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Assessing the hydrological effect of the check dams in the Loess Plateau, China by model simulations

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Abstract

Check dams are commonly used for soil conservation. In the Loess Plateau of China, check dams have been widely constructed as the principal means to retain floodwater and intercept soil sediments since the 1970s. However, little research has been done to quantify the hydrological effects of the check dams.

In this research, the SWAT model (Soil and Water Assessment Tool) was applied to simulate the runoff and sediment in the Yanhe watershed in the Loess Plateau. We treated the 1950s to 1960s as "reference period" since there were very few check dams during the period. The model was first calibrated and validated in the "reference period". The calibrated model was then used in the later periods to simulate the hydrological effects of the check dams.

The results showed that the check dams had a regulation effect on runoff and a retention effect on sediment. From 1984 to 1987, the runoff in rainy season (from May to October) decreased by 14.7 to 25.9 % due to the check dams, while in dry season (from November to the following April), runoff increased by 60.5 to 101.2 %; the sediment in rainy season decreased by 34.6 to 48.0 %. From 2006 to 2008, the runoff in rainy season decreased by 15.5 to 28.9 %, and the runoff in dry season increased by 20.1 to 46.4 %; the sediment in rainy season decreased by 79.4 to 85.5 %.

Construction of the large number of in the Loess Plateau has enhanced the region's capacity to control the runoff and sediment. In the Yanhe watershed, the annual runoff was reduced by less than 14.3 % due to the check dams; and the sediment in rainy season was blocked by up to 85.5 %. Thus, check dams are effective measures for soil erosion control in the Loess Plateau.

1 Introduction

Check dam is a type of engineering measure for soil conservation in the erodible areas. A check dam is composed of embankment and spillway. Some simple check dams consist of only embankments. While not common around the world, check dams have been implemented for soil erosion control and reported in some countries, including China, France, Italy, Iran, and Spain.

In the Loess Plateau of China, check dams have been put into effect for hundreds of years for soil erosion control. Especially since the 1970s, thousands of check dams have been constructed in the region. By 2005, there had been 122, 028 check dams in the Loess Plateau (Ministry of Water Resources of the People's Republic of China et al., 2010), averaging 1 check dam per 5 km^2, with an even higher density in the middle reaches of the Loess Plateau.

Check dams retain floodwater and intercept soil sediments. At the beginning of the construction, a water body would be formed behind the check dam (Fig. 1). Gradually, the water body was filled by sediment deposition. The area formed by the deposit is usually used as farmland, which plays an important role in the grain production in the region (Fig. 2). Overtime, check dams would be filled up eventually.

Researches on check dams around the world have focused on their hydrological and geomorphological effects. Bombino (2009) investigated the impact of check dams on channel form, sediment calibre and vegetation in the headwater reaches in Calabria, Southern Italy. The results suggested statistically significant differences in channel form, sediment and vegetation development among the upstream, the downstream, and the intermediate sections of check dams. Hassanli (2009) evaluated the effect of porous check dam location on the retention of fine sediments by field sampling and laboratory analysis in the Droodzan watershed, Southern Iran. Remaitre (2008) used a debris-flow model to evaluate the influence of the number and the location of the check dams on the debris-flow intensity in the Faucon watershed of South French Alps. The results indicated that check dams located near the source area may decrease debris-flow intensity more efficiently.

A series of researches on check dams had been engaged in Spain (Boix Fayos et al., 2007, 2008; Castillo et al., 2007; Conesa García et al., 2007). Based on field observations and modeling analysis, the studies assessed the impact of check dams on channel morphology, channel bed stability and catchment sediment yield. The results showed that the check dams held sediments and caused a decrease in the longitudinal gradient upstream, but accelerated erosion downstream because of the increased flow transport capacity and scour processes; check dams reduced catchment sediment yield, by up to 77 % in the case of the Rogativa catchment (SE Spain). Besides, Martín Rosales (2007) estimated the groundwater recharge induced by check dams and gravel pits. The results showed that the proportion of runoff that infiltrates through the check dams varied from 3 % to more than 50 %.

