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Comprehensive hydrologic calibration of SWAT and water balance analysis in mountainous watersheds in northwest China

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ABSTRACT

Model calibration is important for streamflow simulations using distributed hydrological models, especially in highland and cold areas of northwest China with scarce data. Quantitative analysis of water balance based on the accurate simulation is also essential for reasonably planning and managing water resources in these river basins facing a severe water shortage. In this study, a comprehensive method was proposed to calibrate the Soil and Water Assessment Tool (SWAT) model in the Yingluoxia watershed, upstream area of the Heihe River basin; it was based on multi-temporal, multi-variable and multi-site integrated drainage characteristics. Meanwhile a fresh approach of the parameter transferability and model validation was used by applying the set of calibrated parameters in its tributary to other area of the watershed. The results indicated that the method was effective and feasible; the values of Nash–Sutcliffe Efficiency (*NSE*) and Coefficient of Determination (r^2) were greater than 0.81 and as high as 0.94 and the absolute values of the Percent Bias (*PBIAS*) were less than 2. Based the output of model the water balance in the Yingluoxia watershed was analyzed, that the mean annual precipitation, evapotranspiration, and discharge of the watershed from 1990 to 2000 were 491.8 mm, 334 mm, and 157.8 mm, respectively. The comprehensive calibration method based on multi-temporal, multi-variable and multi-site integrated drainage characteristics can better portray the hydrological processes of watershed and improve the model simulation; and the output of the model then provide a reliable reference for assessing and managing water resource of the watershed.

1. Introduction

In inland river basins in arid regions of northwest China, runoffs from mountainous watersheds are the main water source and play a key role in keeping ecosystems proper functionality. Therefore, accurate flow discharge in mountainous watershed simulations are very important for the prediction, planning and management of water resources, and very critical for the sustainable development of water resources in mid- and downstream regions where the precipitation is very rare (Kang et al., 1999; Yu et al., 2011). However, many inland rivers in northwest China are either ungauged or poorly gauged because of their extremely complex terrains, special climate and lack of technical and financial support. These conditions often limit the application of hydrological techniques and models, which ultimately hinders nation-wide water resources development and management studies.

In particular, physically based distributed hydrological models, whose input parameters have a physical interpretation and explicit representation of spatial variability, are used to solve complex problems in water resource management (Beven, 1989, 2002; Sorooshian and Gupta, 1995). Initial parameters for distributed datasets describing soils, vegetation, and landuse; however, these so-called physically based parameter values are often adjusted through subsequent calibration to improve streamflow simulations. In other words, some model parameters are physically based and can be measured while in some models parameters can only be estimated by calibration (Beven and Binley, 1992; Duan et al., 1992, 1994; Yapo et al., 1996; Refsgaard, 1997; Gupta et al., 1998; Boyle et al., 2000; Beven and Freer, 2001; Anderton et al., 2002; Beven, 2006).

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As a physically based hydrologic model, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) has been applied to water resources management and assessment worldwide, including arid regions of northwest China (Wang et al., 2003; Huang and Zhang, 2004, 2010; Gassman et al., 2007; Li et al., 2009, 2010, 2011; Liu et al., 2012). However, the SWAT was designed based on the soil, vegetation, and hydrological structure of the North American; the databases about soil and vegetation this model comes with are different from the actual situation in somewhere else. In order to efficiently and effectively apply the SWAT model, different calibration methods have been developed and applied to improve the prediction reliability of the SWAT simulations, including manual and automated calibration (Eckhardt and Arnold, 2001; White and Chaubey, 2005; Cao et al., 2006; Bekele and Nicklow, 2007; Kannan et al., 2008; Zhang et al., 2008, 2009a, 2009b, 2010; Lu et al., 2012; Niraula et al., 2012). For example, Zhang et al. (2009a) proposed a combined method, which implemented Genetic Algorithms (GA) and Bayesian Model Averaging (BMA), to conduct calibration by comparing multiple model structures. Niraula et al. (2012) modelled surface water flow in semi-arid watersheds and evaluated the effect of multi-gauge calibration on flow predictions. Undoubtedly, compared to automated calibration, manual calibration of a distributed parameter model is a very time consuming effort. But for the modellers who are familiar with the model and the watershed, manual calibration is a good approach when the model is applied in a complex watershed with scarce data. In addition the parameter transferability, which is very important for Predictions for Ungauged Basins (PUBs) and for application in land surface parameterization schemes (Duan et al., 2006), is a calibration method too.

With population growth and economic development, water scarcity and demand for various purposes especially agriculture and consequently food production is increasingly becoming a crisis that constraints regional sustainable development (Montesinos et al., 2011; Song et al., 2011). The greater emphasis is given to the planning and managing of the most favorable utilization of water resources. Water loss and/or gain in a watershed system are important components of water balance for planning and operation. Therefore, understanding the water balance is very important for studies on the operational management of reservoirs and river basins. Moreover, water balance studies provide an evaluation of an unknown water balance component from the difference between the known components (Dor et al., 2011).

The Heihe River basin, the second largest inland river basin in China, has attracted more attention in China because of its increasing eco-environmental problems. In recent years, hydrological models have been increasingly used by hydrologists and water resources managers to understand watershed systems and hydrological process, including SWAT (Wang et al., 2003; Huang and Zhang, 2004, 2010; Li et al., 2009, 2010, 2011; Liu et al., 2012). In the previous studies that used SWAT in the Heihe River basin, all of them calibrated the model based on streamflow at watershed outlet (Yingluoxia gauge), and did not describe the calibration process in detail. However, it is recognized that an alternative approach that uses interior point data in calibration may help to improve simulations at basin outlet (Andersen et al., 2001). Meanwhile, other information about precipitation, temperature, snowmelt, and baseflow is helpful for model calibration. It is more regrettable that there is not any study on the water balance of Yingluoxia watershed because of scarce data and complex terrain and land cover. The overall objective of this study is to analyze the water balance of Yingluoxia watershed based on the accurate simulation through a comprehensive calibration. The specific objective are: (1) to propose a comprehensive method to calibrate the SWAT model; (2) to examine the adaptability of the parameter transferability in mountainous area with scarce data, and (3) to analyze the water balance of watershed based on the model simulation.

