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Analyses of DEM resolution on SWAT-simulated stream flow in Qihe watershed

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ABSTRACT

Resolution of data is a sensitive issue in hydrological modeling. The sensitivity of stream flow simulated with the Soil and Water Assessment Tool (SWAT) model to Digital Elevation Model (DEM) resolution has been partially understood. However, few studies on the effect of the influence of DEM with resolution over 20 m on daily runoff modeling. The objective of this study was to enhance understanding the impact of DEM (from 8 m to 900 m) within the SWAT model to simulate runoff on annual, monthly and daily scale. The Qihe river, one of the headwaters of Danjiangkou reservoir, was selected as the study area. The key findings were as follows: (1) As DEM resolution becomes coarser, the extracted land form tends to be flat, and the total area of watershed, maximum elevation, and maximum slope generally show a decreasing trend, while the minimum elevation and minimum slope show an increasing trend. (2) The DEM resolution directly affect the water generation and concentration, the increase of DEM mesh size would result in homogenization of simulated stream flow and flood peak attenuation. (3) When DEM resolution is higher than 30 m, the simulated annual and monthly runoff remain unchanged, but the simulated daily runoff will be different very much. The higher the resolution is, the better the simulation results will be, especially for the simulation of flood peak. Therefore, a DEM with higher resolution can describe the runoff process more precisely.

Keywords: Stream flow; SWAT; DEM data resolution

1. Introduction

As the source of life, water is an irreplaceable type of resource supporting the sustainable development of world's socio-economy. Distributed hydrological model has strong physical basis and considers the heterogeneity of ecosystems and complexity of underlying surface factor. According to the difference in watershed topography, land cover and precipitation, the distributed hydrological model can be used to discretize the study area into small areas containing the unique land use, soil and topographic information [1–3]. However, the ability of distributed hydrological models to accurately represent hydrological processes greatly depends on the accuracy of the input data, the quality of the spatial information is presumed to directly affect the simulation results [4,5].

Digital Elevation Models (DEMs) are important input data for hydrological processes modeling. With the growing application and increasing availability of DEMs, the DEM uncertainty has previously attracted the attention of many researchers [6,7]. Several references exist on the interaction between the accuracy of the topographical description and the prediction quality for distributed hydrological model simulation. Li et al. demonstrated that, more accurate river networks can be derived by using higher resolution DEMs, and the flood simulations varied significantly across different DEM spatial resolution [8]. Kalin et al. investigated the effect

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of geomorphologic resolution on runoff hydrographs over two USDA experimental watersheds, and found that high DEM resolution could increase the water flux at the peak runoff, the prediction quality of hydrological model was influenced by the precision of the DEM which was expected to affect the delineation of watershed [9].

The Soil and Water Assessment Tool (SWAT), a distributed hydrological model, has been widely used to predict the impact of underlying surface change on hydrologic process [10–12]. Many researches have been conducted to explore the sensitivity of SWAT models to the resolution of DEMs , and denounced the DEM resolution was one of the most important driving force in SWAT model for simulating streamflow [13–15]. Shen et al. quantified the effect of 4 DEMs with different resolution (30 m, 40 m, 90 m, 200 m) by SWAT model in Daning watershed, and denounced that the coarser DEM would cause reduce slope classes, that would result in lower annual flow simulation [16]. Tan et al. compared the streamflow estimation of SWAT with DEM differing in resolution (from 20 m to 1500 m), and indicated that a prior assessment and understanding of different DEM resolution is of crucial importance in simulating annual hydrological process [17]. V. Chaplot examined the monthly SWAT model outputs based on a rang of 12 DEM spatial resolutions (from 20 m to 500 m) and claimed that reducing the precision of DEM resolution would affect the simulation results of monthly runoff and sediment yield from the Lower Walnut Creek watershed [18]. It has been a key issue in hydrological model study to accurately simulate hydrologic process. However, there are very few studies on the effect of SWAT model on daily runoff, and no one has ever investigated the influence of DEM with resolution over 20 m to SWAT simulation results, especially to the simulation of peak runoff.