By estimating the sediment retained by check dams in the Yellow River watershed, Xu Xiangzhou and his colleagues (Xu et al., 2002, 2004) concluded that check dams system in gullies was one of the most effective soil conservation means in the Loess Plateau, China. In five typical catchments in the Hekou-Longmen section of the midstream of the Yellow River, Ran (2008) analyzed the coarse sediment retention by check dams and found that when the percentage of the drainage area with check dams in the catchments reached 3.0 %, the average sediment reduction ratio could reach 60 %. Moreover, check dams were reportedly to increase carbon retention in Yan'an prefecture of the Loess Plateau, China (Lü et al., 2012).

Two constraints exist in the current researches on check dams. Firstly, mechanisms on the hydrological effect of check dams are unclear. The effect of check dams on flood control and soil retention can only be assessed qualitatively but not quantitatively. The model WATEM-SEDEM was applied to simulate the impact of check dams on sediment transport (Boix Fayos et al., 2008). Check dams were treated as sedimentation areas in the model. However, the model could only simulate the average annual sediment yield but could not judge when the check dams were filled up. The runoff processes in the channels with check dams are difficult to simulate. Secondly, observations of check dams are difficult to obtain. In the Loess Plateau, China, check dams were constructed at the desire of the residents without any long term design schemes. The locations, storage capacities and outflow methods have not been inventoried and documented.

Considering the two constraints, it's hard to quantitatively assess the hydrological impacts of check dams based on the channel flow routing processes in the Loess Plateau. However, simulating the hydrological processes in a watershed without check dams is possible. If the hydrological model was calibrated and validated for the period before check dams were constructed, using the same parameters to simulate the hydrological processes of the watershed with check dams constructed, the difference between the observed hydrological data and simulated ones could be treated as the effect of the check dams.

In this article, the 1950s–1960s were treated as "reference period", when there were few check dams in the study area. A hydrological model (SWAT) was calibrated and validated for the referenced period. The hydrological processes of the study area after the 1970s were simulated by the calibrated SWAT model. Comparing with the observed data, the effect of check dams on runoff and sediment yield were evaluated by the simulated data.

2 Methods

2.1 Study area

The Yanhe watershed (108°38′–110°29′ E, 36°21′–37°19′ N) lies in the middle of the Loess Plateau, China (Fig. 3). The area of the watershed is 7725 km^2. The landform is a typical loess hilly-gullied landscape with elevations ranging from 495 m to 1795 m a.s.l., with an average elevation of 1218 m. The average slope is 23.4°.

The watershed has a typical semiarid continental climate. The average temperature is 8.8 °C and the average annual precipitation is 505 mm. Rainfall shows high seasonal variability, with more than 60 % of the annual precipitation occurring between July and September.

The dominant vegetation in the watershed is grassland. The dominant soil, loess soil, is derived from loess parent material. The soil and the parent material are both very erodible (Xu et al., 2012).

The topography, climate, vegetation and soil collectively cause the serious soil erosion in the watershed. The average erosion rate is 8100 $\mathrm{t\,km^{-2}\,yr^{-1}}$. For conserving soil, re-vegetation and engineering measures have been implemented for decades. The "Grain-for-Green" project launched in 1999 is the largest plantation project, in which much cropland were fallowed or afforested. While the engineering measures have been implemented in the region for quite long period. Check dams are the most common ways in the engineering measures. By the end of 2002, there had been 6572 check dams constructed in the Yanhe watershed, counting as one check dam per 1.18 $\mathrm{km^2}$ (Hui et al., 2002).

2.2 Data sets

Databases of topography, land use, hydrology, soil and meteorology were collected from difference sources. Hydrological data were used for model calibration, validation and assessment of the hydrological effects of the check dams.

A 25 m-resolution digital elevation model (DEM) for the Yanhe watershed, derived from a 1 : 50 000 scale contour map, was supplied by the National Geomatics Center of China.