2. Methods

2.1. Case study area

The Heihe River basin geographically includes the Qilian Mountains, the middle Hexi Corridor and the northern Alxa highplain from south to north. The Yingluoxia watershed at the upper reaches of the Heihe River basin was selected as the study area in this investigation (Fig. 1). It covers an area of 10,009 km^2, with the elevation ranging from 1637 m to 5062 m above sea level (ASL) and the mean elevation of 3737 m ASL. The watershed's topography is mountainous and contains river valleys. It includes the east branch (Babaohe River) and west branch (Yeniugou River) and is the main region for streamflow generation in the entire Heihe River basin.

The climate is characterized as an inland region with cold and dry winters and hot and arid summers, with large spatial and temporal variability. The annual precipitation is more than 200 mm in regions above 2000 m in elevation and increases by 10.9–15.9 mm for every 100 m increase in elevation. More than 80% of the total precipitation occurs from May to September. The annual average air temperature has been lower than 2 °C in the entire watershed. Meteorological stations record the highest air temperatures in July and the lowest air temperatures in January.

The annual mean runoff was about 160 mm, with weak interannual variability because of the contribution of the glaciers and snow and frozen earth meltwater to the discharge (Zhang et al., 2011; Yang, 2011). The dominant vegetation types are meadow, grassland and brush land, occupying nearly 58%, 15% and 11% of the total area, respectively. The main soil types in the watershed include felty soil (40%), dark felty soil (21%), chestnut soil (13%) and alpine frost soil (9%).

2.2. Model and data

The SWAT model was used to simulate the hydrologic processes of Yingluoxia watershed. The model uses readily available inputs, is computationally efficient for use in large watersheds and is capable of simulating long-term yields for determining the impact of land management practices (Arnold and Allen, 1996). SWAT allows a number of different physical processes to be simulated in a basin. The hydrologic routines within SWAT account for snow fall and melt, vadose zone processes (e.g., infiltration, evaporation, plant uptake, lateral flows, and percolation) and ground water flows.

The hydrologic cycle that is simulated by SWAT is based on the water balance equation:

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

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), 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 H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

The data used for model building and calibration can be classified into two types: statistical data and spatial data. The statistical data included daily precipitation data, daily maximum and minimum air temperature, relative humidity, and wind speed at the Qilianxian, Yeniugou, Tuole, and Zhangye stations, in addition to discharge at the Zhamashike, Qilianshan and Yingluoxia gauges

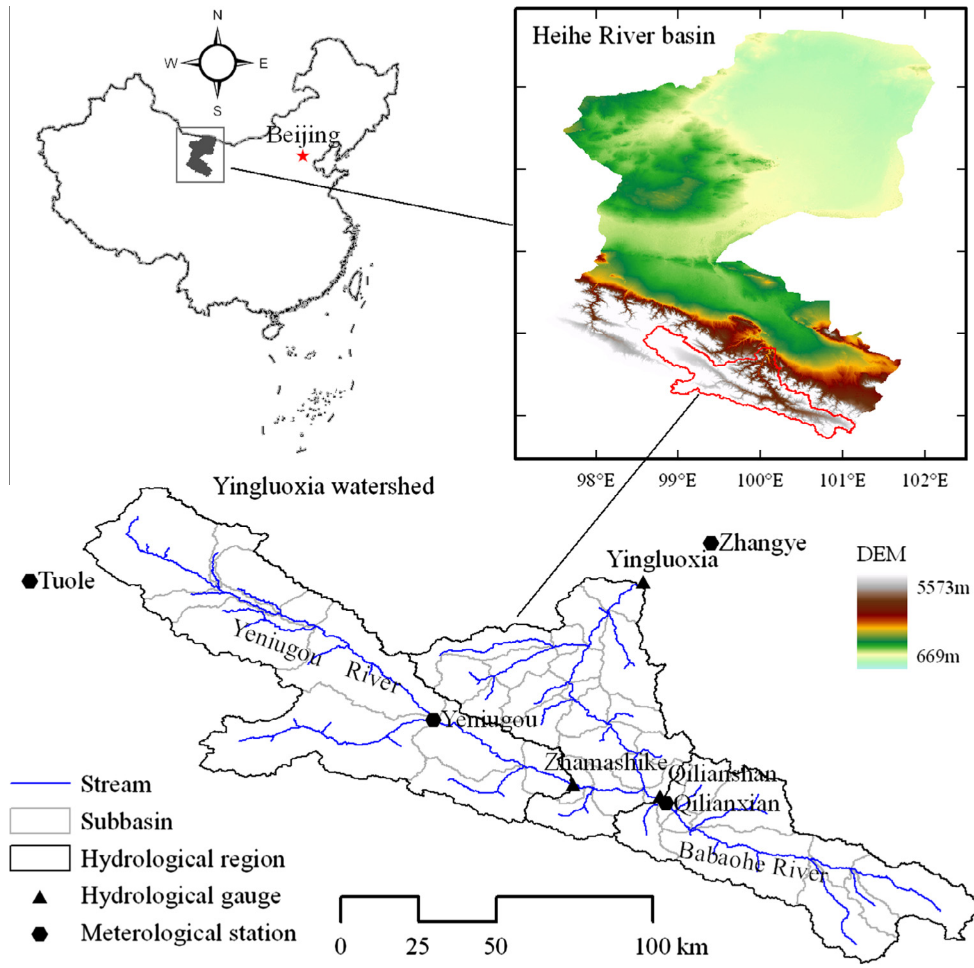

Fig. 1. The location of the Yingluoxia watershed and the hydro-meteorological stations.

(Table 1). The spatial data included a map of vegetation, digital elevation model (DEM) and soil map (Table 2). All data were obtained from the China Administration of Meteorology, the Environmental & Ecological Science Data Center for West China (http://westdc.westgis.ac.cn), Digital River Basin and the Hydrographic Service of Gansu province. Moreover, the values of various attributes of landuse and soil were obtained from many materials, including books, documents and network.

3. Application of SWAT model

3.1. Watershed delineation

The DEM was used to generate flow direction and flow paths in a Geographic Information System (GIS). The watershed outlet was defined at the Yingluoxia gauge, which is located on the mainstream and controls the runoff from the mountainous watershed. Considering that the hydrologic response units (HRUs) were often spatially discontinuous and the values of the surface runoff lag time were identical to a subbasin in the SWAT model, the areas of the subbasins were as small as theoretically possible. A 100 km^2 threshold of accumulative area was used to define the origin of a stream. In addition, two outlets were added based on the Qilianshan gauge and Zhamashike gauge, which controlled Babaohe River catchment and Yeniugou River catchment, respectively. This watershed was divided into 3 hydrological regions and 43 subbasins (Fig. 1).

