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Evaluating the SWAT Model for Hydrological Modeling in the Xixian Watershed and a Comparison with the XAJ Model

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Abstract Already declining water availability in Huaihe River, the 6th largest river in China, is further stressed by climate change and intense human activities. There is a pressing need for a watershed model to better understand the interaction between land use activities and hydrologic processes and to support sustainable water use planning. In this study, we evaluated the performance of SWAT for hydrologic modeling in the Xixian River Basin, located at the headwaters of the Huaihe River, and compared its performance with the Xinanjiang (XAJ) model that has been widely used in China. Due to the lack of publicly available data, emphasis has been put on geospatial data collection and processing, especially on developing land use-land cover maps for the study area based on ground-truth information sampling. Ten-year daily runoff data (1987–1996) from four stream stations were used to calibrate SWAT and XAJ. Daily runoff data from the same four stations were applied to validate model performance from 1997 to 2005. The results show that both SWAT and XAJ perform well in the Xixian River Basin, with percentage of bias (PBIAS) less than 15%, Nash-Sutcliffe efficiency (NSE) larger than 0.69 and coefficient of determination (R^2) larger than 0.72 for both calibration and validation

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periods at the four stream stations. Both SWAT and XAJ can reasonably simulate surface runoff and baseflow contributions. Comparison between SWAT and XAJ shows that model performances are comparable for hydrologic modeling. For the purposes of flood forecasting and runoff simulation, XAJ requires minimum input data preparation and is preferred to SWAT. The complex, processes-based SWAT can simultaneously simulate water quantity and quality and evaluate the effects of land use change and human activities, which makes it preferable for sustainable water resource management in the Xixian watershed where agricultural activities are intensive.

Keywords Hydrologic modeling · Multi-site calibration · Huaihe River · SWAT · Xinanjiang model · Water resource

1 Introduction

Xixian, situated in the upper reaches of the Huai River, is a typical agricultural county, where approximately one billion kilograms of crop yield need to be produced every year to sustain a population of more than one million people. Climate change projections and increasing population are expected to further complicate already strained water use patterns, endangering agricultural activities in Xixian Watershed. Developing sustainable water resource management is a pressing need in this area. Comprehensive watershed models are expected to be effective tools for aiding the sustainable management of land and water resources in the Xixian Watershed. The conceptual lumped-model (e.g., XAJ model) does not take land use changes into account directly and does not have functions for simulating the effect of agricultural activities on water availability. However, it is currently widely used in the Huaihe River Basin for water resources management. Therefore, research extending the XAJ model to support spatially-explicit watershed modeling needs to be conducted or a new watershed model should be adopted.

In recent years, distributed watershed models have been used increasingly to implement alternative management strategies in the areas of water resources allocation, flood control, land use and climate change impact assessments, and finally, pollution control. Many of these models share a common base in their attempt to incorporate the heterogeneity of the watershed and spatial distribution of topography, vegetation, land use, soil characteristics, rainfall and evaporation. Such models include ANSWERS (Beasley and Hyggins 1995), AGNPS (Young et al. 1987), HSPF (Johansen et al. 1984), MIKE SHE (Abbott et al. 1986) and SWAT (Arnold et al. 1996). Among these foregoing models, the physically based, distributed model SWAT is a well-established model for analyzing the impacts of land management practices on water, sediment and agricultural chemical yields in large, complex watersheds. SWAT has been used successfully by researchers around the world for distributed hydrologic modeling and water resources management in watersheds with various climate and terrain characteristics. For example, Arnold et al. (1999) reported that SWAT performed well during a monthly streamflow simulation in the Texas Gulf Basin with drainage areas ranging from 10,000 to 110,000 km^2. Zhang et al. (2008b) evaluated SWAT for snowmelt-driven runoff modeling in the 114,345 km^2 headwaters of the Yellow River in China. Debele et al. (2010) compared the performances of physically based energy budget and simpler temperature-index based snowmelt calculation approaches within the SWAT model at three sites in two different continents. Holvoet et al. (2007) evaluate the impacts of implementation of best management practices on pesticide fluxes entering surface water using SWAT. Cao et al. (2009) evaluated the impacts of land cover change on total water yields, groundwater flow, and quick flow in the Motueka River catchment by means of SWAT. Van Liew and Garbrecht (2003) showed that SWAT is capable of providing adequate hydrologic simulations related to the impact of climate variations on water resources of the Little Washita River Experimental Watershed in southwestern Oklahoma. Based on the extended SWAT model with consideration of dams and floodgates, Zhang et al. (2010) proposed a quantitative framework to assess the impact of dams and floodgates on the river flow regimes and water quality in the middle and upper reaches of Huai River Basin. The SWAT model has been incorporated into the U.S. Environmental Protection Agency's (USEPA) Better Assessment Science Integrating Point & Non-point Sources (BASINS) software package and is being applied by United States Department of Agriculture (USDA) for the Conservation Effects Assessment Project (CEAP) (Van Liew et al. 2007).

The major objectives of the study are to (1) evaluate SWAT model performance and assess the feasibility of using SWAT for hydrologic modeling in the Xixian Basin and (2) compare SWAT with XAJ to provide insight into model selection for supporting water resources management in XiXian Watershed. The remainder of this paper is organized as follows. Section 2 provides a brief description of the study area, SWAT, XAJ and model calibration and validation methods. Section 3 presents and discusses the performance of SWAT and XAJ. Finally, a summary with conclusions is provided in Section 4.

2 Methods and Materials

2.1 SWAT Model

SWAT subdivides a watershed into subbasins connected by a stream network and further delineates subbasins into Hydrologic Response Units (HRUs) consisting of unique soil and land cover combinations. SWAT allows for the simulation of a number of different physical processes in a watershed, including water movement, sediment generation and deposition, and nutrient fate and transport. Hydrologic routines within SWAT account for snowfall and melt, vadose zone processes (i.e., infiltration, evaporation, plant uptake, lateral flows and percolation) and groundwater flows. The hydrologic cycle, as simulated by SWAT, is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{lat} - Q_{gw} \right)$$

where SW_t is the final soil water content (mm water), SW_0 is the initial soil water content on day i (mm water), t is the time (days), R_{day} is the amount of precipitation on day i (mm water), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm water), Q_{lat} is lateral flow from soil to channel and Q_{gw} is the amount of return flow on day i(mm water). Surface runoff volume is estimated using a Soil Conservation Service (SCS) Curve Number (CN) method, and potential evapotranspiration was estimated using the Penman–Monteith method (Neitsch et al. 2005a, b). A kinematic storage model is used to predict lateral flow, whereas return flow is simulated by creating a shallow aquifer (Arnold et al. 1998). The Muskingum method is used for channel flood routing. Outflow from a channel is adjusted for transmission losses, evaporation, diversions and return flow.

