is little accumulation on the steep surfaces. It is also speculated that the initial rainfall is underestimated, with relatively low soil moisture, therefore, increasing the RETDEPRT scaling factor encourages more local infiltration near the river channel.

(3) OVROUGHRTFAC

In the WRF-Hydro, after the surface runoff flows to the channel network, the transfer of runoff along the channels also affects the shape of the hydrograph (Ryu et al. 2017). The speed of streamflow converges to the channel network is controlled by the roughness parameters, i.e., OVROUGHRTFAC and MannN. OVROUGHRT parameters for different land use types in the WRF-Hydro model are affected by scaling factors (OVROUGHTFRA). We may scale initial values of roughness by overland flow roughness scaling parameter (OVROUGHRTFAC) from the high-resolution terrain grid, and which impact on the speed of runoff convergence to channel network. The default value of OVROUGHRTFAC is 1.0

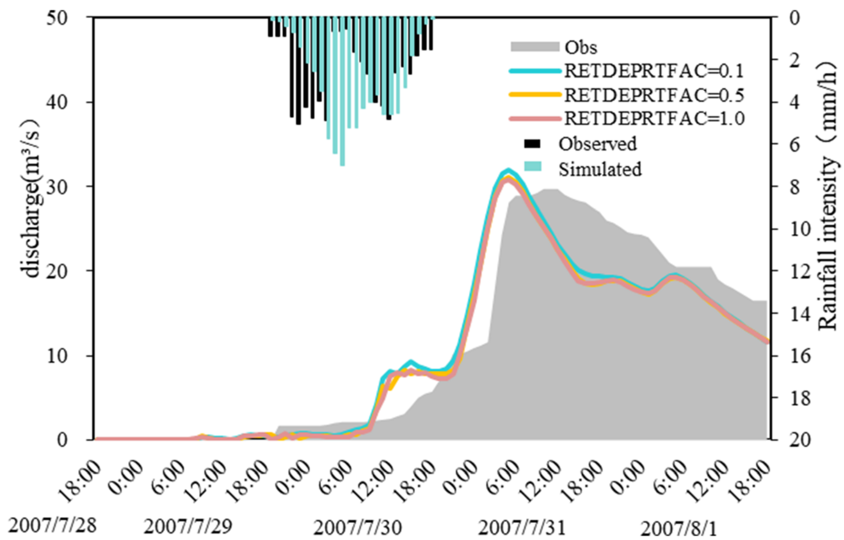


**Fig. 4** Simulated hydrographs of event I with the sensitivity tests of RETDEPRTFAC (0.1, 0.5 and 1.0)

with the feasible range being 0.0 ~ 1.0. In this study, the sensitivity tests are carried out with values of 0.1, 0.5 and 1.0. With the increase of OVROUGHRTFAC, the result show that the confluence time of the surface runoff is prolonged. At the same time, OVROUGHRTFAC also has comparatively obvious influence on the total water volume in the channel (Fig. 5). Some study has pointed out that OVROUGHRTFAC and REFKDT has quite similar impact (but not identical) on the discharge, thus rather than including both of them during calibration, the common practice is to vary one parameter while keeping the other constant (Lahmers et al. 2019).

(4) MannN

Figure 6 shows the simulated hydrographs of the sensitivity tests of the parameter MannN when REFKDT = 2.0, 2.5, 3.0 and 3.5. The MannN parameter is adjusted by multiplying the initial values (Table 6) of the river channels by a constant, which is constrained between 1.0 and 2.0. In this study, the constant is set to be 1.0, 1.2, 1.5, 1.8 and 2.0. It should be noted that this adjustment constant is not the parameters themselves. For instance, if MannN has an adjustment coefficient of 1.2, the initial value of MannN will be multiplied by 1.2 for all the river channels to compute the new parameters. Thus the spatial patterns of the parameters is preserved when calibrating them. From Fig. 6, it can be seen that the MannN parameter has a substantial impact on the transit time of the streamflow: the lower is the MannN value, the faster is the transmit time and the larger amount is the generated flow. The flow peak with the lowest MannN value 1.0 shows the earliest appearance time and the largest discharge in Fig. 6a. It can also be noted that the MannN parameter works closely with REFKDT to affect the simulated hydrograph. When REFKDT increases from 2.0 in Fig. 6a to 3.5 in Fig. 6d, the