The objective of this paper is to provide information to ongoing work on the examination of the sensitivity of streamflow modeling to a wider range of DEM resolutions (from 8 m to 900 m) using SWAT model. Therefore, the Qihe watershed, whose streamflow is one of the headwaters of Danjiangkou reservoir, was selected as the study area. This study also provides insight into the influence of high-precision DEM to the SWAT simulation results of daily streamflow and peak runoff.

2. Study area

The Qihe watershed, with an area of 952 km^2, is located in the southwest of Henan province which is in the middle of China, it is one of the headwaters of Danjiangkou reservoir where is the water source region of Middle Route of South-to-North Water Project (Fig. 1). The watershed with longitude between 110°47′~111°15′E and latitude between 33°20′~33°49′N is wet warm temperate continental monsoon climate, annual precipitation is 820 mm and average annual temperature is about 15.5°C, the elevation of the watershed ranges from about 332 m to 2031 m above sea level. Its annual sunshine hours is about 2320 h, the frost less season is 223 d. Qihe watershed represents a typical peripheral region of the lower mountain range dominated by extensive agriculture and forestry.

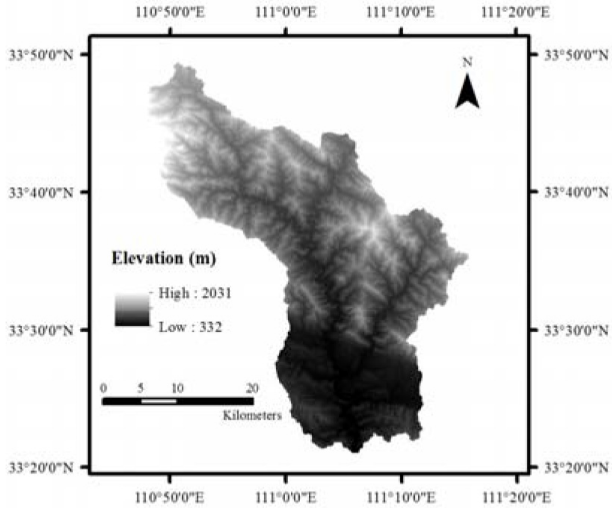

Fig. 1. Location and DEM (8 m) of study area.

3. Methodology and data

3.1. Description of SWAT model

SWAT is an empirical model developed by USDA (United States Department of Agriculture) through summarizing the relationship among precipitation, runoff, water yield, sediment and water quality in many small watersheds with different land use types and soil types. Much spatial diversities have been homogenized at certain scale to enhance the operability in SWAT model [19–21]. SWAT can analyse the catchment by discretising into sub-basins which would further be subdivided into HRUs. SWAT model mainly contains hydrological modeling component, suspended sediment modeling component and nitrogen modeling component, and the hydrological components include evapotranspiration (ET), surface runoff, percolation, lateral flow, groundwater flow, transmission losses and ponds [22].

3.2. Input data

The topographic information, land use, soil type, and daily meteorological record datasets were required for incorporation into ArcSWAT, an ArcGIS interface for the SWAT model.

The DEM resolution was one of the driving force in SWAT model of stream flow simulation. The DEM (8 m) was derived from google earth, and was re-sampled to a series of resolutions, including 12 m, 15 m, 20 m, 25 m. The DEM (30 m) was provided by "National science & Technology Infrastructure: National Earth System Science Data Sharing Infrastructure (http://www.geodata.cn/)", and was re-sampled to a series of resolutions, including 60 m, 90 m, 150 m, 300 m, 600 m, 900 m by the nearest neighbor techniques in Arcgis 10.3 software package.

In addition to DEMs, other important input data are as follows:

1) The soil data, with 30 m resolution provides a database of all these soil properties including particle size, bulk density, organic carbon content etc,

about 7 types of soils were classified by the genetic soil classification of China and marked them number into SWAT soil database (Table 1).