Land use maps for the year 1975, 1990 and 2008 (1 : 100 000 scale) were interpreted by the Institute of Remote Sensing Applications, Chinese Academy of Sciences from remotely sensed Landsat images. Six land use types were identified: forest, shrubland, grassland, cropland, water bodies and residential areas.

A soil survey map (1 : 500 000 scale) by the comprehensive scientific investigation team, Chinese Academy of Sciences was used in the research. The soil in the watershed was divided into seven types: sandy loess soil, loess soil, grey loess soil, chalk loess soil, dark-purple loess soil, red clay soil and alluvial soil. The soil attributes were got from some literatures and field works (Xu et al., 2012).

Precipitation and hydrological data of 1956–1960, 1963–1966, 1984–1987, 2006–2008 were collected. Daily data from precipitation stations and the monthly flow and sediment yield data of the Ganguyi hydrometric station (109°48′ E, 36°42′ N, controlling 76.3 % of the watershed) in the watershed were acquired from "Hydrological Yearbook of the People's Republic of China – Hydrological Data of the Yellow River Basin" published by the Yellow River Water Conservancy Committee. Meteorological data (daily precipitation, maximum and minimum temperatures, average wind speeds and relative humidity) of 1954 to 2008 were obtained for the Yanan (109°30′ E, 36°36′ N) and Wuqi (108°10′ E, 36°55′ N) meteorological stations from China Meteorological Data Sharing Service System (http://www.cma.gov.cn/2011qxfw/2011qsjgx/).

2.3 Methods

2.3.1 Hydrological simulation in the "reference period"

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) was applied for hydrological simulation of the Yanhe watershed in this study. It is a watershed scale model for simulating long-term runoff and nutrient losses from rural watersheds. In the hydrology module of SWAT, rainfall-runoff processes are simulated by either the NCRS Curve Number (CN) method or the Green & Ampt infiltration method. As the latter requires sub-daily precipitation data, its application was limited by the availability of precipitation data in the study watershed. In the soil erosion module, a Modified Universal Soil Loss Equation (MUSLE) is applied, in which the sediment yield is a function of runoff factor, soil erodibility factor, cover and management factor, support practice factor, topographic factor and coarse fragment factor.

The years 1956–1960 and 1963–1966 were treated as the "reference periods", during which there were few check dams in the studied area. Using the DEM, the soil map, the land use map of the year 1975 and the meteorological data between 1954 and 1966, SWAT model was run to simulate the monthly flow and sediment yield from 1956 to 1966. The simulation period was divided into three parts: the warm-up period

(1954–1955), the calibration period (1956–1960) and the validation period (1963–1966). In the calibration, parameters sensitivity was tested by using the ArcSWAT. The sensitive parameters were calibrated by the SWAT Calibration and Uncertainty Programs Version 2 (SWAT-CUP2). The calibrated parameters were used in the validation period. Once validated, the parameters would be applied in the simulation of 1984–1987 and 2006–2008.

The agreement between the simulated and observed flow and sediment yield was quantitatively evaluated using the coefficient of determination (R^2) and the Nash–Sutcliffe coefficient (E_{NS}) (Nash and Sutcliffe, 1970), calculated as:

$$R^2 = \frac{\left[\sum_i \left(O_i - \overline{O}\right)\left(S_i - \overline{S}\right)\right]^2}{\sum_i \left(O_i - \overline{O}\right)^2 \sum_i \left(S_i - \overline{S}\right)^2} \tag{1}$$

$$E_{\mathrm{NS}} = 1 - \frac{\sum_i (O - S)_i^2}{\sum_i \left(O_i - \overline{O}\right)^2} \tag{2}$$

where O is the observed value, and S is the simulated value.

Generally, if $R^2 > 0.6$ and $E_{\mathrm{NS}} > 0.5$, the simulation results were regarded as credible.