2.2 XAJ Model

Xinanjiang (XAJ) model is a conceptual hydrologic model developed by Zhao et al. (1980) based on extensive observed data from the Xinanjiang reservoir watershed. The XAJ model has been widely used in China for flood forecasting, hydrologic station network design and water availability estimation (Zhao 1992). XAJ has been used in all major river basins in China, including the Yellow River, Yangtze River, Huaihe River, etc. XAJ divides a watershed into a set of subbasins to capture the spatial variability of precipitation and the underlying surface. Instead of further delineating each subbasin into HRUs, XAJ uses the subbasin as the basic operation unit. XAJ requires precipitation and measured pan evaporation inputs. Outflow simulation from each subbasin consists of four major parts: evapotranspiration, runoff generation, runoff separation and concentration. The water balance of XAJ is described using the following equation:

$$S_t + W_t = S_0 + W_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - Q_{lat} - Q_{gw} \right)$$

where W_t is areal mean tension water storage, which includes the storage capacities of three conceptual soil layers (i.e., upper, lower and deepest layer), and S_t is the areal mean free water storage capacity. XAJ uses the runoff formation at natural storage mechanism to calculate runoff, making it valid only in humid and semi-humid regions. The runoff-producing area is critical for calculating runoff. Runoff distribution is usually non-uniform across a region because the soil moisture deficit is heterogeneous. In order to accommodate the non-uniformity of the soil moisture deficit or the tension water capacity distribution, XAJ model adopted the storage capacity curve (Zhao et al. 1980) to calculate total runoff. Shi et al. (2008) proposed a method for calculating the water capacity from a topographic index. After calculating the total runoff, three components including surface runoff Q_{surf}, groundwater contribution Q_{gw} and contribution to lateral flow Q_{lat} are separated (Zhao 1992). By applying the Muskingum Method to successive sub-reaches (Zhao 1993), flood routing from subbasin outlets to the total basin outlet is achieved.

2.3 Study Area

The Xixian Basin covers an area of 10,191 km^2 and is located at the headwaters of Huaihe River, between 112° and 121° E latitude and 31° and 35° N longitude (Fig. 1). Xixian Watershed is dominated by mountains and hills, but some flat depressions cover a small part of the catchment. The watershed is situated in the transition zone between the northern subtropical region and the warm temperate

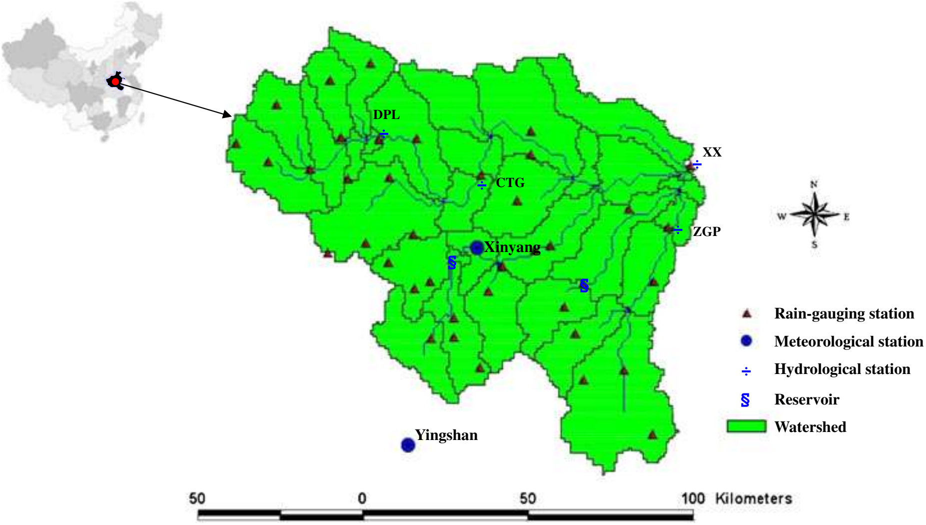


Fig. 1 Location of the Xixian Watershed and its subbasins with hydro-meteorological stations marked

zone. Mean annual precipitation is 1,145 mm and the annual average temperature is about 15.2°C. During the flood season, rainfall is affected mainly by monsoons. Therefore, most of the precipitation (~50%) falls between June and September. The highest average monthly temperature is in July, and the lowest is in January. There are seven soil types in the catchment (Fig. 2b), and the top five are as follows: Shuidaotu (56%), Huanghetu (23.87%), Huangzongrangtu (9.93%), Cugutu (5.71%) and Shizhitu (3.23%%). Major land use/land cover classes are shown in Fig. 2a, including agriculture, forest and brush cover with sesbania and honey mesquite. Agriculture is the dominant land use, the majority of which is wheat (44.11%) and rice (16.29%) production.

2.4 Input Data and Model Setup

As a physically-based, distributed parameter watershed model, SWAT requires intensive geospatial input data to drive watershed dynamics (Table 1). The major geospatial input data include, climate data, a terrain map, soil properties and a land use/land cover map. The following datasets were prepared for the Xixian Watershed study: (1) a Digital Elevation Model (DEM) with a spatial resolution of 1 km (http://srtm.datamirror.csdb.cn/), (2) a year-2000 land-use map at a scale of 1:210,000 (Table 2) provided by the government of Xinyang city, (3) a soil map at a scale of 1:100,000 in which the physical soil layer properties (including texture, bulk density, available water capacity, saturated conductivity, soil albedo and organic carbon) were collected mainly from Henan Soil Handbook and field observations, (4) daily climate data provided by from Xinyang and Yingshan weather stations (maximum and minimum air temperature, wind speed, solar radiation and relative humidity) and 67 rain gauges (precipitation).