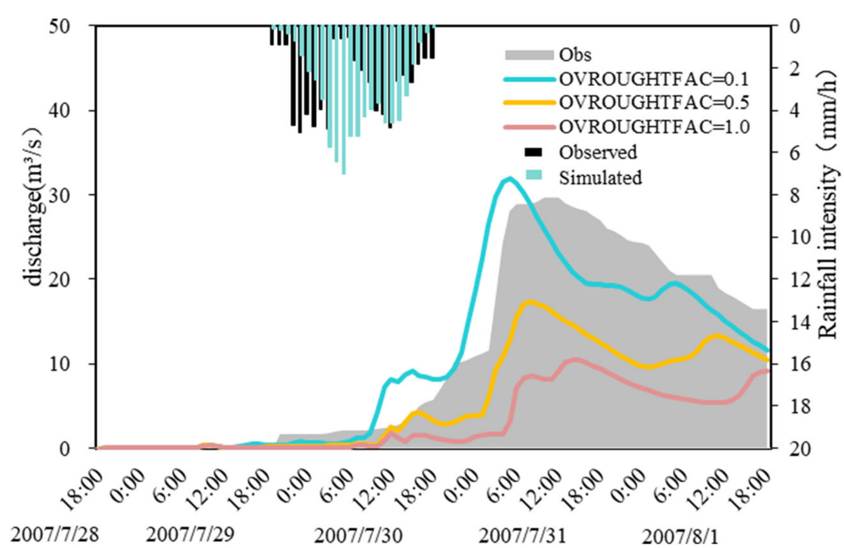


**Fig. 5** Simulated hydrographs of event I with the sensitivity tests of OVROUGHRTFAC (0.1, 0.5 and 1.0)

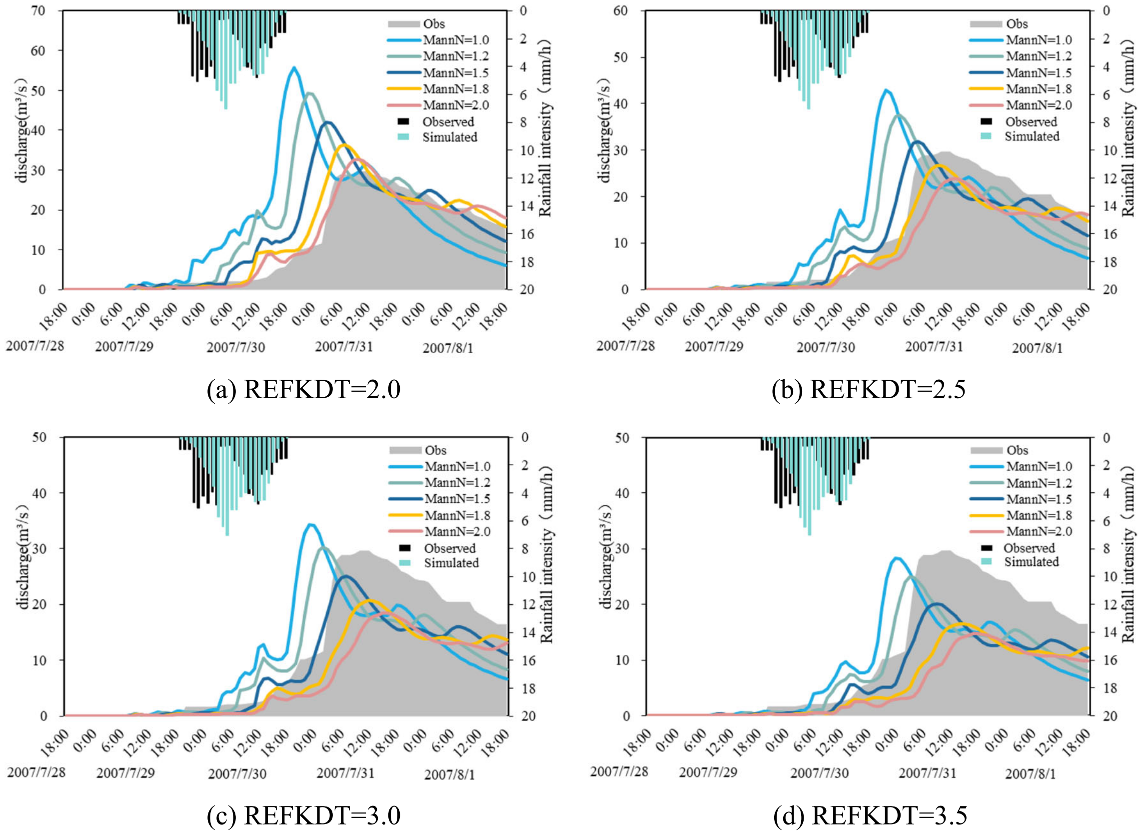


**Fig. 6** Simulated hydrographs of event I with the sensitivity tests of MannN by using a scaling factor (1.0, 1.2, 1.5, 1.8 and 2.0) when REFKDT = 2.0, 2.5, 3.0 and 3.5. (**a**) REFKDT = 2.0, (**b**) REFKDT = 2.5, (**c**) REFKDT = 3.0, (**d**) REFKDT = 3.5

same MannN value can gradually lead to a smaller peak discharge and an earlier peak time. Therefore, special attention should be paid to the two parameters of REFKDT and MannN, which should be calibrated cooperatively in the WRF-Hydro modeling system.

**Table 6** Default channel parameter values of channel bottom width (Bw, unit of meters), initial depth of water in the channel (HLINK, unit of meters), channel side slope (ChSSlp, units of rise/run), and the Manning roughness coefficient based on scaling factor corresponding to each stream order

| Stream order | BW | HLINK | ChSSlp | MannN |
|---|---|---|---|---|
| 1 | 1.5 | 0.02 | 3.0 | 0.55 |
| 2 | 3.0 | 0.02 | 1.0 | 0.35 |
| 3 | 5.0 | 0.02 | 0.5 | 0.15 |
| 4 | 10 | 0.03 | 0.18 | 0.10 |
| 5 | 20 | 0.03 | 0.05 | 0.07 |
| 6 | 40 | 0.03 | 0.05 | 0.05 |