2.3.2 Hydrological effects assessment of the check dams

Once the model was satisfactorily validated, it could be regarded as suitable for the watershed without check dams. The model would be applied for the period after the construction of check dams. There would be a bias between the simulated and observed data. The bias was the assessment criteria of the effect of the check dams:

$$E = (\overline{O} - \overline{S})/\overline{S} \cdot 100\% \quad (3)$$

where E is the hydrological effect of the check dams expressed as percentage, O is the observed value, and S is the simulated value.

For the years 1984–1988 and 2006–2008, land use map of 1990 and 2008 were used instead, respectively.

3 Results

3.1 Simulation results in the "reference period"

The SWAT model was warmed up in 1954–1955, calibrated in 1956–1960 and validated in 1963–1966. In the calibration period, parameters sensitivity was analyzed by the ArcSWAT. The ranked sensitive parameters are listed in Table 1.

The sensitive parameters were calibrated using the Sequential Uncertainty Fitting (SUFI2) in the SWAT-CUP2. In addition, another important parameter USLE_K (USLE soil erodibility factor) was added, for its sensitivity cannot be tested by ArcSWAT. The SWAT-CUP2 was run repeatedly until the simulated results were acceptable. The adjustment ranges of the parameters were narrowed during calibration. The final adjustment ranges and the best adjustment values are listed in Table 2. The simulation results are shown in Fig. 4, and the modeling efficiencies are listed in Table 3.

In the validation period (1963–1966), the adjustment ranges of the parameters remained unchanged. The results of runoff and sediment simulation were both acceptable (Table 3), which are illustrated as Fig. 5.

3.2 Simulation results in 1980s and 2000s

After calibration and validation, SWAT was proved to be applicable in the study area. Using ArcSWAT and SWAT-CUP2, the calibrated model was applied to simulate the hydrological processes in the 1980s (1984–1987) and 2000s (2006–2008).

However, the simulation results looked apparently unreasonable (Figs. 6 and 7), and the modeling efficiencies decreased obviously in the two periods (Table 4). In the former period, the simulated runoff and sediment results kept similar trends with the observation (R^2 was more than or near 0.6), but a large bias existed between them ($E_{NS} < 0.5$). While in the latter period, even the similar trends vanished.

In the two periods, a similar phenomenon existed in the runoff simulation results. From July to September, most of the simulated values were higher than the observed ones; while form February to April, the simulated values were lower than the observed ones. So the results were analyzed separately for the rainy season and dry season. In the study watershed, the months from May to October belonged to the rainy season, whose precipitation accounts for 86.8 % of the annual precipitation. The other months composed the dry season.

The mean observed and simulated values were listed in Table 5.

3.3 Hydrological effects of the check dams

During the simulation in 1984–1987 and 2006–2008, the land use data and meteorological data for the corresponding period were applied. Thus the hydrological impacts of the climate and land use change were excluded. The biases between the observed and simulated values calculated by the formula 3 were treated as criteria of the effect of the check dams. By the results in Table 5, the following inferences could be made:

1. In the rainy season, runoff had decreased because of the existence of the check dams, by about 14.7 to 25.9 % (1984–1987) and 15.5 to 28.9 % (2006–2008), respectively.

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2. In the dry season, runoff had increased by 60.5 to 101.2 % (1984–1987) and 20.1 to 46.4 % (2006–2008), respectively.
3. Annually, the check dams tended to decrease the runoff by up to 11.5 % (1984–1987) and 14.3 % (2006–2008), respectively.
4. During the dry season, sediment transported with water was rarely observed, so the impact of the check dams on sediment could only be assessed in the rainy season. The simulations showed that the check dams reduced the sediment in the rainy season by 34.6 to 48.0 % (1984–1987) and 79.4 to 85.5 % (2006–2008), respectively.

4 Discussion

The simulations showed that the check dams increased the runoff in the dry season. It could be due to the enhanced lateral flow and return flow, which were the main components of the runoff in the dry season. As mentioned previously, the check dams intercept surface runoff and may even lead to the formation of water bodies. This function promoted the infiltration in the soil profile and recharged the ground water (Callow and Smettem, 2009). Thereby the lateral subsurface flow and the groundwater return flow were enhanced.