In the Yingluoxia watershed, the landuse types were divided into 14 categories based on the dominant species and constructive species and the soil was categorized into 24 types. The vegetation,

Table 1
Basic information of the hydro-meteorological stations in the Yinluoxia watershed.

Station	Latitude	Longitude	Elevation (m ASL)	Annual precipitation[a] (mm)			Annual temperature[a] (°C)			Annual discharge[a] (10^8 m^3)		
				Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Yeniugou	38°25′	99°35′	3320	321	602	425	−3.55	−1.44	−2.56	–	–	–
Tuole	38°49′	98°25′	3367	181	404	304	−3.04	−1.05	−2.08	–	–	–
Zhangye	38°56′	100°23′	1487	72	216	130	6.91	9.10	7.89	–	–	–
Qilianxian	38°11′	100°15′	2787	349	573	417	0.59	2.28	1.44	–	–	–
Qilianshan	38°12′	100°14′	2590	–	–	–	–	–	–	4.0	6.9	4.9
Zhamashike	38°14′	99°59′	2635	–	–	–	–	–	–	6.1	10.34	7.47
Yingluoxia	38°49′	100°11′	1674	–	–	–	–	–	–	11.4	23.12	16.7

[a] The annual precipitation, annual temperature and annual discharge are calculated from the period of 1985 to 2009.

Table 2
Geographical data used for the model setup.

Data	Parameters/extracted parameters	Description
DEM	Slope, aspect, drainage network, flow direction, ...	30 m × 30 m resolution
Vegetation map	Blai, Chtmx, Rdmx, T_opt, T_base, Cn2, Ov_n, ...	1:1000,000 scale
Soil map	Hydgrp, Sol_Zmx, Sol_Z, Sol_Bd, Sol_Awc, Sol_K, ...	1:1000,000 scale

soil and slope layers were overlaid to create hydrologic response units (HRUs) within each subbasin. A total of 2566 HRUs were created in the Yingluoxia watershed. Because the elevation span of some subbasins was large, many elevation bands were defined to account for orographic effects on both precipitation and temperature.

3.2. Selection of model structures

In practical application of hydrologic models, modelers often select a single model among the several choices that are assumed to best represent the hydrologic system (Zhang et al., 2009a). Therefore, before calibrating the water balance and streamflow, we need to have a profound understanding of the actual watershed characteristics and the information provided in previous SWAT literature (Neitsch et al., 2005).

Evapotranspiration is the primary mechanism by which water is removed from the Yingluoxia watershed. Three options are available for evapotranspiration estimation in SWAT and the Hargreaves method was selected, which was originally derived from eight years of cool-season Alta fescue grass lysimeter data from Davis, California (Neitsch et al., 2005); and its reference crop is similar to meadow and grassland which are the dominant landuse types in this watershed. Moreover this method requires least parameters. Snow processes were significant for the Yingluoxia watershed, and the snow routing method used in this study was the degree day "DD". The surface runoff volume was estimated using a modified version of the Soil Conservation Service (SCS) Curve Number (CN) method with a simple structure and few parameters (Neitsch et al., 2005). The CN is the only undetermined parameter and depends on the soil hydrological group, landuse type and previous soil water content. A kinematic storage model was used to predict lateral flow, and return flow was simulated by creating a shallow aquifer (Arnold et al., 1998). The Variable Storage was used for channel flood routing. Outflow from a channel was adjusted for transmission losses, evaporation, diversions, and return flow (Arnold et al., 1998). In some options, the methodology used in previous literature on model structures selection was followed (Wang et al., 2003; Huang and Zhang, 2004, 2010).

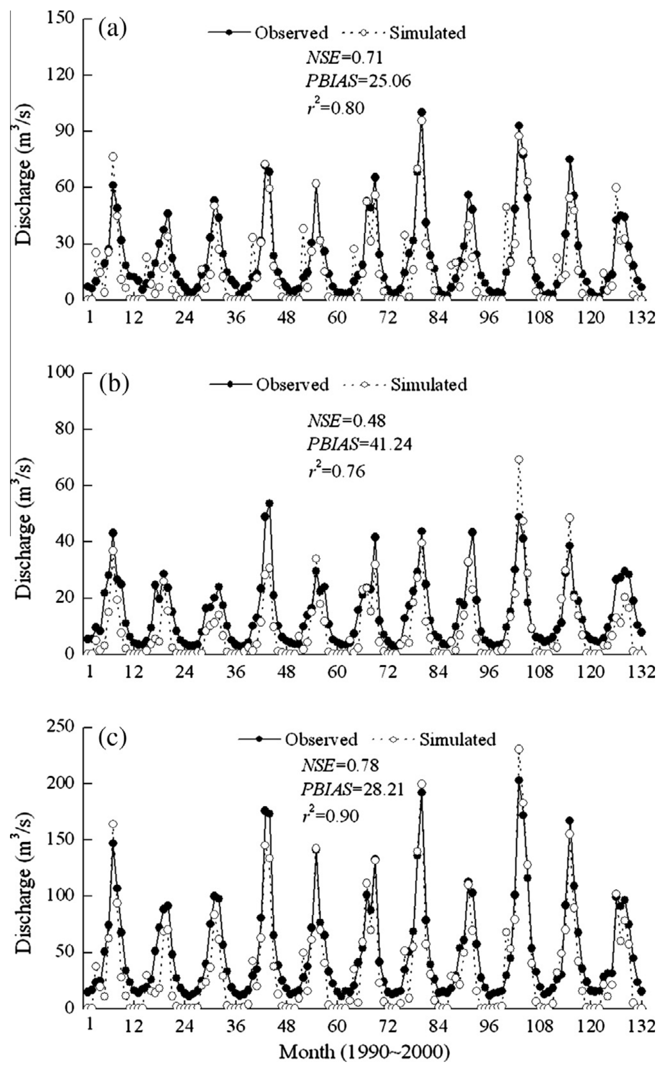

Fig. 2. The monthly observed and simulated discharge without calibration ((a) Zhamashike gauge; (b) Qilianshan gauge; (c) Yingluoxia gauge).