| 7 | 60 | 0.03 | 0.05 | 0.04 |
| 8 | 70 | 0.10 | 0.05 | 0.03 |
| 9 | 80 | 0.30 | 0.05 | 0.02 |
| 10 | 100 | 0.30 | 0.05 | 0.01 |

The Nash-Sutcliffe efficiency (NSE) coefficient and the root mean squared error (RMSE) is used to evaluate the simulated streamflow from the sensitivity tests of the parameters REFKDT, OVROUGHTFAC, RETDEPRTFAC, and MannN scaling factors. The results are shown in Table 7. Calculations of the two statistics are shown by Eqs. (2) and (3). To the value NSE ranges between -∞ and 1.0 (1 inclusive) with those between 0.0 and 1.0 are considered acceptable (Moriasi et al. 2007). The higher is NSE and the larger is RMSE, the better is the simulated streamflow.

$$\mathrm{NSE} = 1-\frac{\sum_{i=1}^{N}\left(Q_i'-Q_i\right)^2}{\sum_{i=1}^{N}\left(Q_i-\overline{Q}\right)^2} \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Q_i'-Q_i\right)^2} \tag{4}$$

In Eqs. (3 and 4), $Q_i$' and $Q_i$ denote observed and model-simulated discharge at each time step $i$, respectively; $N$ represents the number of the time steps; $\overline{Q}$ representes the average $Q_i$ calculated.

**Table 7** Statistics of the simulated streamflow for the sensitivity tests of REFKDT, OVROUGHTFAC, RETDEPRTFAC, and MannN for event I