In the rainy season, the surface runoff, which was dominant in the total runoff, was largely intercepted by the check dams, so the runoff in the rainy season decreased. However, the reduced proportion was not as high as expected (less than 30 %). It could be attributable to the fact that a portion of surface runoff became subsurface lateral flow and return flow, which entered the channels downstream.

Overall, the annual runoff was reduced by the check dams. The reason may be that the existence of the check dams lead to the increase of evaporation and soil water storage (Wittenberg, 2003).

Lateral and groundwater flow did not contribute significantly to sediment yields (Arnold et al., 1998; Callow and Smettem, 2009). As a result, the sediment which was transported mainly by surface runoff in the rainy season declined significantly.

The hydrological effect of the check dams was different between the two simulation periods. The total runoff, the runoff and the sediment in the rainy season decreased more in the period of 2006–2008 than did in the period of 1984–1987. It could be due to the increased check dams, which were constructed continuously between the two periods.

However, the runoff in the dry season was simulated to have increased more in the period of 1984–1987 than in the period of 2006–2008 because of the check dams. It could be explained like this: numerous check dams encouraged the lateral flow and return flow, however, if the check dams kept increasing, the flow emerging onto the channels would be obstructed by the downstream check dams. In other words, there was a threshold of the check dams' amount, before which the lateral flow and return flow increased, and after which decreased.

Due to the lack of sediment data, the impact of check dams on the sediment in the dry season was not specifically assessed. It could be inferred that the sediment amount in the dry season would not increased a lot, because the runoff in the dry season was dominant by lateral flow and return flow, which had smaller kinetic energy to detach soil particles (Arnold et al., 1998).

In summary, the check dams reduced the total runoff, regulated runoff in both rainy and dry seasons and decreased sediment yields. Due to the check dams, total runoff decreased by less than 14.3 %, meanwhile, sediment yields decreased up to 85.5 %. The construction of check dams was an effective measure for soil erosion control in the studied watershed.

If the amount of the check dams keeps increasing, it's likely that the sediment yield will decline; however, it's unclear how the runoff will change. It's crucial to probe into the mechanism of the hydrological processes with check dams and determine appropriate scales for check dam construction.

5 Conclusion

The SWAT model, after calibration and validation, was used to simulate the hydrological processes of the Yanhe watershed. For the periods when a large number of check dams had been constructed, the bias between the observations and simulated values were used to assess the hydrological effects of the check dams.

The check dams had a regulation function for runoff. In the rainy season (from May to October), the runoff of the Yanhe watershed had decreased by 14.7 to 25.9 % (1984–1987) and 15.5 to 28.9 % (2006–2008) respectively due to the check dams. While in the dry season (from November to the next April), the runoff rate increased by 60.5 to 101.2 % (1984–1987) and 20.1 to 46.4 % (2006–2008), respectively. The check dams tended to decrease the annual runoff by up to 11.5 % (1984–1987) and 14.3 % (2006–2008), respectively.

The check dams lead to a decrease of the sediment in the rainy season, by a range of 34.6 to 48.0 % (1984–1987) and 79.4 to 85.5 % (2006–2008), respectively.

The check dams system intercepted up to 85.5 % of the sediment while reducing the runoff decline by less than 14.3 %. It has been proven to be an effective measure for soil erosion control in the Loess Plateau, China. This study only simulated the hydrological effects of the check dams in the study watershed. For thorough assessment of the impacts of the check dams, a detailed survey of the amounts, locations and characteristics of the check dams are needed, though it's a difficult task in the Loess Plateau, China.

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Table 1. Parameters sensitivity analysis results.