3.3. Running SWAT model without calibration

The simulated streamflow without calibration in dry season and snowmelt season did not agree with the observed well (Fig. 2). In addition, different statistical criteria were used to evaluate individual SWAT model predictions in this study. Following Santhi et al. (2001) and Moriasi et al. (2007), the evaluation coefficient for deterministic predictions included the Nash–Sutcliffe Efficiency (*NSE*), Coefficient of Determination (r^2) and Percent Bias (*PBIAS*). Although some evaluation coefficient of gauges were good, the *PBIAS* was too large, which indicated underestimation model bias.

3.4. Model parameters sensitivity analysis

Parameter sensitivity analysis is an approach to evaluate how the changes in model parameters affect the model output variables and provide the information on the ability to identify model parameters. If parameters are poorly identified or are not important for the reproduction of the system response, then the dimension of calibration can be reduced. Parameter sensitivity can be broadly classified into local or global approaches (Saltelli et al., 1999). In local techniques, the output responses are determined by sequentially varying each parameter while keeping the other parameters constant. Unlike local techniques, global techniques explore the entire range of parameter space, allowing investigation of output variation as a result of all model parameters and their possible interaction (Muleta and Nicklow, 2005).

Sensitivity analysis was carried out using those model parameters identified from the instructions for the calibration of the SWAT model, as given in the user's manual (Neitsch et al., 2005). The results of sensitivity analysis for the Yeniugou River catchment and the Yingluoxia watershed were shown in Table 3. From Table 3,

Table 3
The results of parameter sensitivity analysis.

Parameter	Definition	File name	Hydrologic process or variable affected	Yingluoxia watershed		Yeniugou River catchment	
				Rank	Value	Rank	Value
Cn2	Moisture condition curve number	*.mgt	Surface runoff	1	1.48	1	2.39
Alpha_Bf	Baseflow recession constant	*.gw	Baseflow	2	0.678	3	0.606
Tlaps	Temperature lapse rate (°C/km)	*.sub	Evapotranspiration	3	0.633	2	0.426
Esco	Soil evaporation compensation factor	*.bsn	Soil water and soil evaporation	4	0.2	4	0.291
Sol_K	Saturated hydraulic conductivity of first layer (mm/h)	*.sol	Infiltration and soil water	5	0.154	5	0.2
Ch_K2	Effective hydraulic conductivity in main channel alluvium (mm/h)	*.rte	Concentration of channel	6	0.148	9	0.099
Sol_Z	Depth from soil surface to bottom of layer (mm)	*.sol	Soil water	7	0.124	6	0.168
Slope	Average slope steepness (m/m)	*.hru	Hillslope runoff	8	0.0932	7	0.151
Blai	Potential maximum leaf area index for the plant	corp.dat	Interception	9	0.0868	12	0.0586
Canmx	Maximum canopy storage (mm)	*.hru	Interception	10	0.0657	10	0.0871
Sol_Awc	Available soil water capacity (mm/mm)	*.sol	Soil water	11	0.0482	11	0.0669
Gwqmn	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	*.gw	Baseflow	12	0.0313	13	0.0405
Biomix	Biological mixing efficiency	*.mgt	Interception	13	0.00372	17	0.00508
Surlag	Surface runoff lag coefficient	*.bsn	Concentration of surface runoff	14	0.00293	16	0.00569
Timp	Snow pack temperature lag factor	*.bsn	Snow melt	15	0.00222	15	0.00729
Epco	Plant evaporation compensation factor	*.bsn	Evapotranspiration	16	0.00203	14	0.0101
Ch_N2	Manning coefficient for channel	*.rte	Concentration of channel	17	0.000395	20	0.00056
Gw_Delay	Groundwater delay (days)	*.gw	Baseflow	18	0.000232	21	0.00044
Sol_Alb	Soil albedo	*.sol	Evapotranspiration	19	8.08E−05	18	0.00142
Slsubbsn	Average slope length (m)	*.hru	Hillslope runoff	20	4.91E−05	22	0.000425
Gw_Revap	Groundwater 'revap' coefficient	*.gw	Baseflow	27	0	19	0.00138
Revapmn	Threshold depth of water in the shallow aquifer for 'revap' to occur (mm)	*.gw	Baseflow	27	0	8	0.112
Sftmp	Snowfall temperature (°C)	*.bsn	Snow melt	27	0	27	0
Smfmn	Minimum melt rate for snow during the year (occurs on winter solstice) (mm/°C/day)	*.bsn	Snow melt	27	0	27	0
Smfmx	Maximum melt rate for snow during the year (occurs on summer solstice) (mm/°C/day)	*.bsn	Snow melt	27	0	27	0
Smtmp	Snow melt base temperature (°C)	*.bsn	Snow melt	27	0	23	0.00018

it appeared that the five most important parameters were same except there were subtle differences in their ranks. It implied that the runoff of these two regions was decided by the same parameters mainly. Among the parameters, Cn2 was the most sensitive parameter, which determines the surface runoff and is a function of soil's permeability, landuse and antecedent soil water conditions. The Yingluoxia watershed is located in a high-cold region, where snowfall accounts for a certain percentage of annual precipitation and there is a great amount of perennial snow above 4000 m ASL. In such a region, evapotranspiration, snow melt and temperature are closely related. According to previous studies, the interflow and baseflow made a great contribution on the discharge in this watershed (Wang et al., 2009; Zhao et al., 2011; Zhang et al., 2011; Yang, 2011), making Alpha_Bf, Sol_K and Tlaps also important for hydrological simulations. Esco, the soil evaporation compensation coefficient, directly affects the soil water evaporation. In addition, Plaps (the precipitation lapse rate) is as important as these five parameters, even more important than them, because it controls the amount of precipitation. The other parameters also can affect the simulation more or less.

3.5. Model calibration

Because the manual calibration is time consuming and affected by the area of basin to a great extent, the Yeniugou River catchment was selected to calibrate whose climate is controlled by more meteorological stations in simulation compared with the Babaohe River. In addition, it can exam if the calibrated parameters of the Yeniugou catchment were fit for the whole watershed by applying its calibrated parameters to the other area of the watershed.

In this study, the periods from 1985 to 1989, 1990 to 1995 and 1996 to 2000 were taken as warm-up period, calibration period and validation period respectively, and the SWAT calibration procedure followed three aspects for Yeniugou River catchment: multi-temporal calibration, multi-variable calibration and calibration based on drainage characteristics (Fig. 3).