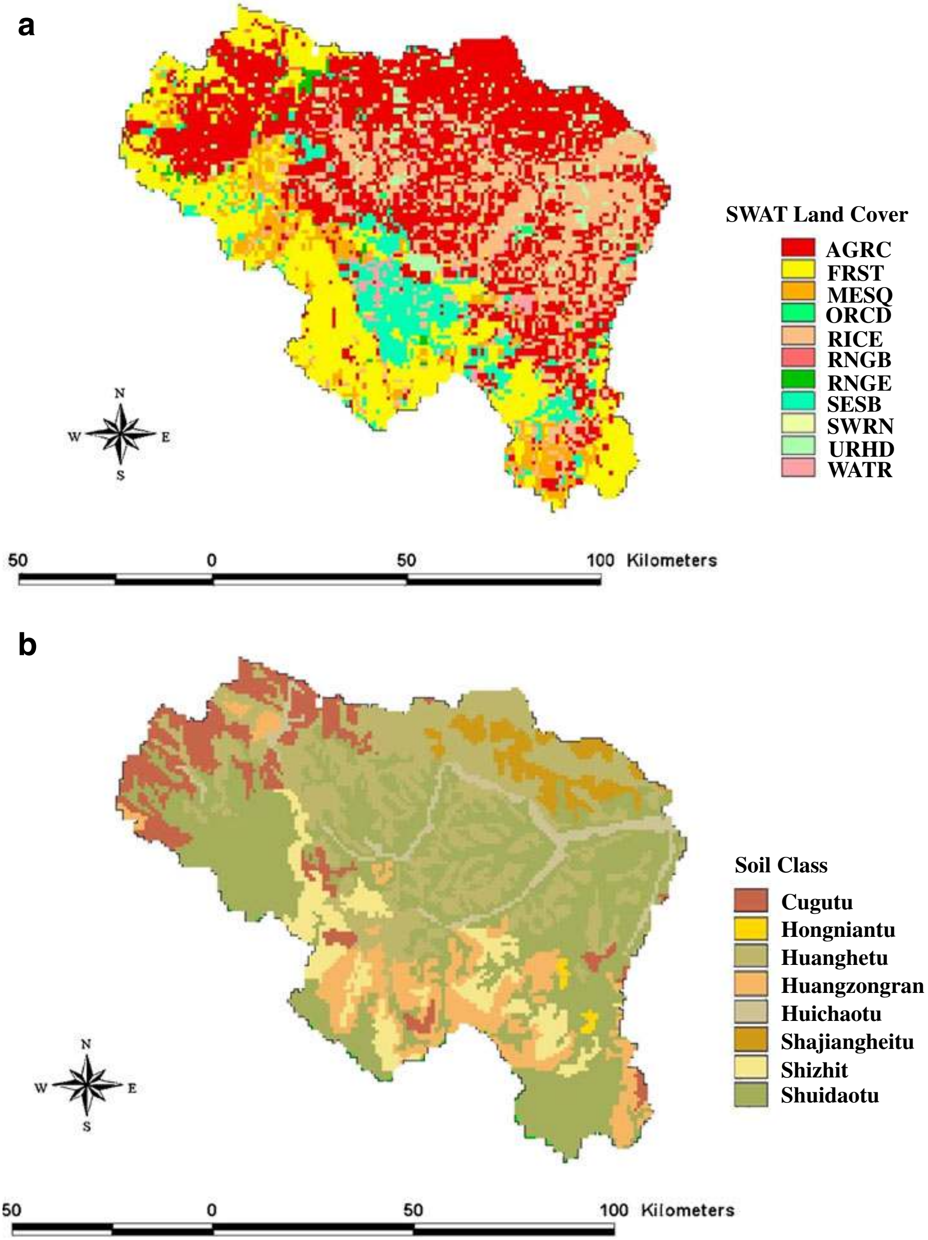


Fig. 2 **a** Land cover and **b** soil maps in Xixian Basin

In the delineation of subbasins within the Xixian Watershed, the locations of stream stations and reservoirs were considered. Nanwan Resevoir and Shishankou Resevoir) have control areas of 1,090 and 327 km^2, respectively. These two reservoirs and four stream stations, Dapoling (DPL), Changtaiguan (CTG), Zhuganpu (ZGP)

Table 1 Basic information on hydro-meteorological stations in the Xixian watershed

Type of station	Name	Latitude	Longitude	Elevation	Data series
Meteorological station	Xinyang	32.117	114.083	759	1951–2005
	Yingshan	31.617	113.767	933	1951–2005
Hydrological station	Dapoling	32.417	113.750	107	1980–2005
	Changtaiguan	32.317	114.067	72	1981–2005
	Zhuganpu	32.167	114.650	47	1988–2005
	Xixian	32.333	114.733	41	1980–2005

and Xixian (XX)), located within the watershed served as subbasin outlets. In addition, to characterize the spatial variability of the watershed, a total of 33 subbasins were delineated (Fig. 2).

2.5 Model Calibration and Validation

The period from January 1, 1986 to December 31, 1986 served as a warm-up period for the model, allowing state variables to assume realistic initial values for the calibration period. Daily runoff data from January 1, 1987 to December 31, 1996 were used for calibration, and the remaining data from January 1, 1997 to December 31, 2005 were used to validate model performance. During the periods of calibration, 1987, 1989, 1991 and 1996 were rainy years, the annual precipitation were 1,515, 1,261, 1,279 and 1,279 mm, separately; 1988 was drought year, the annual precipitation was 823 mm; and the remaining years were average years, the average annual precipitation was 1,000 mm.

In this study, we followed Santhi et al. (2001) and Moriasi et al. (2007) by using the following statistical evaluation tools: percent bias (***PBIAS***), coefficient of determination (***R***^{2}), and Nash-Sutcliffe efficiency (***NSE***). ***PBIAS*** is calculated as:

$$PBIAS = \left(\sum_{t=1}^{T} \left(Q_{s,t} - Q_{m,t} \right) \Big/ \sum_{t=1}^{T} Q_{m,t} \right) \times 100$$

Where $Q_{s,t}$ is the model simulated value at time unit t. $Q_{m,t}$ is the observed data value at time unit t, and $t = 1,2,\ldots,T$. ***PBIAS*** measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. ***PBIAS*** values with small magnitude are preferred. Positive values indicate model overestimation bias while negative values indicate underestimation (Gupta et al. 1999).