2) The land use map with 30 m resolution in 2005 was constructed from digitizing the land use map. According to the requirement of SWAT model, about 10 land use categories were reclassified. It's worth noting that, the resolution of land use map and soil map would be transformed to the resolution of DEM when watershed delineation of SWAT model is finished.
3) The climate data was derived from Henan metro logical Bureau for the period of 2000–2010, including rainfall, temperature, wind speed, solar radiation and other data.
4) The daily time series of stream flow observation data was derived from interpolating the daily data in Xixia hydrologic station and the observation data of Qihe watershed.

4. Results and discussion

4.1. Topographic and watershed characteristics

The SWAT model delineated the Qihe watershed using different DEM data, and divided the resulting watershed into hydrologic response units (HRUs) by using land use and soils information. In order to capture even small areas, the sub-basins were portioned into HRUs by setting 5% thresholds of land use, soil type and slope.

Table 3 shows the topographic characteristics of DEMs with different resolutions and the impact of DEMs on watershed definition of SWAT model, it is assumed that:

1) With the decrease of DEM resolution, the watershed area extracted are generally decreased. Using the watershed area extracted by DEM30 as baseline, the amplitude of variation of watershed area extracted by DEM with resolution ranging between 8 m–30 m is within 1%; when the DEM resolution is lower than 600 m, the extracted watershed area is significantly decreased by 3.6% and 4.7% for DEM600 and DEM900, respectively. Watershed boundary division also shows identical trend. In aspect of sub-basin division, when DEM resolution is higher than 300 m, the number of sub-basins is 35; when DEM resolution is 600 m and 900 m, the number is 33 and 28, respectively, which is relatively decreased. This is mainly due to that the watershed boundary normally varies significantly and the grid of DEM will cause a homogenization effect on the watershed. Therefore, the difference in DEM mesh size will cause the difference in flow direction. A high-resolution of DEM can reflect the topographical change more clearly, resulting in the difference of watershed area under different DEM resolutions.
2) With the increase of DEM resolution, the maximum elevation of watershed gradually decreases, as shown in Table 3. When the resolution becomes coarser from 8 m to 30 m, the maximum elevation decreases from 2031 m to 2028 m, which is a small decreasing amplitude. When the resolution varies between 30 m and 150 m, the maximum elevation decreases from 2028 m to 2022 m, which is a relatively larger decreasing amplitude. When the resolution is lower than 300 m, the decreasing amplitude

Table 2
Land use information of Qihe watershed

Land use code	Land use definition	Area (km^2)	Proportion (%)
URML	Residential-Med	10.8	1.09
URHD	Residential-High Density	1.37	0.14
FRST	Forest-Mixed	874.35	88.55
AGRL	Agricultural Land	54.33	5.5
WATR	Water	6.57	0.66
UIDU	Industrial	0.83	0.08
ORCD	Orchard	8.15	0.83
PAST	Pasture	28.12	2.85
BARL	Spring Barley	0.58	0.07
UTRN	Transportation	2.26	0.23

Table 1
Soil types and hydraulic properties in Qihe watershed

Soil number	Depth of the first soil layer (mm)	Bulk density (g/cm^3)	Composition			AWC (mm h_2o)	SHC (mm/h)	Area	
			Clay (%)	Silt (%)	Sand (%)			(km^2)	Proportion (%)
1	0–150	1.4	12.7	47.1	40.2	0.15	28.89	257.69	26.1
2	0–300	1.53	19.3	39.4	41.3	0.13	12.01	184.13	18.65
3	0–100	1.47	16.9	52.5	30.6	0.16	13.46	60.03	6.08
4	0–70	0.96	11.8	45.5	42.7	0.18	81.16	98.34	9.96
5	0–140	1.36	14	40.2	45.8	0.14	32.83	128.84	13.05
6	0–150	1.56	7	51	42	0.15	30.82	61.02	6.18
7	0–130	1.45	10.6	56.2	33.2	0.17	23.9	197.26	19.98