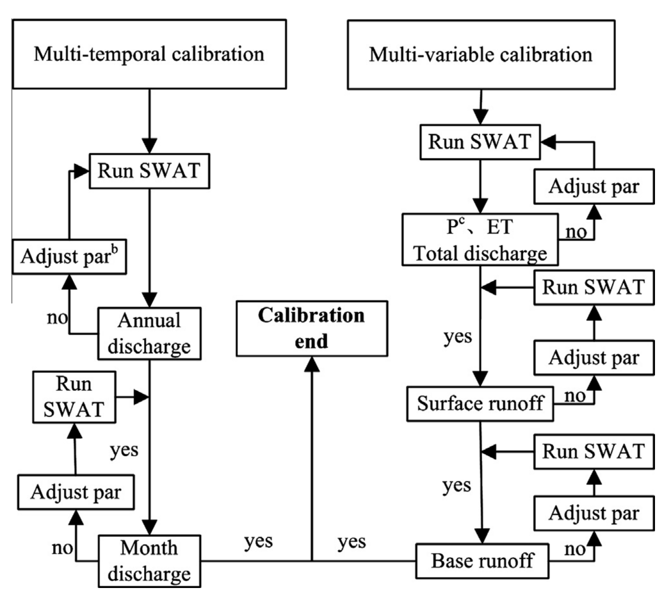

Fig. 3. Calibration method of the SWAT model ([b] Note: parameter; [c] Note: precipitation).

3.5.1. Multi-temporal calibration

Calibration for water balance and streamflow was first done for average annual conditions. The calibrations were then shifted to monthly averages to fine-tune the calibration. On the yearly scale, precipitation was one of the most important inputs for accurate runoff simulations. Because precipitation controls the water balance, it is critical that the amount and distribution of precipitation in space and time is accurately simulated (Arnold et al., 1998). In the Yingluoxia watershed, the water vapor sources for precipitation vary according to the season. They mainly come from the ocean air mass in spring and summer and from the continental recycling of water in autumn and winter. The temperature was also a significant factor that directly affected the evapotranspiration and melt of the ice and snow. In this study, subbasins were first divided into many elevation bands based on their elevation range. The Plaps was then set to 130 (mm H_2O/km) for Yeniugou River catchment (Ding et al., 1999; Jia, 2010; Liu et al., 2011; Lu, 2012). In contrast, the temperature was relative uniform, and the temperature lapse rate (Tlaps) was set to -5 (°C/km) (Lu, 2012). An accurate value of precipitation and temperature of each band could be calculated as a function of the respective lapse rate and the difference between the gauge elevation and its elevation, in other words, the input and output of water of the whole watershed was quantified and the average annual discharge was determined. On the monthly scale, considering the rainy and dry season, the related parameters were adjusted such as Cn2, Sol_Awc, Sol_K and Alpha_Bf to calibrate the proportion of surface runoff, lateral flow and baseflow to total discharge.

3.5.2. Multi-variable calibration

The equifinality problem is of particular importance in distributed models because of the huge number of parameter values. When calibrating a complex numerical model with many parameters, the single-criterion method has been found to be limited (Gupta et al., 1999; Anderton et al., 2002; Beven, 2006). Because the single-criterion method selects a single variable, e.g. outlet streamflow, as the sole calibration criterion, but the streamflow is a comprehensive product of the watershed. In this study, a multi-variable calibration method was proposed that could fully use previous results regarding the precipitation, evapotranspiration and baseflow.

First, because precipitation controls the water balance, it is critical that the amount and distribution of precipitation in space and time is accurately simulated by the model. In addition, evapotranspiration is the primary mechanism by which water is removed from the watershed and an accurate estimate of evapotranspiration is critical for the assessment of water resources (Arnold et al., 1998). Next, the surface runoff was calibrated by adjusting the Cn2, Sol_Awc and Esco parameters. According to the previous results, the discharge was contributed by baseflow in winter when the precipitation was scarce and almost solid in state, the baseflow index was about 0.4–0.7 (Wang et al., 2009; Zhao et al., 2011; Zhang et al., 2011; Yang, 2011). Finally an approximate value of the baseflow was obtained.

3.5.3. Calibrating based on drainage characteristics

It is helpful and crucial for model calibration to understand drainage characteristics. In this study, the water vapor source, terrain, surface cover, etc were took into account. For example, almost the entire watershed was frozen from November to February, so the surface runoff side flow and infiltration volume were zero while the river recharge was coming from underground runoff. After March, there were few surface runoffs; however, the soil below the surface was still frozen. The water production increased in April and May, which was caused by rapid increase in the air temperature and a large melting of ice, which triggered ice–snow runoff to the recharge river channel. The precipitation concentration period was from July to September and in this period the surface runoff and side stream were large, resulting in the maximum mountainous runoff for the Heihe River basin (Huang and Zhang, 2004, 2010). Using the hydrological gauges controlling the east and west branches and the representative meteorological station in the corresponding hydrological regions as an example, the relationship between monthly discharge, precipitation and average temperature was demonstrated (Fig. 4).

The data from 1996 to 2000 was used for validation after calibration. In the validation process, the model was operated with input parameters set during the calibration process without any change and the results were compared to the remaining observational data to evaluate the model prediction. The monthly simulated and observed discharge of Yeniugou River catchment fitted well, which also could be indicated by the evaluation coefficients (Fig. 5).

3.6. Parameter transferability

After calibration and validation for Yeniugou River catchment, its calibrated parameters were applied to the other area of the