| Parameters | Value | RMSE | NSE |
|---|---|---|---|
| REFKDT | 1.0 | 26.28 | −4.51 |
| | 2.0 | 7.15 | 0.59 |
| | 2.5 | 4.29 | 0.85 |
| | 3.0 | 4.82 | 0.82 |
| | 3.5 | 6.42 | 0.67 |
| | 4.0 | 7.91 | 0.50 |
| OVROUGHTFAC | 0.1 | 4.29 | 0.85 |
| | 0.5 | 7.78 | 0.52 |
| | 1.0 | 11.27 | −0.01 |
| RETDEPRTFAC | 0.1 | 4.29 | 0.85 |
| | 0.5 | 4.25 | 0.86 |
| | 1.0 | 4.25 | 0.86 |
| MannN(REFKDT = 2.0) | 1.0 | 14.38 | −0.65 |
| | 1.2 | 11.17 | 0.00 |
| | 1.5 | 6.95 | 0.62 |
| | 1.8 | 3.23 | 0.92 |
| | 2.0 | 1.93 | 0.97 |
| MannN(REFKDT = 2.5) | 1.0 | 10.19 | 0.17 |
| | 1.2 | 7.75 | 0.52 |
| | 1.5 | 4.29 | 0.85 |
| | 1.8 | 3.42 | 0.91 |
| | 2.0 | 4.55 | 0.83 |
| MannN(REFKDT = 3.0) | 1.0 | 8.52 | 0.23 |
| | 1.2 | 6.53 | 0.50 |
| | 1.5 | 4.82 | 0.69 |
| | 1.8 | 5.97 | 0.74 |
| | 2.0 | 7.19 | 0.26 |
| MannN(REFKDT = 3.5) | 1.0 | 7.95 | 0.50 |
| | 1.2 | 6.59 | 0.65 |
| | 1.5 | 6.42 | 0.67 |
| | 1.8 | 7.99 | 0.49 |
| | 2.0 | 9.09 | 0.34 |

For storm event I, the results show that a range of REFKDT from 2.0 to 3.0 and the range of OVROUGHRTFAC from 0.1 to 0.5 provides the closest surface runoff relative to the observations, however, the influence of RETDEPRTFAC on the total flow in the channel is not obvious. Meanwhile, when REFKDT equals to 2.0, 2.5, 3.0 and 3.5, the best MannN value which generates to closest simulation to the observed flow is found to be 2.0, 1.8, 1.8 or 1.5 and 1.5 or 1.2, which is on a decreasing trend.

### 4.2 Results of the Remaining Three Storm Events

From the results of Section 4.1, REFKDT and MannN are found to be the most sensitive parameters after the analyses of event I, which are also consistent with the studies of Naabil et al. (2017) and Yucel et al. (2015). In order to further verify the calibration rules and the plausible ranges of two most important parameters and to provide guidance for similar semi-humid and semi-arid areas like the Daqinghe catchment, sensitivity tests of REFKDT and MannN are carried out for event II - IV. The results of the simulated hydrographs are respectively shown in Figs. 7, 8 and 9.

Similarly, when the values of REFKDT increase, that of MannN decreases. Table 8 shows the statistics (RMSE and NSE) for the simulation results of the sensitivity tests for Event II - IV. Compared with Event I, Event II - IV has higher Cv values but lower RMSEs and NSEs. As the unevenness of the rainfall distribution in spatial and temporal dimensions increases, the WRF-Hydro simulations are worsen. This may be due to the error of the FNL data, the driven data of WRF, which indirectly influences the performance of WRF-Hydro in the streamflow simulation. When REFKDT ranges from 2.5 to 3.0 and MannN ranges from 1.5 to 1.8, the simulation results is best relatively. This is in consistence with the results of event I.

## 5 Discussion

a. Error of the Baseflow Bucket Model

The baseflow, to the river channel network in WRF-Hydro, is calculated using a conceptual bucket model. The conceptual bucket model assumes one-way direct connection between reduced baseflow from a groundwater basin and the overlaying channel. This model is particularly suitable for long-term simulation, where linked to WRF-Hydro through the deep drainage discharge from the land surface soil column (Senatore et al. 2015). In semi-humid and semi-arid areas, the current conceptual bucket model provides a relatively poor representation of baseflow because the groundwater recharge is not necessarily to reach the river network, especially in ephemeral channels (Lahmers et al. 2019). According to Naabil et al. (2017), the bucket model was switched off due to inadequate information about the channel characteristics. In north China, water, deriving from channels, often infiltrates to recharge the local aquifer, and this source of recharge is currently not represented in the model. Therefore, to avoid unrealistic simulations of the baseflow in the river network due to the lack of insufficient information about the channel characteristics, the conceptual bucket model is disabled in study.