Table 2 Xixian land use classes matched with the SWAT land use classes

Land use class	Percentage of total catchment area
AGRC (Agriculture land-close-grown)	44.11
FRST (Forest-mixed)	33.66
RICE (Rice)	16.29
SESB (Sesbania)	5.27
MESQ (Honey mesquite)	0.67

The formula for calculating coefficient $\boldsymbol{R}^2$ is:

$$R^2 = \left\{ \sum_{t=1}^{T} \left(Q_{m,t} - \bar{Q}_m\right)\left(Q_{s,t} - \bar{Q}_s\right) \Bigg/ \left[\sum_{t=1}^{T} \left(Q_{m,t} - \bar{Q}_m\right)^2 \right]^{0.5} \left[\sum_{t=1}^{T} \left(Q_{s,t} - \bar{Q}_s\right)^2 \right]^{0.5} \right\}^2$$

where $\bar{Q}_m$ is mean observed data value for the entire evaluation time period, $\bar{Q}_s$ is the mean simulated data value for the entire evaluation time period. The other symbols have the same meaning defined above. $\boldsymbol{R}^2$ is equal to the square of Pearson's product-moment correlation coefficient (Legates and McCabe 1999). It represents the proportion of total variance in the observed data that can be explained by the model. $\boldsymbol{R}^2$ ranges between 0.0 and 1.0. Higher values mean better performance.

NSE is calculated as:

$$NSE = 1.0 - \sum_{t=1}^{T} \left(Q_{m,t} - Q_{s,t}\right)^2 \Bigg/ \sum_{t=1}^{T} \left(Q_{m,t} - \bar{Q}_m\right)^2$$

NSE indicates how well the plot of observed values versus simulated values fits the 1:1 line and ranges from -∞ to 1 (Nash and Sutcliffe 1970). Larger ***NSE*** values are equivalent with better model performance.

The original design objective of the SWAT model was to operate in large-scale, ungauged basins with little or no calibration efforts (Arnold et al. 1998). Several studies have demonstrated that SWAT input parameter values can be successfully estimated without calibration in a wide variety of hydrologic systems and geographic locations using readily available GIS databases that have been developed based on prior knowledge (Srinivasan et al. 1998; Arnold et al. 1999; Zhang et al. 2008a). Srinivasan et al. (2010) showed that, given appropriate input data, SWAT was able to provide a satisfactory hydrologic modeling performance in the Upper Mississippi River Basin without calibration. In contrast, previous studies (e.g., Zhang et al. 2008a, 2009, 2011) showed that calibrating SWAT using automatic methods may bias parameter values towards optimization objectives, leading to unintended performance in other hydrologic variables that are not used for calibration. Therefore, in this study, we chose a multi-site, manual calibration of SWAT parameters within a small area of the Xixian Watershed. In the XAJ model, there are 15 parameters related to runoff generation. However, determining them using field measurements is nevertheless impractical (Zhao 1992). Therefore, an optimization algorithm determined many parameter values by matching simulated and observed runoff.

2.6 Parameter Sensitivity Analysis for SWAT

A sensitivity analysis was implemented to identify sensitive parameters for model calibration. Since we adopted a manual calibration approach, the sensitivity analysis plays a critical role in reducing parameter dimension. It helped us reduce time spent in model calibrated period. The sensitivity analysis method implemented in SWAT is Latin Hypercube One-factor-At-a-Time (LH-OAT). The details of the method can be found in SWAT2005 Advanced Workshop (Griensven 2005).

The sensitivity analysis resulted in a list of parameters ranked from most to least sensitive (Table 3). Based on this ranking, we chose the nine most sensitive parameters (CH_K2, SURLAG, ALPHA_BF, CN2, CH_N, SOL_AWC, GWQMN and

Table 3 Sensitivity analysis results

Rank	1	2	3	4	5	6	7	8
Parameter	CH_K2	SURLAG	ALPHA_BF	CN2	CH_N	SMFMX	SOL_AWC	SMTMP
Rank	9	10	11	12	13	14	15	16
Parameter	GWQMN	ESCO	SLOPE	SOL_K	SLSUBBSN	TIMP	SOL_Z	CANMX
Rank	17	18	19	20	21	22	23	24
Parameter	SFTMP	SMFMN	BIOMIX	EPCO	BLAI	GW_DELAY	SOL_ALB	GW_REVAP

Table 4 SWAT flow-sensitive parameters and fitted values after calibration

Parameter	Definition	DPL	CTG	ZGP	XX
CH_K2	Effective hydraulic conductivity in main channel	1.2	1.2	1.5	1.5
SURLAG	Surface runoff lag coefficient	2	2	2	2
ALPHA_BF	Baseflow alpha factor	0.55	0.45	0.6	0.6
CN2	Curve number	14%	9%	5%	5%
CH_N	Manning's "n" value	0.035	0.035	0.035	0.035
SOL_AWC	Available water capacity	−0.1	−0.1	−0.1	−0.1
GWQMN	Threshold depth of water for return flow	100	100	100	100
ESCO	Soil evaporation compensation factor	0.65	0.8	0.9	0.9

ESCO) within the Xixian Watershed and then adjusted these parameters manually. Table 3 shows that two parameters, SMFMX and SMTMP, are more sensitive than GWQMN and ESCO, but these two parameters represent snowmelt. Due to high temperatures, snowfall and snowmelt are not important hydrologic components in our research, so we ignored these two parameters. Sensitive parameters and post-calibration fitted values are listed in Table 4.

3 Results and Discussion

3.1 Mean Annual Streamflow

Average annual streamflow simulated by SWAT and XAJ is listed in Table 5. The relative, simulated mean annual runoff errors of both XAJ and SWAT were less than 15% at all four monitoring stations for both calibration and validation periods. The difference between observed and simulated annual runoff volumes for XAJ ranged from −1.4% (station ZGP) to 12.1% (station DPL) for the validation period. For SWAT, the relative error in the annual runoff volumes ranged from 2.3% (station CTG) to −12.3% (station DPL) for the validation period. The accuracy of both models was similar for the calibration and validation periods. In general, both SWAT and XAJ can capture long-term runoff yield in the Xixian watershed.

Table 5 Observed and simulated annual runoff volumes in the Xixian Watershed

Subwatershed	Annual runoff volume (mm year^{-1})			Relative error (%)	
	Observed	SWAT	XAJ	SWAT	XAJ
Calibration period					
DPL	492	446	520	−9.3	5.7
CTG	430	467	440	8.6	2.3
ZGP	438	450	453	2.7	3.4
XX	320	322	338	0.6	5.6
Validation period					
DPL	446	391	500	−12.3	12.1
CTG	384	393	373	2.3	−2.9
ZGP	495	481	488	−2.8	−1.4
XX	345	323	350	−6.4	1.4

3.2 Daily Streamflow

Figures 3 and 4 show SWAT-simulated time series of measured and simulated daily flow for all four river gauging stations during calibration and validation periods. Both figures show that the observed and simulated flow discharge follows area rainfall patterns. For example, higher discharge occurs between June and September, corresponding to the rainy season. Above 80% of annual flow occurs during this period.