Parameter name	Description	Rank for runoff simulation	Rank for sediment simulation
CN2	Initial NCRS CN II value	1	1
ESCO	Soil evaporation compensation factor	2	2
ALPHA_BF	Baseflow alpha factor (days)	3	3
SOL_AWC	Available water capacity (mm H_2O (mm soil)$^{-1}$)	4	5
SOL_K	Saturated hydraulic conductivity (mm h^{-1})	5	–
SOL_Z	Soil depth (mm)	6	6
SLSUBBSN	Average slope length (m)	7	7
USLE_P	USLE support practice factor	–	4

Table 2. Results of parameters calibration.

Parameter	Type of parameter alteration[a]	Adjustment range		Best adjustment value
		Lower limit	Upper limit	
CN2	r	0.070	0.149	0.115
ESCO	v	0.736	0.805	0.743
ALPHA_BF	v	0.022	0.066	0.023
SOL_AWC____SLS[b]	r	−0.018	0.064	−0.010
SOL_K____SLS	r	−0.188	−0.139	−0.154
SOL_Z____SLS	r	0.008	0.141	0.066
USLE_K____SLS	r	−0.717	−0.629	−0.644
SOL_AWC____LSUP	r	0.319	0.484	0.358
SOL_K____LSUP	r	−0.187	−0.085	−0.102
SOL_Z____LSUP	r	0.070	0.106	0.097
USLE_K____LSUP	r	−0.543	−0.305	−0.440
SOL_AWC____LS	r	−0.039	0.005	−0.003
SOL_K____LS	r	−0.043	0.055	−0.033
SOL_Z____LS	r	0.126	0.182	0.132
USLE_K____LS	r	0.063	0.343	0.259
SOL_AWC____GLS	r	−0.079	0.040	−0.028
SOL_K____GLS	r	−0.006	0.107	0.103
SOL_Z____GLS	r	−0.503	−0.220	−0.475
USLE_K____GLS	r	−0.387	−0.268	−0.352
SLSUBBSN	r	0.575	0.844	0.709
USLE_P	v	0.329	0.435	0.417

[a] "v" means the parameter value would be replaced by the given value; "r" means the parameter value would be multiplied by (1+ the given value).

[b] The phrases after the soil parameters are used to calibrate the four main soil types separately.

Table 3. The modeling efficiencies of the "reference period" (1956–1966).

Period	Variable	$R^{2\text{a}}$	E_{NS}^{b}
Calibration period (1956–1960)	Runoff	0.81	0.76
	Sediment yield	0.73	0.72
Validation period (1963–1966)	Runoff	0.83	0.63
	Sediment yield	0.87	0.73

[a] R^2 – the coefficient of determination.
[b] E_{NS} – the Nash–Sutcliffe coefficient.

Table 4. The modeling efficiencies of 1984–1987 and 2006–2008.

Period	Variable	R^2	E_{NS}
1984–1987	Runoff	0.74	−0.21
	Sediment yield	0.58	0.12
2006–2008	Runoff	0.39	−2.23
	Sediment yield	0.14	−27.62

Table 5. The mean observed and simulated values of 1984–1987 and 2006–2008.

Period			Observation	Simulation range	Bias (Formula 3)
1984–1987	Monthly runoff ($m^3 s^{-1}$)	Mean value	6.42	6.21 ~ 7.25	−11.5 % ~ 3.3 %
		Mean value in rainy season	8.95	10.49 ~ 12.08	−25.9 % ~ −14.7 %
		Mean value in dry season	3.88	1.93 ~ 2.42	60.5 % ~ 101.2 %
	Monthly sediment (ton)	Mean value in rainy season	4.71E+06	7.20E+06 ~ 9.06E+06	−48.0 % ~ −34.6 %
2006–2008	Monthly runoff ($m^3 s^{-1}$)	Mean value	3.69	3.60 ~ 4.31	−14.3 % ~ 2.6 %
		Mean value in rainy season	4.31	5.10 ~ 6.06	−28.9 % ~ −15.5 %
		Mean value in dry season	3.07	2.10 ~ 2.56	20.1 % ~ 46.4 %
	Monthly sediment (ton)	Mean value in rainy season	5.29E+05	2.56E+06 ~ 3.65E+06	−85.5 % ~ −79.4 %

Fig. 1. Water body behind a check dam (Photo: Yafeng Wang).