However, subsurface routing in the saturated zone of the 2 m soil column and a groundwater bucket model for evaluating the contribution of baseflow to river discharge are possible (Arnault et al. 2015), but not activated in this study. Streamflow errors in the Daqinghe basin is also likely due to shut off the baseflow bucket model. To produce a more

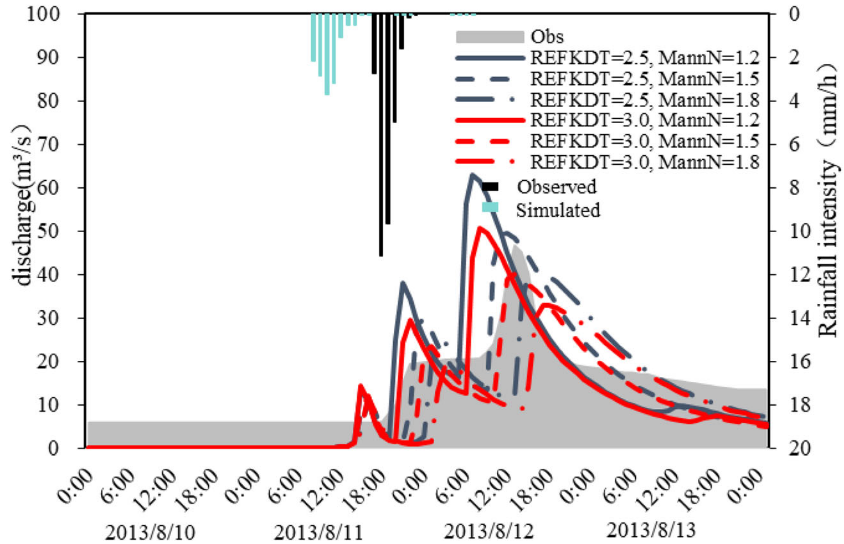


**Fig. 7** Simulated hydrographs of event II with the sensitivity tests of REFKDT (2.5 and 3.5) and MannN (the scaling factor = 1.2, 1.5 and 1.8)

realistic hydrologic response, future work is needed to eliminate parameters biases of the WRF-Hydro. This might be accomplished through modification or elimination of the WRF-Hydro baseflow bucket scheme to permit deep groundwater recharge in semi-arid regions.

It can be inferred that better runoff simulation results can be achieved by a reasonable application of the groundwater model. Considering the limitations of the current baseflow bucket model adopted in the WRF-Hydro modeling system, a more realistic and physically-based groundwater model coupled to the WRF-Hydro modeling system could be helpful in the future.

b. Error of the Precipitation Forcing

The simulation results of the WRF-Hydro modeling system are not only closely related to the uncertainty of the key parameters, but also to the driving data. It is found that the inherent uncertainty in climate forecasts necessarily causes parallel uncertainty in hydrological forecasts (Fiori et al. 2014; Strobach and Bel 2015). In this study, the accuracy of the WRF simulation results depends on the quality of the driving, i.e., the FNL data, which therefore affects the simulation results of WRF-Hydro. Table 9 shows the relative errors (RE) of the 24 h accumulations of the observed and simulated storm events. The calculation of RE is shown by Eq. (5). In Fig. 10, accumulative curves and time series bars are shown to display the temporal variations in the observed and simulated rainfall for the four storm events.

$$\mathrm{RE} = \frac{(P-Q)}{Q} \times 100\% \tag{5}$$

where $P$ is the simulated value, which is the average value of all the grids inside the study area, and $Q$ is the observed value, which is calculated by the Thiessen polygon method according to the rainfall observed by the rain gauges (Sivapalan and

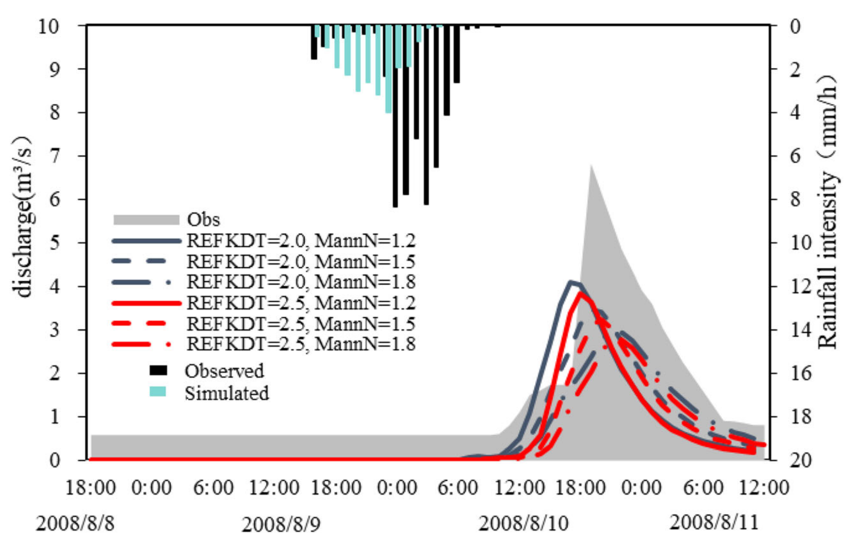


**Fig. 8** Simulated hydrographs of event III with the sensitivity tests of REFKDT (2.5 and 3.5) and MannN (the scaling factor = 1.2, 1.5 and 1.8)