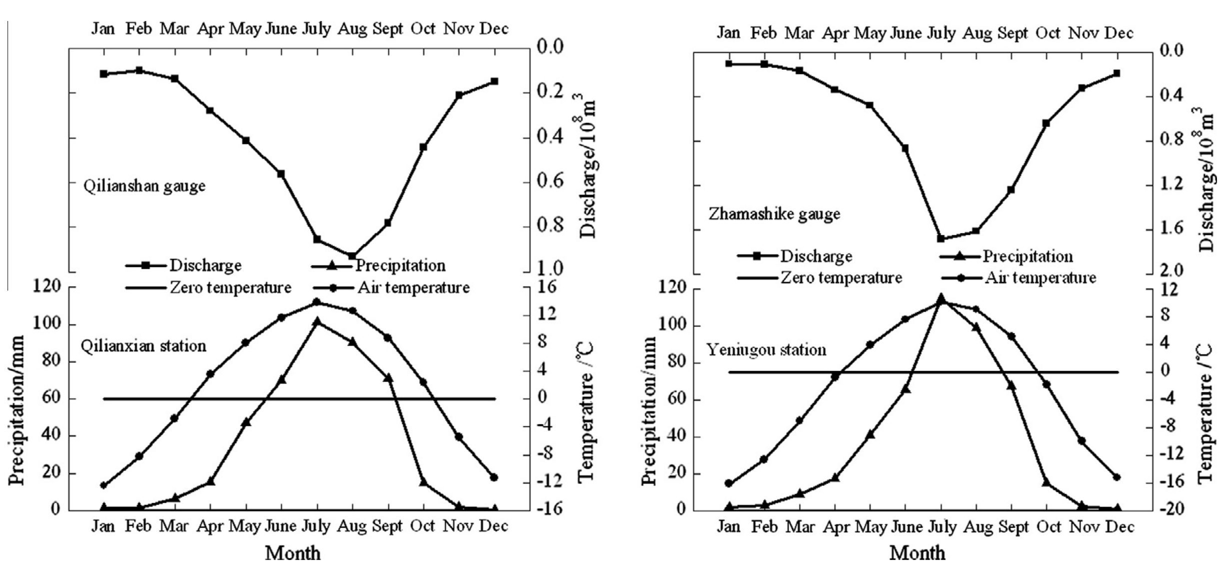

Fig. 4. The average monthly discharge, precipitation and temperature in the Yingluoxia watershed.

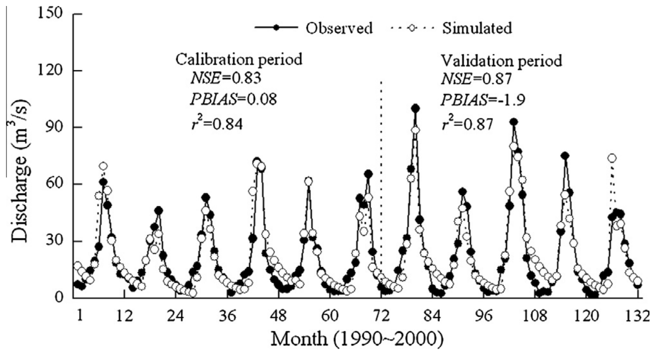

Fig. 5. The monthly observed and simulated discharge of Zhamashike gauge after calibration.

watershed, and the simulated and observed discharge at Qinlianshan gauge and Yingluoxia gauge were used to assess the suitability of calibrated parameters in the whole watershed (Fig. 6).

The simulated and observed discharge fitted well, even in some year with two peak of runoff (Fig. 6). Compared with the simulations of the Zhamashike gauge and Yingluoxia gauge, the Qilianshan gauge's was slightly less effective. This was mainly because there was one meteorological station (Qilianxian station) almost representing the climate of the whole Babaohe River catchment and it located at the outside of the catchment. In addition, the simulated values were slightly lower than the observed, this was due to the condition of the precipitation in Babaohe River catchment were differences from the Yeniugou River catchment (Ding et al., 1999; Jia, 2010; Yang, 2011; Zhang et al., 2011). The Plaps in the east branch is greater than the west because of various water vapor sources and terrain. The base flow is also different because of the differences in the distribution of snow and ice and land cover and terrain. By adjusting the precipitation lapse rate and parameters about the groundwater for Babaohe River catchment without changing the parameters of the calibrated catchment, the simulations of the Qilianshan gauge and Yingluoxia gauge were shown in Fig. 7. Although the graph hardly changed because of slight adjust of some parameter, the *NSE* of the Qilianshan gauge increased and the *PBIAS* of two gauges improved.

4. Results

4.1. Precipitation

The precipitation in mountain is important for the whole Heihe River basin, but there were no long-term precipitation data for the whole watershed. It is difficult to observe intensively and evaluate accurately because of the vast difference in the precipitation at various space distributions. In spite of this, there were still some studies on the precipitation in upper Heihe River basin or Qilian Mountain region using interpolation method based on the station data; the average precipitation estimated in Yingluoxia watershed were between the range from 400 to 550 mm, but different from each other study because factors involved and the weight to them were different (Liu and Zou, 2006; Sun et al., 2011; Liang and Xu, 2011). In addition, fortunately, the multi-satellite precipitation analysis (TMPA) product from the Tropical Rainfall Measuring Mission (TRMM) could provide an effective solution. Based the results from Liu et al. (2011), Wu et al. (2013), and Wang and Zhao (2013), the average annual precipitation in Yingluoxia watershed was about 500 mm.

In this study, many elevation bands were defined and different value for the Plaps were set to simulate the precipitation. The simulated precipitation were shown in Fig. 8, compared with the observed data of representative stations including Yeniugou and Qilianxian, the variation trends were identical for the rainy years and low flow years. The average annual amount of simulated precipitation for the whole watershed from 1990 to 2000 was

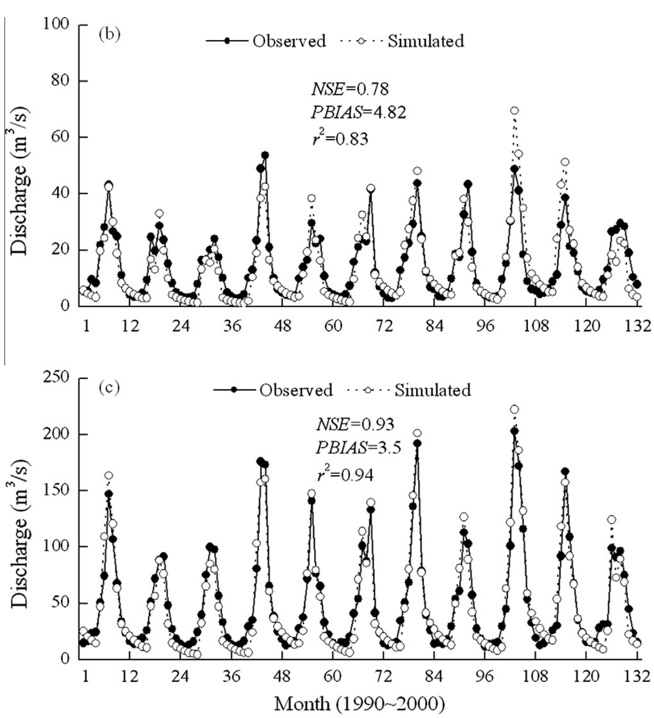

Fig. 6. The monthly observed and simulated discharge with the calibrated parameters of Yeniugou River catchment ((b) Qilianshan gauge; (c) Yingluoxia gauge).