Table 6 summarizes statistical performance measures for daily runoff volumes. Previous studies (Moriasi et al. 2007; Santhi et al. 2001) suggested that model simulation be judged as satisfactory if R^2 is greater than 0.6 and *NSE* is greater

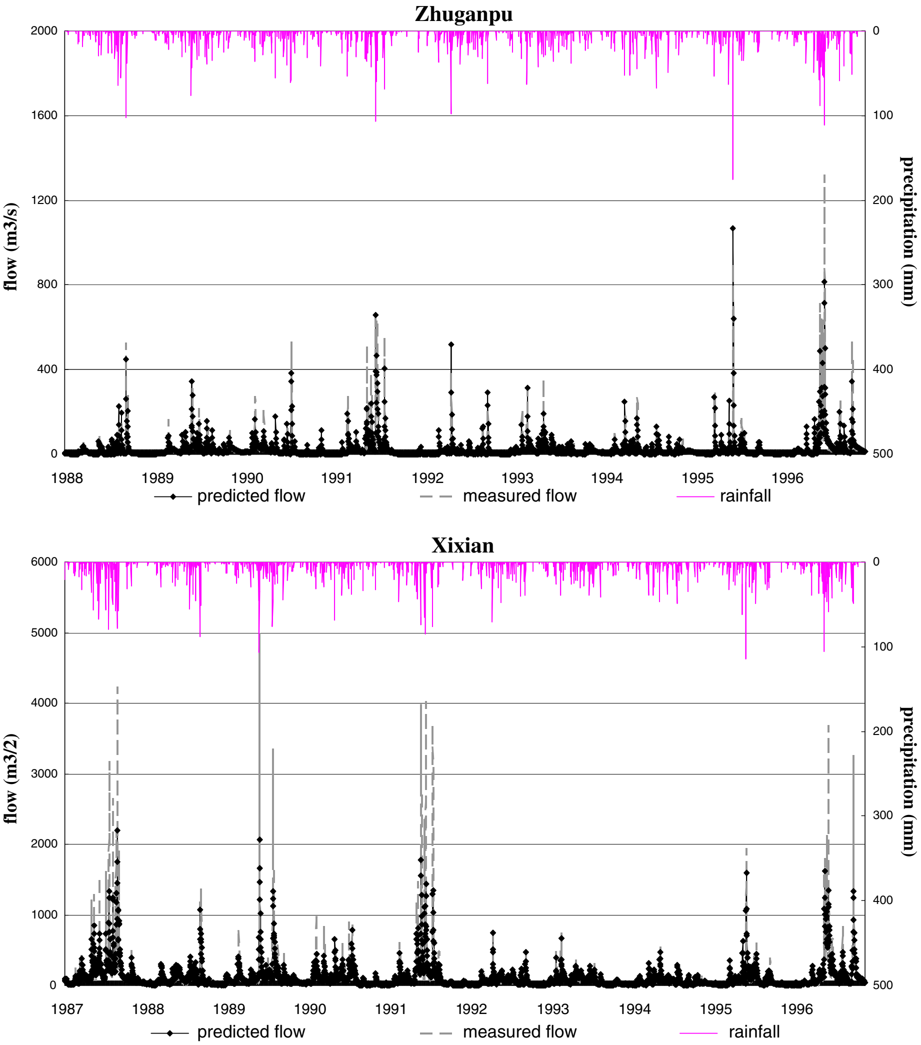


Fig. 3 Calibration of streamflow at four gauging stations

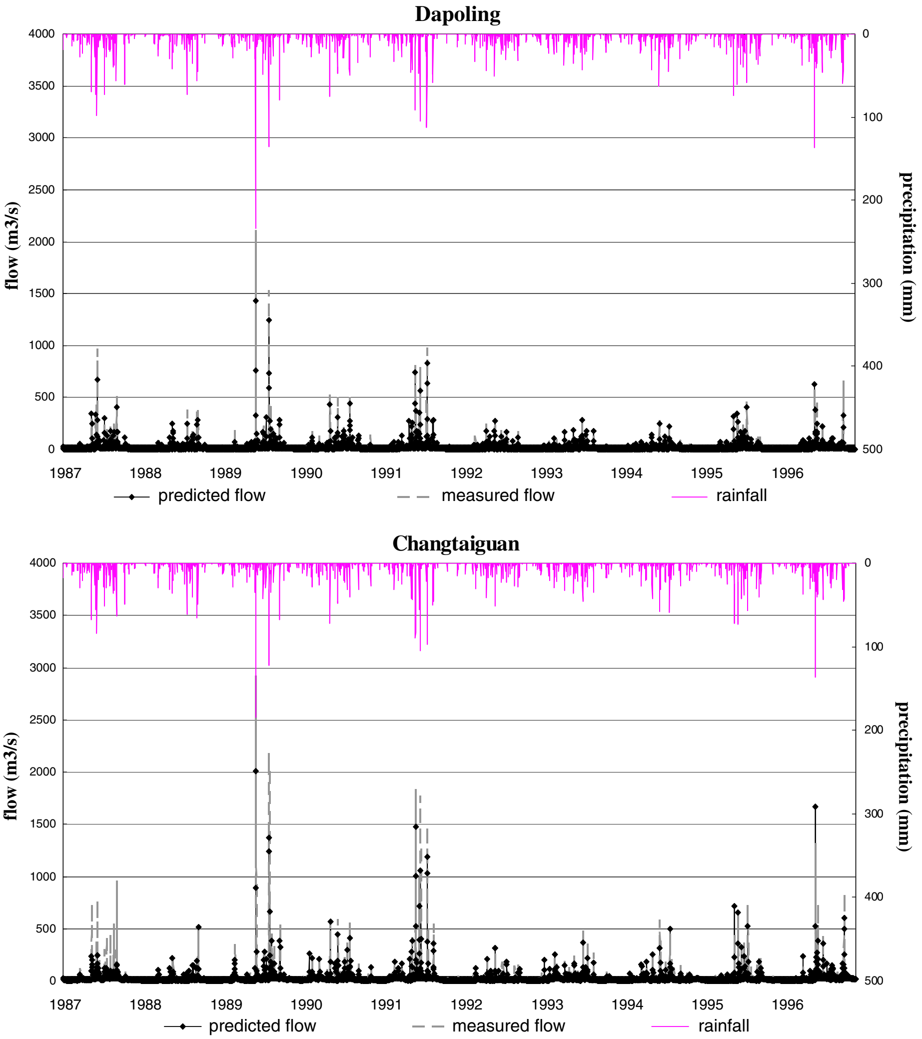
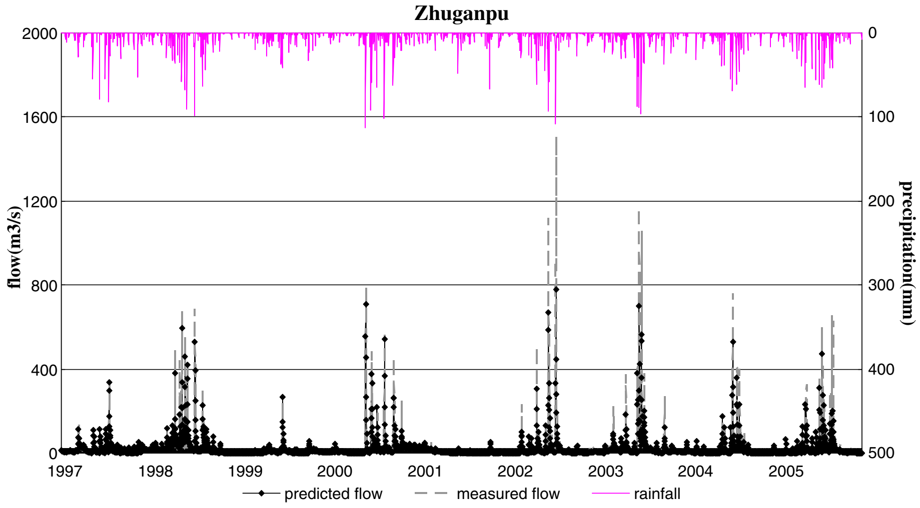