Table 3
Topographic characteristics of DEMs with different resolution and the impact of DEMs on watershed definition of SWAT model

Symbol	Resolution (m)	Elevation (m)				Area (km^2)	Length (m)	HRU	Sub- basins
		Max	Min	Mean	SD				
DEM8	8	2031	332	920.71	320.45	952.36	249016	256	35
DEM12	12	2031	332	920.71	320.45	952.3	246168	256	35
DEM15	15	2030	332	920.71	320.45	952.31	244470	253	35
DEM20	20	2030	332	920.72	320.45	952.19	241760	253	35
DEM25	25	2028	332	920.71	320.45	952.87	243300	253	35
DEM30	30	2028	332	920.71	320.45	952.15	240950	250	35
DEM60	60	2026	336	920.76	320.42	950.65	239520	250	35
DEM90	90	2022	336	920.98	320.31	953.88	238140	252	35
DEM150	150	2022	338	920.33	319.77	954.17	234600	250	35
DEM300	300	1980	342	920.76	318.89	947.08	228600	241	33
DEM600	600	1980	348	921.66	312.31	917.62	215640	236	33
DEM900	900	1975	348	921.81	317.23	907.03	208800	230	28

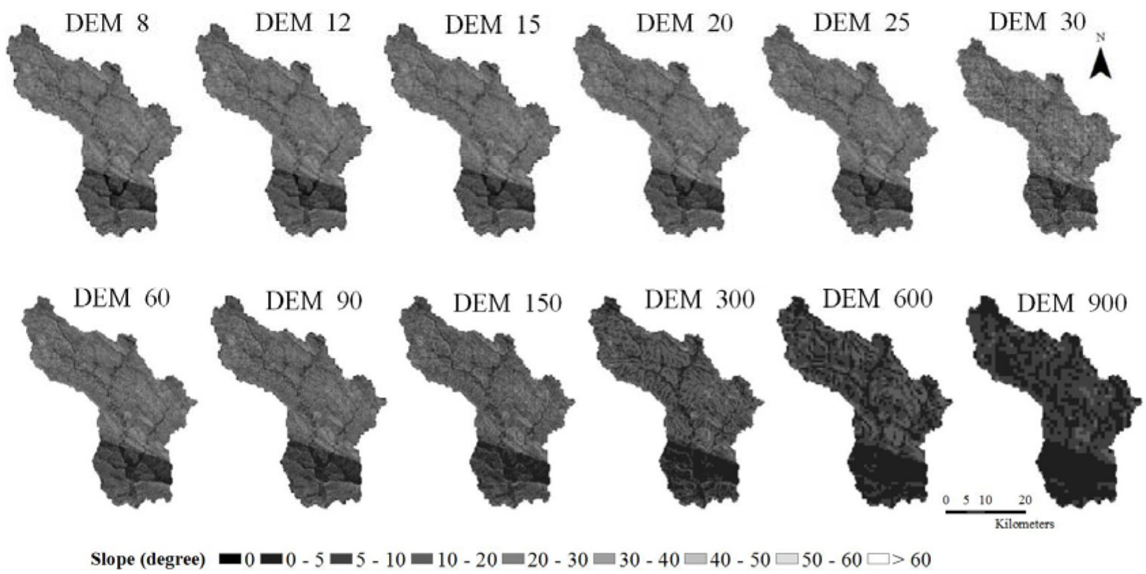

Fig. 2. Slope characteristics of DEM with different resolutions.

of maximum elevation will be significantly larger. Comparing with DEM8, the maximum elevation at DEM900 is decreased by as much as 56 m. In addition, the minimum elevation is proportional to the increase of DEM resolution in certain degree. Comparing with DEM8, the minimum elevation at DEM900 is increased by as much as 4.82%. Therefore, the topographic relief amplitude of watershed gradually decreases while the uncertainty degree of watershed topographic information gradually increases as the DEM mesh size increases; DEM will be increasingly less able to reflect the characteristics of Qihe watershed and the distorting phenomenon of watershed elevation information will become increasingly obvious.