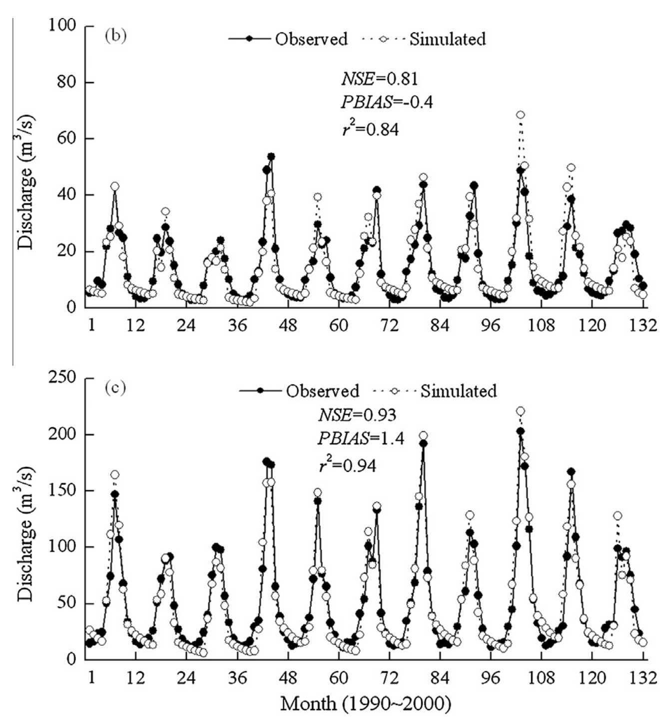

Fig. 7. The monthly observed and simulated discharge after calibration with the calibrated parameters of Yeniugou River catchment ((b) Qilianshan gauge; (c) Yingluoxia gauge).

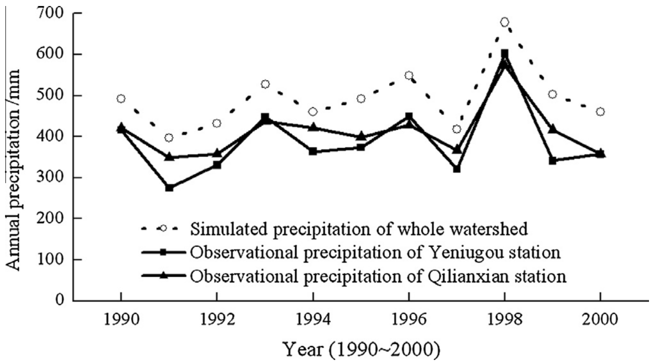

Fig. 8. Simulated precipitation of the entire watershed.

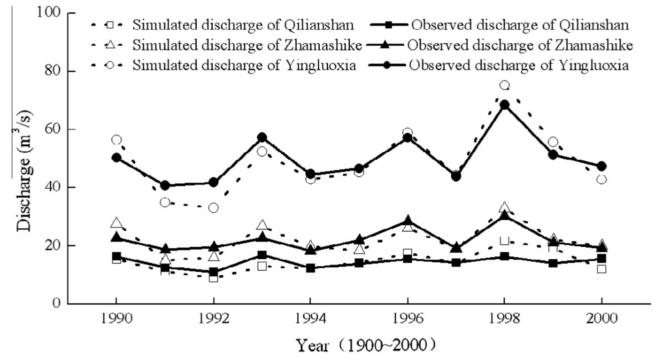

Fig. 10. The annual discharge of three gauges.

491.8 mm, which was reasonable based on previous results (Yin et al., 2009; Sun et al., 2011; Liu et al., 2011; Wu et al., 2013; Wang and Zhao, 2013), and the simulated snow fall was up to 102.5 mm, concentrated in the March, Aril, May, September, and October, because the summer was too hot and the winter was dry.

4.2. Evapotranspiration

Compared to the middle and lower reaches of the Heihe River, there is more precipitation and lower temperatures in the Yingluoxia watershed, but evapotranspiration is still the main water output of the watershed. However, because of the watershed's complex terrain and harsh environment, it is difficult to observe and measure the watershed's evapotranspiration systematically and continuously. In this period, neither the measured data nor the remote sensing data were available to be used to verify the results obtained from SWAT, only simple comparisons were made on hydrological components and meteorological factors in this study.

In this study, evapotranspiration in the entire watershed was simulated to be up to 334 mm from 1990 to 2000. It depended on many factors including precipitation, temperature and soil water content (Fig. 9). In this period, the precipitation was increasing and the temperature was rising with fluctuation, causing the evapotranspiration to also increase. Furthermore, the evapotranspiration changed less rapidly than the precipitation, and lagged behind the precipitation trends because of soil storages. In the model warm-up period from 1985 to 1989, the soil layers were storing water, so the evapotranspiration was increasing as the stored water increased.

4.3. Annual and monthly discharge

The simulated and observational annual discharge of three gauges was shown in Fig. 10. The simulated and observational data

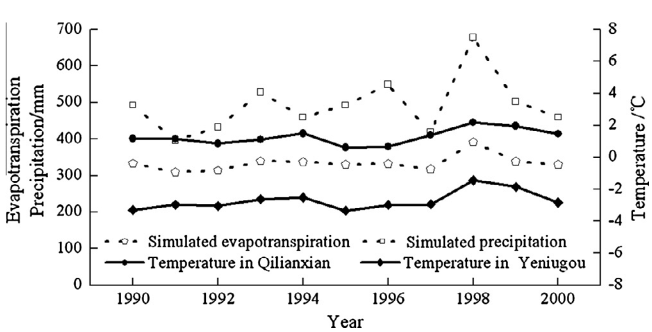

Fig. 9. The simulated evapotranspiration and its impact factors.

showed the same trends for the different gauges in the watershed. From 1990 to 2000, the average annual amount of simulated discharge of the whole watershed was 157.8 mm.

According to Fig. 5 and Fig. 7, the curves of the observed and simulated monthly values of all gauges matched well, and the evaluation coefficients of the simulated monthly discharge were very good and listed in the Table 4. In this study, the lowest value of the *NSE* was 0.81 for the Qilianshan gauge. The other gauges had *NSE* values greater than it and the Yingluoxia gauge had an *NSE* value as high as 0.93. The values of r^2 were equal to or greater than 0.84, and the highest value was 0.94. The absolute values of the *PBIAS* were less than 2. Comparing the gauges, the performance of Yingluoxia gauge was the best, followed by the Zhamashike gauge and then the Qilian gauge.