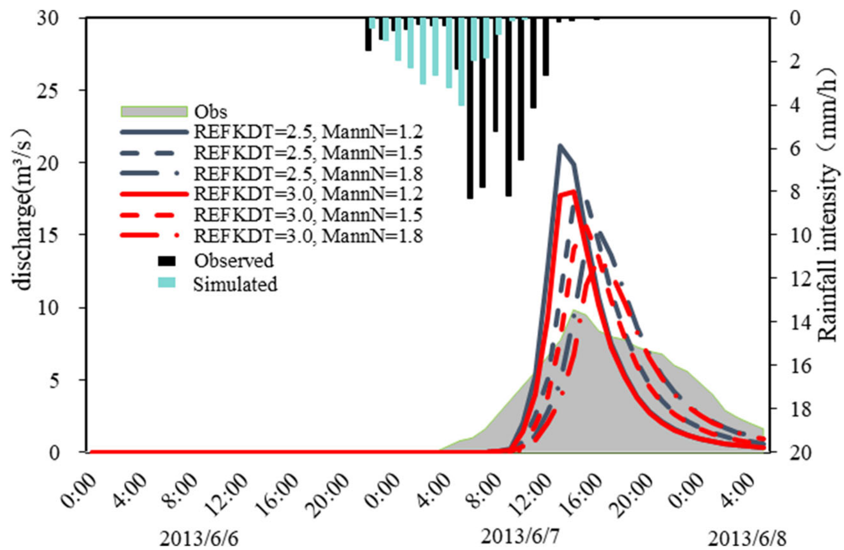


**Fig. 9** Simulated hydrographs of event IV with the sensitivity tests of REFKDT (2.5 and 3.5) and MannN (the scaling factor = 1.2, 1.5 and 1.8)

Blöschl 1998; Jarvis et al. 2013).

Event I has the most even rainfall distribution in space and time, with the spatial and temporal Cv being respectively 0.39 and 0.60, as shown in Table 3. It is found to has the best simulation results among all the four storm events with the lowest RE value of 13.88%. On the other hand, the rainfall rate of event II has the most tremendous variations (spatial Cv = 0.74 and temporal Cv =2.39), and the WRF model shows the worst performance for the simulated rainfall accumulation (RE = −53.24%). Therefore, it can be seen that the simulated uncertainty of rainfall increases with the increase of the spatial and temporal rainfall unevenness (a higher Cv value). It is also interesting to find that WRF-Hydro shows the best simulation results of the streamflow for event I, while the worst for event II. It should be mentioned that the calibration of the WRF-Hydro parameters in this study cannot eliminate the rainfall simulation errors of the driving data.

**Table 8** Statistics of the simulated streamflow for the sensitivity tests of REFKDT and MannN for event II, III and IV

| | Parameters | MannN | RMSE | NSE |
|---|---|---|---|---|
| EventII | REFKDT = 2.5 | 1.2 | 10.75 | −0.37 |
| | | 1.5 | 6.79 | 0.45 |
| | | 1.8 | 8.92 | 0.06 |
| | REFKDT = 3.0 | 1.2 | 8.26 | 0.19 |
| | | 1.5 | 6.42 | 0.51 |
| | | 1.8 | 9.80 | −0.14 |
| EventIII | REFKDT = 2.5 | 1.2 | 1.00 | 0.34 |
| | | 1.5 | 0.84 | 0.53 |
| | | 1.8 | 0.89 | 0.48 |
| | REFKDT = 3.0 | 1.2 | 0.98 | 0.36 |
| | | 1.5 | 0.92 | 0.44 |
| | | 1.8 | 0.98 | 0.37 |
| EventIV | REFKDT = 2.5 | 1.2 | 2.31 | 0.04 |
| | | 1.5 | 1.73 | 0.46 |
| | | 1.8 | 1.53 | 0.58 |
| | REFKDT = 3.0 | 1.2 | 1.96 | 0.31 |
| | | 1.5 | 1.50 | 0.59 |
| | | 1.8 | 1.43 | 0.63 |