Fig. 3 (continued)

than 0.5. Comparisons between observed and simulated runoff values agreed well, indicating that both SWAT and XAJ models represented observed runoff well at the four gauging stations, DPL, CTG, ZGP and XX. For the calibration period, R^2 and *NSE* values obtained from XAJ at the four stations ranged from 0.77 to 0.87 and 0.72 to 0.85, respectively. R^2 and *NSE* values obtained from SWAT were very similar, ranging from 0.77 to 0.87 and 0.75 to 0.85, respectively. For the validation period, R^2 and *NSE* values obtained from XAJ at the four stations ranged from 0.72 to 0.87 and 0.70 to 0.86, respectively. Finally, R^2 and *NSE* values obtained from SWAT ranged from 0.73 to 0.86 and 0.69 to 0.82, respectively. After the calibration of several parameters, both SWAT and XAJ models captured the study area's hydrologic characteristics well and reproduced acceptable daily runoff simulations.



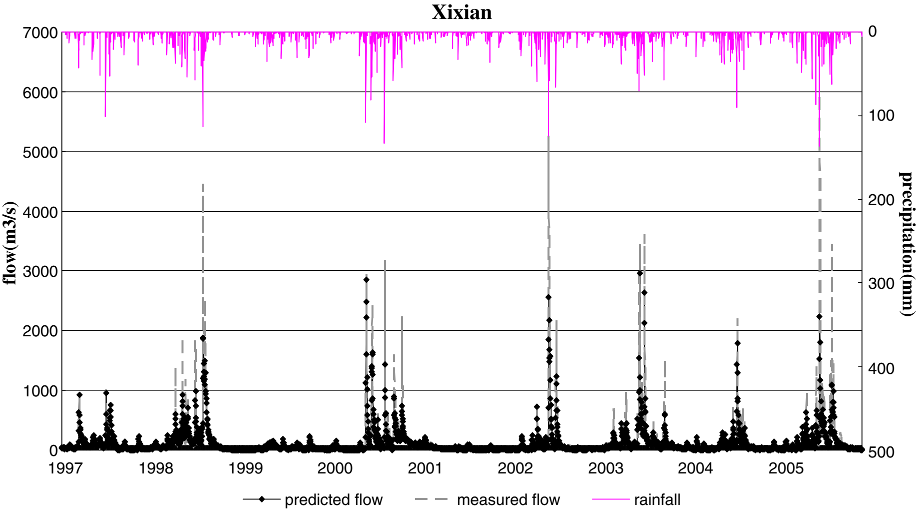
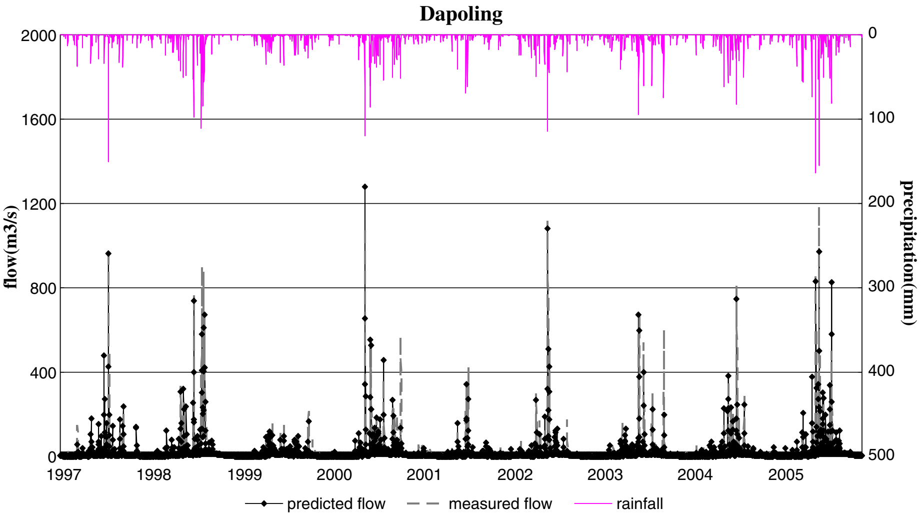