For comparison, simulations obtained from the previous studies are also given in Table 4. As can be seen, our result shows better than the previous studies with *NSE*, r^2 and *PBIAS* as the indicators. In detail, four of them (Huang and Zhang, 2004; Li et al., 2009, 2010; Liu et al., 2012) performed poorly with the relative low *NSE* and r^2 values, and great error indicated by *PBIAS*; Li et al. (2011) obtained the same agreeable precision as this study with *NSE* reaching 0.948 and 0.923 during calibration and validation periods, whereas r^2 were not considered and *PBIAS* were larger than it in this study.

4.4. Water balance

Based on the simulated precipitation, evapotranspiration and total discharge of SWAT model the water balance of Yingluoxia watershed was analyzed, and the simulated precipitation was equal to the sum of the simulated evapotranspiration and discharge in the period from 1990 to 2000. However in each year, the difference was obvious, which to some extent may due to the adjustment capacity of the underlying surface (Fig. 11). The difference was calculated as:

$$Q_{difference} = Q_{precipitation} - Q_{evapotranspiration} - Q_{discharge} \quad (2)$$

5. Discussion

The results above indicated that the comprehensive method based on multi-temporal, multi-variable and multi-site integrated drainage characteristics was an effective technique to calibrate the SWAT model. In previous studies only the discharge at Yingluoxia gauge was used to calibrate model. In this study, the hydrothermic factor was determined and many components of hydrologic cycle were calibrated; in addition, the watershed was portrayed using a spatial scale by calibrating three hydrologic gauges. However,

Table 4
The performance of SWAT model in the Yingluoxia watershed.

Related studies	Calibrate gauge	Calibration/validation periods	*NSE*	r^2	*PBIAS*
This study	Zhamashike gauge	1990–1995/1996–2000	0.83/0.87	0.84/0.87	0.08/−1.9
	Qilianshan gauge	1990–2000	0.81	0.84	−0.4
	Yingluoxia gauge	1990–2000	0.93	0.94	1.4
Liu et al. (2012)	Yingluoxia gauge	1990–1995/1996–2000	0.81/0.88	0.94/0.93	16.3/15.6
Li et al. (2011)	Yingluoxia gauge	1990–1996/1997–2000	0.948/0.923	–	−7.1/−8.4
Li et al. (2010)	Yingluoxia gauge	1990–1996/1997–2000	0.87/0.85	0.93/0.87	–
Li et al. (2009)	Yingluoxia gauge	1990–1996/1997–2000	0.87/0.84	–	–
Huang and Zhang (2004)	Yingluoxia gauge	1990–2000	0.88	0.91	3.7

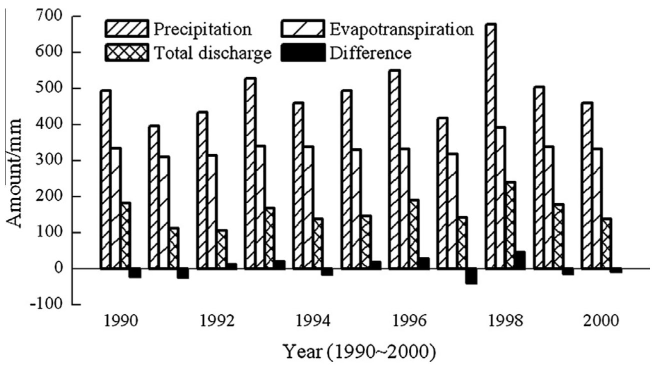

Fig. 11. The water balance of the Yingluoxia watershed.

this method required comprehensive knowledge of the watershed and was time consuming and computationally intensive.

Furthermore, there were only two meteorological stations in the watershed. The other stations were outside of the watershed, which caused problems because those stations were not well representative of the watershed climate. From the fitting effects of the three gauges, the Yingluoxia gauge was the best fit, followed by the Zhamashike gauge and then the Qilianshan gauge. The poor fit of the Qilanshan gauge could be a result of the distribution of the meteorological stations. In the east branch, where runoff was controlled by the Qilianshan gauge, the primary driving meteorological station, Qilianxian station, was near the outlet where the Qilianshan gauge was located.

In addition, meteorological stations were located in mid and low altitude mountainous regions, the highest station is the Tuole station whose altitude is just 3367 m ASL, which is less than the mean altitude of the watershed. Therefore the high altitude region lacked meteorological data, which remains a problem. In the future, it may be necessary to strengthen observations by adopting new techniques and practical and feasible means, such as remote sensing inversion, rain detection with radar and satellite cloud images and isotopic tracing.

Besides, improving model structures to portray the processes of the watershed preferably and parameterisation are essential and effective ways to optimize the model simulation. But in the area with scare data, these methods are often limited. Perhaps more attention needs to be pay to the parameter transferability issue.

Ultimately, in order to better assessing and managing the water resource in a mountainous watershed under the environment of global change, it is necessary for analyzing the water balance on the smaller scale, such as subbasin, elevation band, and land use types. Of course, it needs to strengthen the observation at sites to verify, which is what the Major Research Plan "Integration of Eco-hydrological Process Research in Heihe River Basin" is ongoing.

6. Conclusions

In this study, a proposed calibration approach integrating multiple temporal scales, multiple variables and multiple sites based on drainage characteristics was developed for SWAT model and was applied to the Yingluoxia watershed in the Heihe River basin of northwest China. The performance of the model in this study was better than previous results. This indicated that this method was an effective technique to calibrate SWAT model and could be applied in other areas; as well the parameter transferability could be used for PUBs and for application in land surface parameterization schemes.

Based on the model's output, the water balance of the watershed was analyzed. From 1990 to 2000, the mean annual precipitation, evapotranspiration, and discharge were 491.8 mm, 334 mm, and 157.8 mm, respectively. In each year, the difference between the simulated precipitation and the sum of the simulated evapotranspiration and discharge was a result of small amount water stored in soil, which was the better function of water conservation of the mountain and it was important for the stability of inter-annual variability of discharge as the ice and snow. The result of the water balance in Yingluoxia watershed could provide valuable information for assessing and managing water resource of the watershed.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

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