3) The watershed slope is a key factor influencing the rainfall-runoff characteristics. Theoretically, the expanding of mesh size has a flattening effect on topography, so that the slope will become relative flat. Fig. 2 shows the variation of average slope of watersheds with DEM of different solutions. It can be seen that the mesh size has a significant impact on watershed slope. The larger the mesh size is, the smaller the average slope and maximum slope of watershed will be. It is worth noting that the average slope decreases from 17.89° for DEM8 to 5.06° for DEM900, the maximum slope decreases from 66.35° to 16.59°, and the maximum slope of DEM900 accounts only for 25% of that of DEM8. The Slope distortion is more significant than elevation distortion.

Table 4
Description of the calibrated model parameters

Parameter	Definition	Range	Calibrated value
CN2	Curve number	0–99	48–93
SOL_AWC	Soil available water capacity	0–1	0.11–0.21
GWQMN	Threshold depth of water in shallow aquifer for percolation to occur	0–300	20
ESCO	Soil evaporation compensation factor	0–1	0.5
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm/h)	0–500	0.09
GW_REVAP	Groundwater revap coefficient	0.02–2	0.28
ALPHA_BF	Base flow alpha factor	0–1	0.048
SURLAG	Surface runoff lag coefficient	0–10	4
CH_K2	Effective hydraulic conductivity in main channel alluvium	0–150	0
SOL_K	Saturated hydraulic conductivity (mm/h)		5.39–2.68

4.2. Model calibration and validation

The capability of SWAT model to adequately simulate stream flow processes typically depends on the accurate calibration of parameters. In this study, the SWAT model was calibrated for 3 years by using the recorded daily stream flow data measured at the outlet from January 1, 2002 to December 31, 2004. For the sake of the parameters being selectively optimized, the sensitivity analysis was performed to address whether the appropriate quantity and quality of data can be obtained to provide realistic model outputs given parameter sensitivity. According to the sensitivity analysis, a total of 10 parameters were chosen, including CN2, SOL_AWC, GWQMN, ESCO, REVAPMN, GW_REVAP, ALPHA_BF, SURLAG, CH_K2, SOL_K, sorted by the degree of sensitivity.

The flow data at daily time for the hydrological years from 2005 to 2007 was used for model validation and the Nash–Sutcliffe efficiency (ENS) was chosen to assess the performance of the SWAT model. The results of the flow calibration (Table 5) show a good model performance for both the calibration and validation data sets, the ENS values in yearly, monthly and daily simulation based on different DEM are all above 0.5 (only the ENS value of daily runoff based on DEM900 in calibration period relatively lower, which is 0.47), which satisfied the accuracy requirements of the model simulation. The results suggest that the SWAT model based on different DEM is capable for simulating runoff during calibration and validation periods in Qihe watershed. The ENS in validation period are generally higher than that in calibration period. This is mainly due to that a very high peak runoff occurred in 2005, which increased the simulation accuracy of SWAT model in validation period.

Through further analysis, it can be known that:

(1) Annual scale. The evaluation index ENS are all more than 0.7, which satisfies the accuracy requirements of the model simulation, both for the calibration and validation periods. When the DEM resolution varies within 8 m to 30 m, the simulation results remain unchanged, ENS value is 0.86 for calibration and 0.87 for validation. When the DEM resolution becomes coarser from 30 m to 150 m, ENS value starts to decrease accordingly from 0.86 to 0.81 in calibration, and from 0.87 to 0.81 in validation. When DEM mesh size is more than 150 m, the ENS value decreases significantly. Specifically, the ENS value at DEM900 is decreased than that at DEM8 by 0.15 and 0.14 for calibration and validation, respectively.

(2) Monthly scale. The simulation of monthly runoff displays similar variation tread as that of annual runoff simulation. When DEM resolution varies between 8 m and 30 m, the simulation results remain unchanged; when DEM resolution varies in the range of 30 m to 150 m, ENS value starts to decrease; when DEM resolution is lower than 150 m, ENS values decreases more significantly.