Fig. 4 Validation of streamflow at four gauging stations

3.3 Runoff Components Simulated by SWAT and XAJ

A reasonable representation of different runoff components is critical for capturing the hydrologic cycle. To separate baseflow from total runoff, we used the digital baseflow filter (Arnold and Allen 1999), a program that has performed well in comparisons with measured field estimates in multiple watersheds. The results show that baseflow contributes about 48–49% of the streamflow. Table 7 shows Xixian Watershed runoff components simulated by both SWAT and XAJ. For the XAJ model, surface runoff contributes 52% and 47% to the water yield during the calibration and validation period respectively. Groundwater contributes 48% and 53% to the water yield during calibration and validation periods, respectively. For the



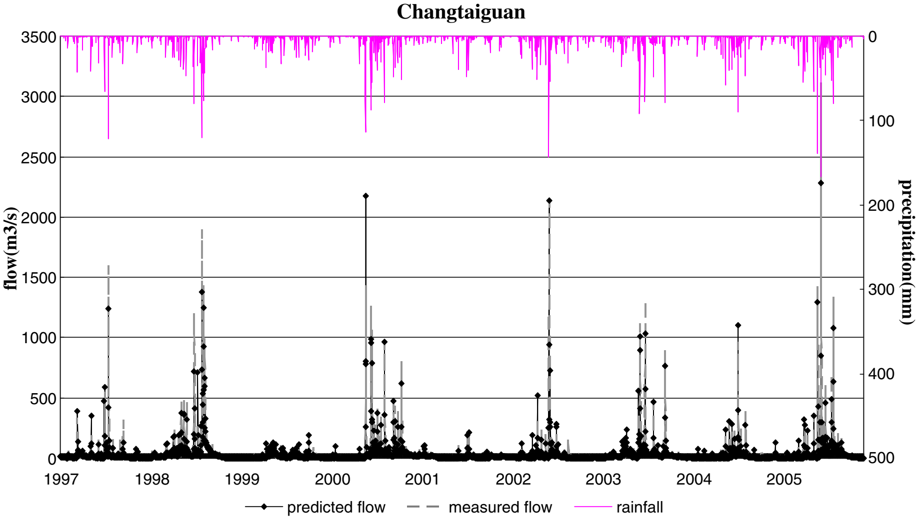


Fig. 4 (continued)

SWAT model, results indicate that surface runoff contributions during calibration and validation periods are 53% and 56%, respectively, and groundwater contributes 47% and 44% to the water yield for calibration and validation periods, respectively. Overall, both SWAT and XAJ provide reasonable surface runoff and baseflow contributions, indicating their ability to represent the hydrologic cycle well.

3.4 Comparison of Model Structure and Functions in SWAT and XAJ

As indicated in previous sections, SWAT and XAJ perform similarly in runoff simulations. In order to provide insight into the suitability of each model for

Table 6 Statistical comparison of observed and simulated daily runoff for the Xixian Watershed

Subwatershed	PBIAS (%)		R^2		NSE	
	XAJ	SWAT	XAJ	SWAT	XAJ	SWAT
Calibration period						
DPL	5.53	−9.32	0.87	0.84	0.85	0.84
CTG	2.46	−14.8	0.86	0.87	0.79	0.85
ZGP	5.04	−1.30	0.77	0.81	0.73	0.79
XX	5.58	1.75	0.78	0.77	0.72	0.75
Validation period						
DPL	8.2	−12.3	0.87	0.82	0.86	0.82
CTG	−2.93	−3.9	0.74	0.86	0.72	0.79
ZGP	−1.52	−13.0	0.76	0.78	0.71	0.76
XX	1.31	−6.41	0.72	0.73	0.70	0.69

sustainable water resource management in the Xixian Watershed, Table 8 provides a comprehensive comparison of the models' characteristics.

Concerning model structure, XAJ is a traditional, conceptual, lumped hydrologic model with simple structure. In contrast, SWAT is a distributed hydrologic model with a relatively complicated process-based model structure. Both of these two models are widely used. XAJ is typically used for forecasting flood and runoff over a catchment scale. On the other hand, SWAT divides a watershed into multiple subbasins, which are then further subdivided into HRUs to represent the heterogeneity of land use, management and soil characteristics. In XAJ, the catchment was represented as homogeneous. Human activities (e.g., urban, reservoir, agricultural activity, etc.) cannot be reflected directly in XAJ. To some extent, this limitation restricts the application domain of XAJ to water quantity modeling only. Many human activities (e.g., industry discharge and fertilizer application on crop land) impact water quality and can be directly input and simulated in the SWAT model.

It is also worth noting that, in order to successfully apply these two models, input data preparation efforts are substantially different. The input data required by XAJ is relatively simple, including only areal mean precipitation and measured pan evaporation. However, intensive data collection and processing work are required to run the SWAT model. DEM, land use, soil type and human activity data must be provided. Although SWAT's GIS interface can reduce data preparation efforts, it takes much longer to run SWAT than XAJ. Therefore, for flood forecasting and runoff simulation, XAJ is a preferred tool. In order to maintain water sustain-

Table 7 Annual water balance components for calibration and validation periods in the Xixian Basin (mm)

Period	Model	Surface flow	Ground flow	Total flow	Baseflow ratio	Baseflow separation
Calibration	XAJ	176	162	338	0.48	0.48
	SWAT	172	150	322	0.47	
Validation	XAJ	163	187	350	0.53	0.49
	SWAT	182	141	323	0.44	

Table 8 Comparison of SWAT and XAJ

	SWAT	XAJ
Model Structure	Processed-based	Conceptual
Spatial scale	HRU within subbasin	Subbasin
Temporal scale	Hourly and daily	Hourly an daily
Input data requirements	Intensive data collection on climate, soil, topography, land use, vegetation, hydrologic structures and human activities.	Climate inputs and topography
Extendibility for water quality modeling	Includes sediment, nitrogen, phosphorus, bacteria, heavy metals,and pesticides	No water quality modeling functions
Interface	User friendly GIS interface for preprocessing and preprocessing	No GIS interface available

ability, two inherent two dimensions—quantity and quality—should be emphasized simultaneously. SWAT's strong point is that it can simultaneously simulate water quantity and quality and evaluate the impacts of human activities on sustainable water resource management in the Xixian Watershed.