Fig. 2. Farmland formed by a check dam (Photo: Yanda Xu).

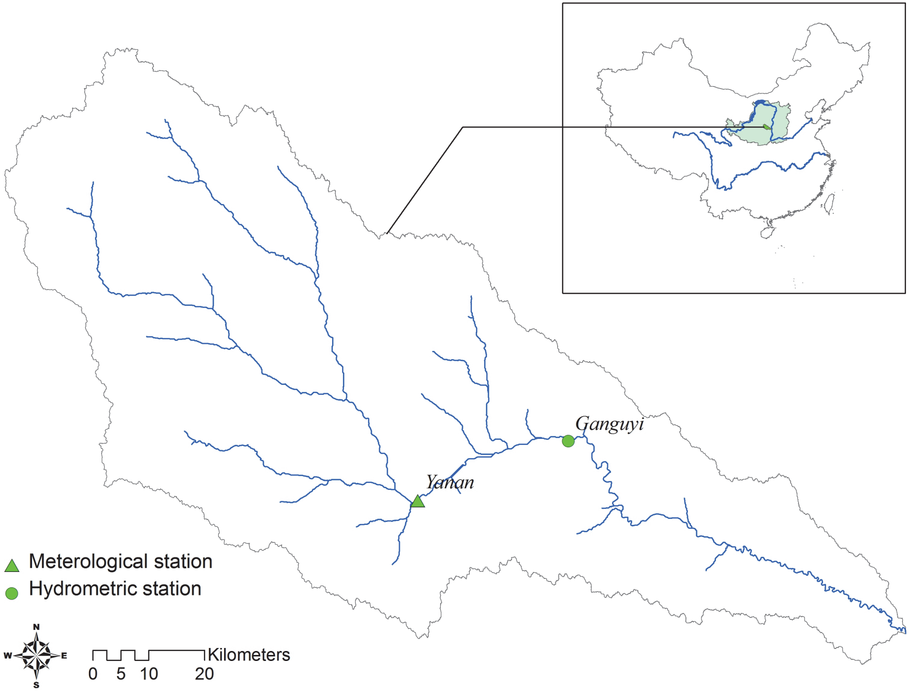

Fig. 3. Study area and the locations of hydrometric station and meteorological station.

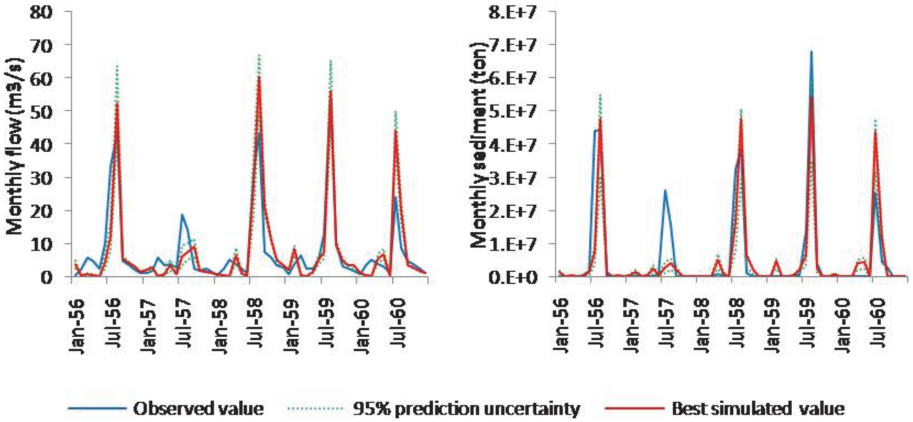

Fig. 4. Simulation results of 1956–1960.