(3) Daily scale. When DEM mesh size increases from 8 m to 30 m, the daily runoff simulation results are slowly decreased. When DEM resolution is lower than 20 m, ENS value decreases from 0.65 to 0.64 during calibration period, and from 0.69 to 0.67 during validation period, wherein the largest difference is 0.02. When DEM resolution is between 30 m and 150 m, the simulation accuracy is further decreased, but the decreasing amplitude is not significant, with maximum difference of 0.07; as DEM resolution is coarser than 150 m, the decreasing amplitude is relatively larger; when DEM mesh size is 900 m, the simulation accuracy is the lowest. It is worth noting that ENS value with DEM600 in calibration period are slightly increased compared with DEM300. One of main reasons is that when DEM resolution is coarser than 300 m, the mesh size is larger than the width of Qihe river, and the topographic information from DEM can no longer describe actual land form. Therefore, the increase of ENS values based on low-resolution DEM should be seen as an illusion, and cannot be used as a judgment criterion for DEM simulation results. To avoid the occurrence of such phenom-

Table 5
Evaluation of model simulation results

DEM	Calibration (2002–2004)			Validation (2005–2007)		
	Year	Month	Day	Year	Month	Day
DEM 8	0.86	0.75	0.65	0.87	0.77	0.69
DEM 12	0.86	0.75	0.65	0.87	0.77	0.69
DEM 15	0.86	0.75	0.65	0.87	0.77	0.69
DEM 20	0.86	0.75	0.65	0.87	0.77	0.69
DEM 25	0.86	0.75	0.64	0.87	0.77	0.68
DEM 30	0.86	0.75	0.64	0.87	0.77	0.67
DEM 60	0.84	0.73	0.62	0.85	0.74	0.66
DEM 90	0.83	0.71	0.6	0.83	0.73	0.63
DEM 150	0.81	0.69	0.58	0.81	0.7	0.6
DEM 300	0.75	0.63	0.53	0.77	0.64	0.58
DEM 600	0.72	0.62	0.55	0.74	0.65	0.56
DEM 900	0.71	0.6	0.47	0.73	0.59	0.5

enon, a preliminary understanding of watershed topographic characteristics is needed in selection of DEM resolution. If DEM mesh size is far larger than the width of river in study area, the watershed geomorphologic characteristics will not be well fitted, and the simulation effect will be always unreal no matter how high the ENS value is.

4.3. Daily stream flow and peak runoff

Figs. 3–5 show the simulated runoffs with different resolutions of DEM during concentrating period of precipitation (July–August) in validation period of (2005–2007). It can be seen that the hydrograph of stream flow simulated by SWAT model with different resolutions shows similar variation as that of observed stream flow. However, some simulated results are significantly different from observation data. On one hand, this is due to that Qihe watershed locates in mountainous area where the climatic conditions are complex, some precipitation data cannot represent the meteorology change of the whole watershed; on the other hand, there is also some errors in the observation data of hydrometric station.

Further analysis indicates that, the higher the DEM resolution is, the larger the fluctuation of stream flow hydrograph is, and the more the simulation results in different precipitation phases will be consistent to measured runoff. When the precipitation is lower than 12 mm, the larger the DEM resolution is, the lower the simulated value will be, and the more it will be consistent with observation data. However, due to low base of runoff value, there is a minor difference among the SWAT simulation results based on different DEM resolutions. When the precipitation varies from 12 mm to 28 mm, the simulated result based on high-resolution DEM starts to exceed the simulated result based on low-resolution DEM, but still the difference is insignificant. When the precipitation exceeds 28 mm, the simulated results based on high-resolution DEM is significantly higher than that based on low-resolution DEM, especially for the simulation of flood peak in which the simulation results are more close to the observation data. For example, the stream flow occurred on August 10th, 2005 was the peak runoff during validation period, which was measured to be 181.3 m^3/s. The simulated values based on DEM8 and DEM900 differ from measured runoff value by –2.01% and –17.03%, respectively. The simulated runoff value based on DEM8 is more accurate than that based on DEM30 by 1.01%, and more accurate than that based on DEM900 by 15.02%. Through analysis based on Table 3, it can be concluded that as the DEM resolution becomes coarser, the topographic relief amplitude and watershed area are both decreased gradually, the simulated runoff peak gradually decreases and flood peak is gradually attenuated. This indicates that the error brought by low-resolution DEM will lead to the change of peak runoff value, thus resulting in large deviation between simulated runoff value and observation data.