The optimal values and the recommended ranges of the parameters may to some extent be subject to the forcing data. To reveal objective laws of the WRF-Hydro parameters, more realistic rainfall driving (i.e., observations from dense rain gauges or weather radar) may be useful. The precipitation data obtained from the WRF model can be used to drive the WRF-Hydro model for hydrological forecasting, which can extend the forecast period of hydrological forecasting. Furthermore, through multi-source data assimilation and the blending techniques of weather radar and numerical weather prediction model, the accuracy of rainfall forecast and the results of hydrological forecast can be improved to some extent.

Further improvement and development of precipitation forcing accuracy and application in hydrological forecast is an important trend in hydrometeorological forecast in the future. At present, the application of hydrological forecast is mainly based on one-way coupling of meteorology and hydrology. As the core of the transformation of precipitation and runoff, the WRF-Hydro model should strengthen the research on the physical parameter value, parameter calibration and uncertainty of the precipitation forcing, so as to explore the uncertainty of coupled atmospheric-hydrological modeling under regional atmospheric variability and produce more realistic hydrologic response.

c. Further Research

**Table 9** Observed and WRF simulated 24 h rainfall accumulations of the four storm events

| Storm events | Observations (mm) | WRF simulations (mm) in the innermost domain | RE (%) |
|---|---|---|---|
| Event I | 63.38 | 72.18 | 13.88 |
| Event II | 30.82 | 14.41 | −53.24 |
| Event III | 45.53 | 23.13 | −49.19 |
| Event IV | 52.06 | 32.46 | −37.64 |

Given the limitations of the storm event characteristics and the coupling mode of WRF-Hydro, our study exposes several possible directions for future studies.

- It is found that when there are two rainfall peaks, the sensitivity of simulation to the change in REFKDT for the second peak is weak, compared to that for the first peak (Ryu et al. 2017). This may be caused by the differences in the soil moisture deficit between the two peaks, i.e., the soil becomes more saturated when the second peak happens. The rainfall rate of the storm events in this study is either even or with one just peak. Subsequent sensitivity tests for the key WRF-Hydro parameters should be considered with the more complicated cases, i.e., rainfall with more variations of more than one peaks.
- The parameter sensitivity tests in this study are based on the stand-alone WRF-Hydro model. However, the two-way coupling of WRF and WRF-Hydro has become more widely applied due to the interactive communication between the atmospheric and hydrologic components which is deemed to be able to generate more realistic rainfall-runoff results. However, with two-way coupling of WRF/WRF-Hydro, whether the sensitivities of the parameters still follow the same rules found in this study, is worth studying in the future.