4 Conclusion

This research compared the runoff simulation performance of two widely used hydrologic models in the Xixian Watershed, located in the upper reaches of the Huaihe River Basin. The results show that SWAT and XAJ perform equally and both can simulate daily runoff satisfactorily. Comparing simulated and observed daily flow at four monitoring stations, both models produced R^2 and NSE values larger than 0.69 and PBIAS values lower than 15% for both calibration and validation periods. These two models can also simulate runoff components well in comparison to the results from the baseflow filter.

The XAJ model is easy to use with minimum input data preparation. In order to run SWAT, many data-preparation effors must be made. For the purposes of flood forecasting and runoff simulation, XAJ is preferred. However, the complex, processes-based SWAT model can simultaneously simulate water quantity and quality and evaluate the impacts of land use changes and human activities. This makes SWAT a better tool for sustainable water resources management in the Xixian Watershed, where agricultural activities are intensive.

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References

Abbott MB, Bathurst JC, Cunge JA, O'Connell PE, Rasmussen J (1986) An introduction to the European hydrological system-systeme hydrologique European 'SHE'. 1: history and philosophy of a physically based distributed modeling system. J Hydrol 87:45–59

Arnold JG, Allen PM (1999) Automated methods for estimating baseflow and ground water recharge from streamflow records. J Am Water Resour Assoc 35(2):411–424

Arnold JG, Williams JR, Srinivasan R, King KW (1996) In soil and water assessment tool, user's manual. USDA, Agriculture Research Service, Grassland, Soil and Water Research Laboratory, Temple

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development. J Am Water Resour Assoc 34(1):73–89

Arnold JG, Srinivasan R, Ramanarayanan TS, DiLuzio M (1999) Water resources of the Texas Gulf Basin. Water Sci Technol 39(3):121–133

Beasley DB, Hyggins LF (1995) ANSWERS-User's Manual. U.S. Environmental Protection Agency, Chicago, EPA-905/9-82-001, p54

Cao W, Bowden WB, Davie T, Fenemor A (2009) Modelling impacts of land cover change on critical water resources in the Motueka River catchment, New Zealand. Water Resour Manag 23:137–151

Debele B, Srinivasan R, Gosain AK (2010) Comparsion of Process-Based and Temperature-Index Snowmelt Modeling in SWAT. Water Resour Manag 24:1065–1088

Griensven AV (2005) AVSWAT-X SWAT-2005 Advanced Workshop. In: SWAT 2005 3rd International Conference, Zurich, Switzerland

Gupta HV, Sorooshian S, Yapo PO (1999) Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. J Hydrol Eng 4(2):135–143

Holvoet K, Gevaert V, Griensver AV, Seuntjens P, Vanrolleghem PA (2007) Modelling the effectiveness of agricultural measures to reduce the amount of pesticides entering surface waters. Water Resour Manag 21:2027–2035

Johansen NB, Imhoff JC, Kittle JL, Donigian AS (1984) Hydrological Simulation Program-Fortran (HSPF): User's Manual for Release 8. US Environmental Protection Agency, Athens, EPA-600/3-84-066

Legates DR, McCabe GJ (1999) Evaluating the use of "goodness of fit" measures in hydrologic and hydroclimatic model validation. Water Resour Res 35(1):233–241

Moriasi DN, Arnold JG, Van Liew MU, Binger RL, Harmel RD, Veith T (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE 50(3):885–900

Nash JE, Sutcliffe JC (1970) River flow forecasting through conceptual models. Part I—A discussion of principles. J Hydrol 10:282–290

Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2005a) SWAT theoretical documentation version 2005. Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Temple

Neitsch SL, Arnold JG, Kiniry JR, Williams JR (2005b) SWAT input/output file documentation version 2005. Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Temple

Santhi C, Arnold JG, Williams JR, Dugas WA, Srinivasn R, Hauck LM (2001) Validation of the SWAT model on a large river basin with point and nonpoint sources. J Am Water Resour Assoc 37(5):1169–1188

Shi P, Rui X, Qu S (2008) Calculating storage capacity with topographic index. Advances in Water Sci 19(2):264–267 (in Chinese)

Srinivasan R, Ramanarayanan TS, Arnold JG, Bednarz ST (1998) Large area hydrologic modeling and assessment part II: model application. J Am Water Resour Assoc 34(1):91–101

Srinivasan R, Zhang X, Arnold JG (2010) SWAT Ungauged: hydrologic and Biofuel Crops Prediction in the Upper Mississippi River Basin. Trans ASABE 53(5):1533–1546

Van Liew MW, Garbrecht JD (2003) Hydrologic simulation of the Little Washita River Experiment Watershed using SWAT. J Am Water Resour Assoc 39(2):413–426

Van Liew MW, Veith TL, Bosch DD, Arnold JG (2007) Suitability of SWAT for the conservation effects assessment project: comparison on USDA agricultural research service Watersheds. J Hydrol Eng 12(2):173–189

Young RA, Onstad CA, Bosch DD, Anderson WP (1987) AGNPS: an agricultural nonpoint source pollution model: a large watershed analysis tool. Conservation Research Report 35. US Department of Agriculture, Washington, DC, p77

Zhang X, Srinivasan R, Debele B, Hao F (2008a) Runoff Simulation of the Headwaters of the Yellow River Using the Swat Model with Three Snowmelt Algorithms. J Am Water Resour Assoc 44(1):48–61

Zhang X, Srinivasan R, Van Liew M (2008b) Multi-Site Calibration of the SWAT Model for Hydrologic Modeling. Trans ASABE 51(6):2039–2049

Zhang X, Srinivasan R, Bosch D (2009) Calibration and uncertainty analysis of the SWAT model using Genetic Algorithms and Bayesian Model Averaging. J Hydrol 374(3–4):307–317

Zhang Y, Jun X, Tao L, Quanxi S (2010) Impact of water projects on river flow regimes and water quality in Huai River basin. Water Resour Manag 24:889–908

Zhang X, Srinivasan R, Arnold J, Izaurralde RC, Bosch D (2011) Simultaneous calibration of surface flow and baseflow simulations: a revisit of the SWAT model calibration framework. Hydrol Process 25. doi:10.1002/hyp.8058

Zhao RJ (1992) Xinanjiang model applied in China. J Hydrol 135(2):371–381

Zhao RJ, Zuang Y, Fang L, Liu X, Zhang Q (1980) The Xinanjiang Model. IAHS AISH Publ 129:351–356

Zhao RJ (1993) A non-linear system for basin concentration. J Hydrol 142(7):477–482