The SWAT models were computed by AMD FX-6300 Six-Core Processor to model daily stream flow in 2002 to 2007. The operation time of SWAT models with DEM900 is 31 S , with DEM30 is 39 S and 43 S with DEM8. It can be conclude that, with the increase of DEM resolution, the computation time is gradually increased, but still acceptable. In addition the reduction of DEM resolution resulted in a decrease of watershed slope and the convergence speeds would be underestimated. However, the peak flow on daily scale modeled based on different DEM resolution was not appeared hysteresis, this mainly because the difference of concentration time is no more than 24 h.

5. Conclusion

In watershed delineation process, SWAT models with different DEM resolutions can obtain different watershed areas, maximum watershed elevations, average watershed elevations, and watershed slopes. As DEM resolution becomes coarser, the extracted land form tends to be flat, and the total area of watershed, maximum elevation,

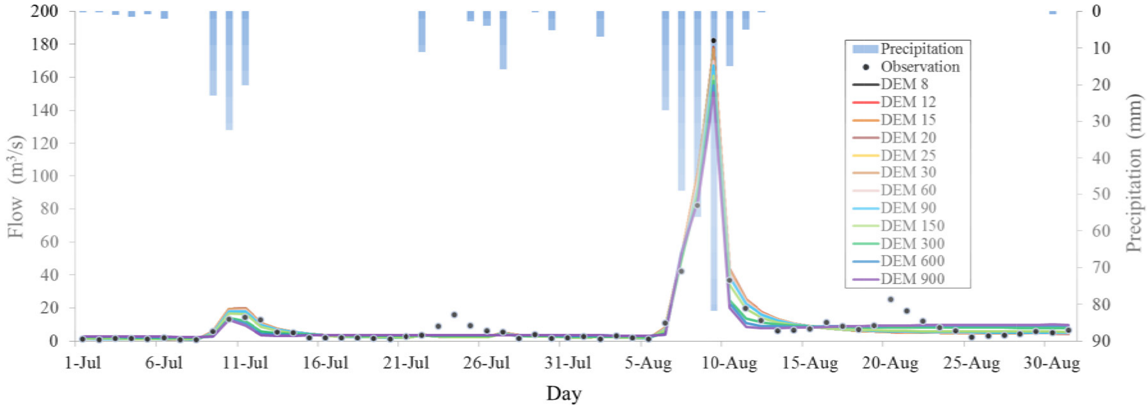

Fig. 3. Daily flow hydrograph during concentrating period of precipitation in validation period of 2005.