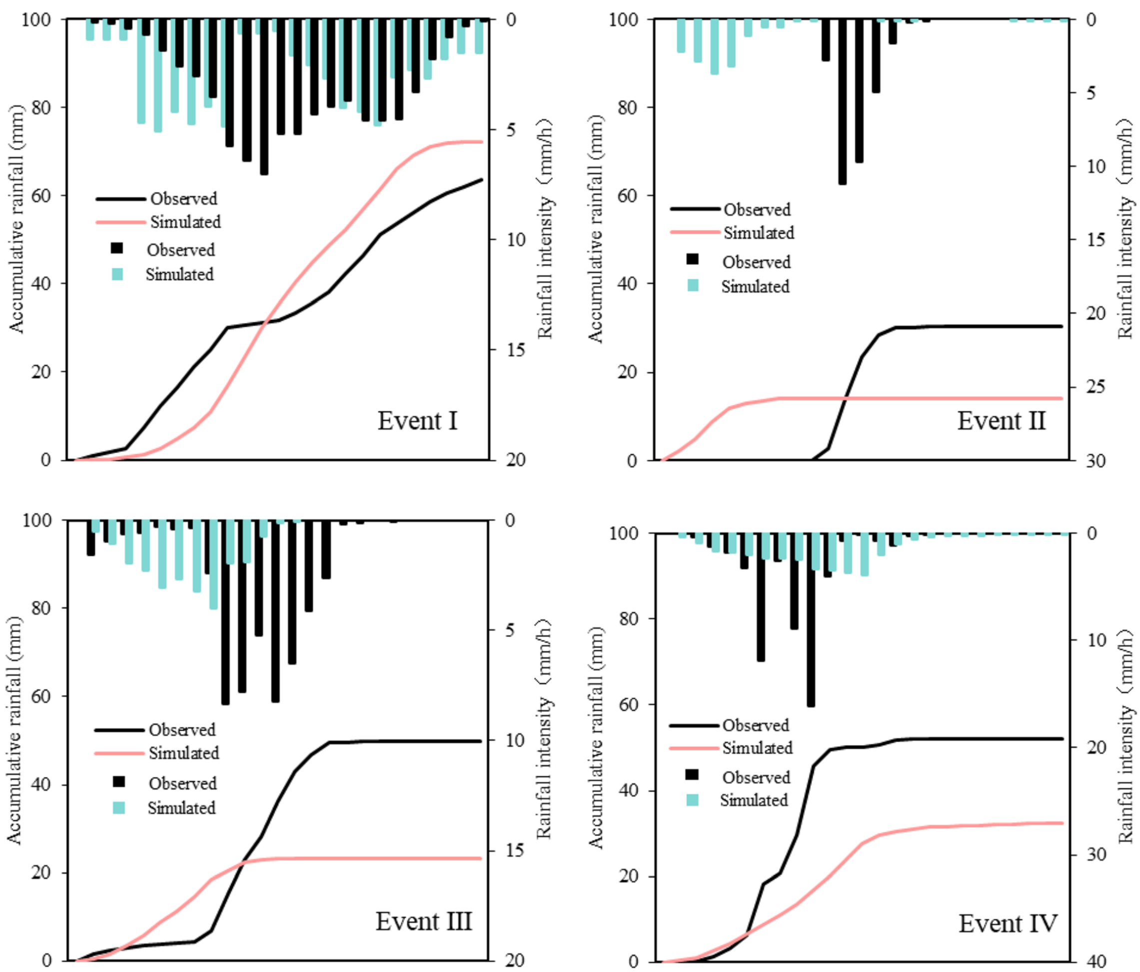


**Fig. 10** The accumulative curves of the observed and the simulated rainfall of the four storm events

Finally, it should be noted that due to the complexity of the hydrological processes, the quality of the driving data and different meteorological conditions, WRF-Hydro needs to be carefully calibrated when the study area changes. In this study, the calibration rules of the WRF-Hydro parameters are only confined in the semi-humid and semi-arid catchments of northern China. It is suggested that researchers conduct similar parameter sensitivity tests when applying the WRF-Hydro modeling system in various catchments with different hydrological and meteorological conditions so that more general laws could be reached.

## 6 Conclusions

Parameter sensitivity analysis is an important part of model uncertainty quantification, which helps identify key parameters effectively, reduce the impact of parameter uncertainty, and improve the efficiency of parameter optimization. Sensitivity tests are carried out in this study for the most important parameters influencing the streamflow generation of the WRF-Hydro modeling system by targeting at the semi-humid and semi-arid catchments of the Daqinghe basin in Northern China. A stepwise approach is employed to obtain the reasonable approximations in proper sequence for four parameters of WRF-Hydro, i.e., REFKDT, MannN, RETDEPRTFAC and OVROUGHRTFAC, firstly for a storm event selected from the study area with relatively even rainfall distributions in space and time. The range of REFKDT from 2.0 to 3.0, OVROUGHRTFAC from 0.1 to 0.5, and the MannN scale factor from 1.5 to 1.8 is found to give the best results. Meanwhile, it is also found that when the REFKDT value increases, the best MannN value which generates the closest simulation to the observed flow is on a decreasing trend. The sensitivity of RETDEPRTFAC is, however, not as pronounced as that of the other three parameters. After the most sensitive parameters and their calibration rules are determined, the most plausible ranges of the most sensitive parameters, i.e., REFKDT and MannN are further verified by another three storm events in the study area. The results show that the WRF-Hydro modeling system can successfully simulate the peak time and the peak discharge of the streamflow generation process. The purpose of this study is to explore the variation laws of the key parameters in semi-humid and semi-arid areas, and to provide a reference for calibration and application of the WRF-Hydro modeling system.

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