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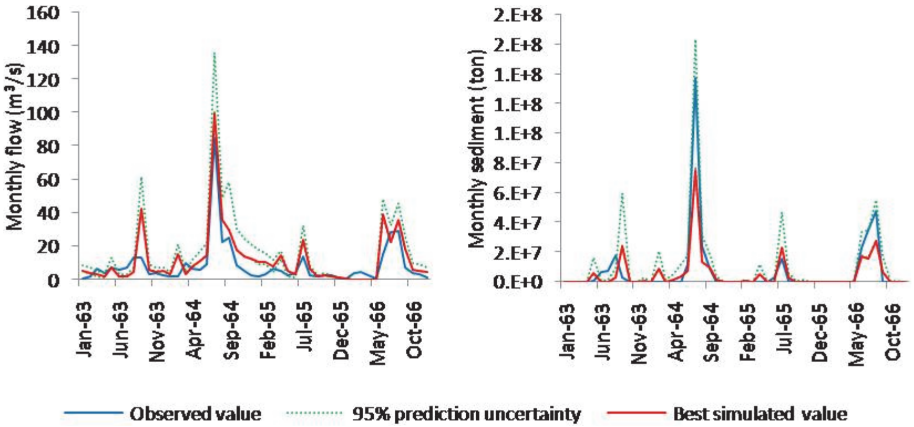

Fig. 5. Simulation results of 1963–1966.

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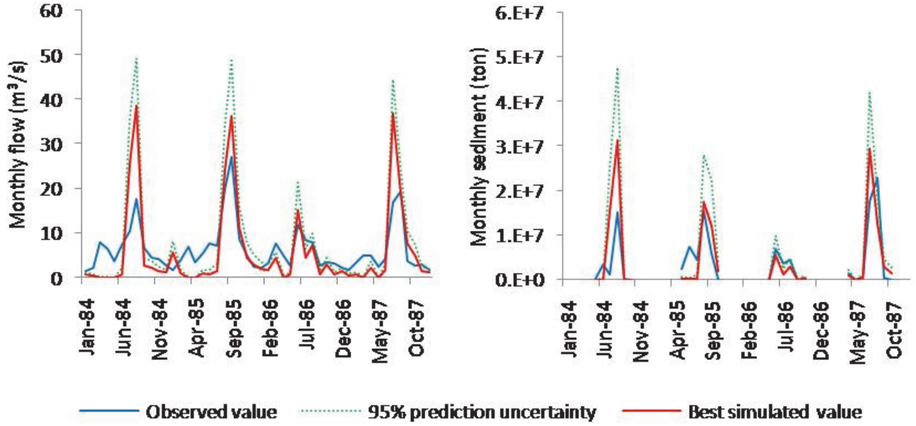

Fig. 6. Simulation results of 1984–1987.

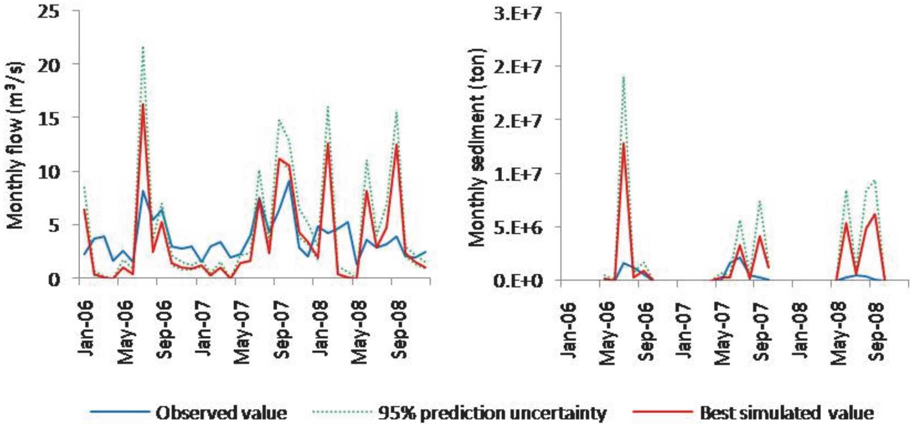

Fig. 7. Simulation results of 2006–2008.