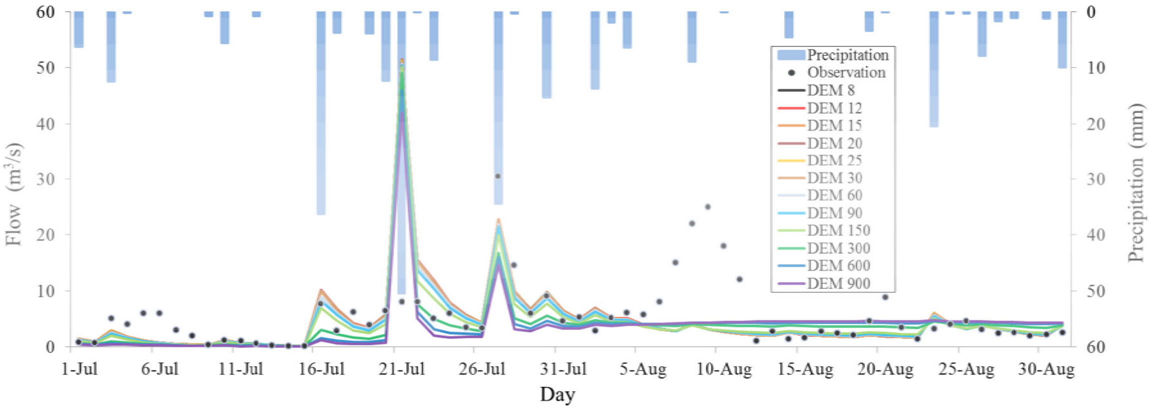

Fig. 4. Daily flow hydrograph during concentrating period of precipitation in validation period of 2006.

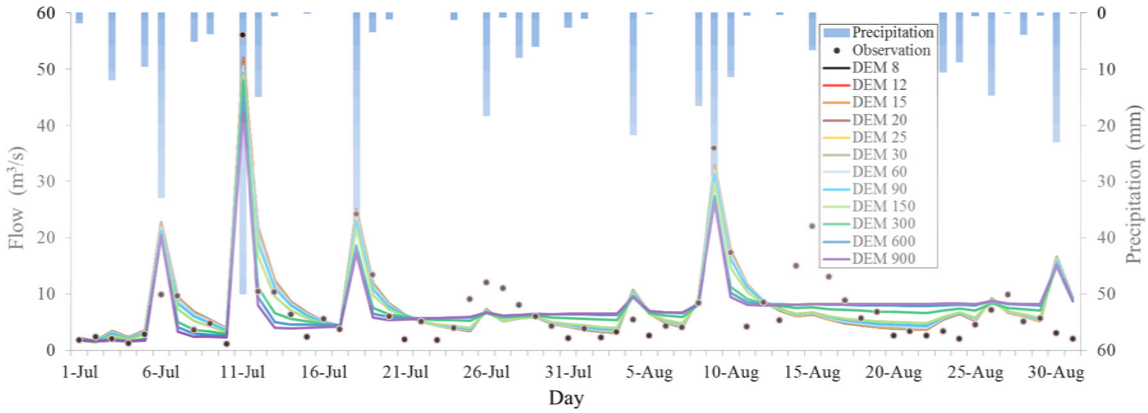

Fig. 5. Daily flow hydrograph during concentrating period of precipitation in validation period of 2007.

and maximum slope generally show a decreasing trend, while the minimum elevation and minimum slope show an increasing trend. If these parameters were put into SWAT model, the difference of information will affect the hydrological simulation results. As DEM resolution is lower, ENS shows a trend of fluctuating downward. However, when DEM resolution is lower than 300 m, the extracted watershed information will be unreal even though ENS is still satisfactory.

As a main input factor of hydrological model, DEM resolution will affect the simulated stream flow. High-resolution DEM is more suitable for actual land form, the simulation results will be more consistent with observation data, and the runoff simulation accuracy will be higher. With the decrease of DEM mesh size, the watershed topography will tend to be flat, the watershed slope will gradually decrease, which will directly affect the water generation and concentration, thus resulting in homogenization of simulated stream flow, and flood peak attenuation.

When DEM resolution is higher than 30 m, the simulated annual and monthly runoff remain unchanged, but the simulated daily runoff will be different very much. The higher the resolution is, the better the simulation results will be, and the more the simulated stream flow will be consistent with observed stream flow, especially for the simulation of flood peak. Therefore, a DEM with higher resolution can describe the runoff process more precisely.

This study analysed the the impact of DEM within the SWAT model to simulate streamflow, which will provide reference for the research about the uncertainty of other distributed hydrological models at different DEM resolutions, and the examination of the sensitivity of sediment and non-point source pollution modeling to a wider range of DEM resolutions is also needed for further study.

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