Moulding SWAT model for Chines Qingjiang river for rainfall-runoff simulations

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Outline

- Introduction
- Study Area
- Soil Database Construction
- Weather Generator Establishment
- Application
- Conclusions

1 Introduction

- Compared with lumped hydrological models, spatially distributed hydrological models can evaluate the influence of the spatial variability of meteorological data and river basin physical characteristics, such as precipitation, evaporation, infiltration, topography, soil, and vegetation, on water circulating processes.

- As an representative of these models, Soil and Water Assessment Tool (Arnold et al., 1993) was developed by the U.S. Department of Agriculture (USDA) in early 1990s. It has been widely used in hydrologic (Zhang et al., 2004), soil erosion (Xiao et al., 2013), and the point source pollution (Wan and Zhang, 2003) simulations in China.

- SWAT model requires two types of data:

1) Spatial data

DEM, landuse map and soil map belong to the spatial data. They have to be converted to fit ESRI Grid data format, which is conducted by using ArcGIS.

2) Attribute data

Attribute data including weather, soil, hydrology, pollution sources require a large number of parameters.

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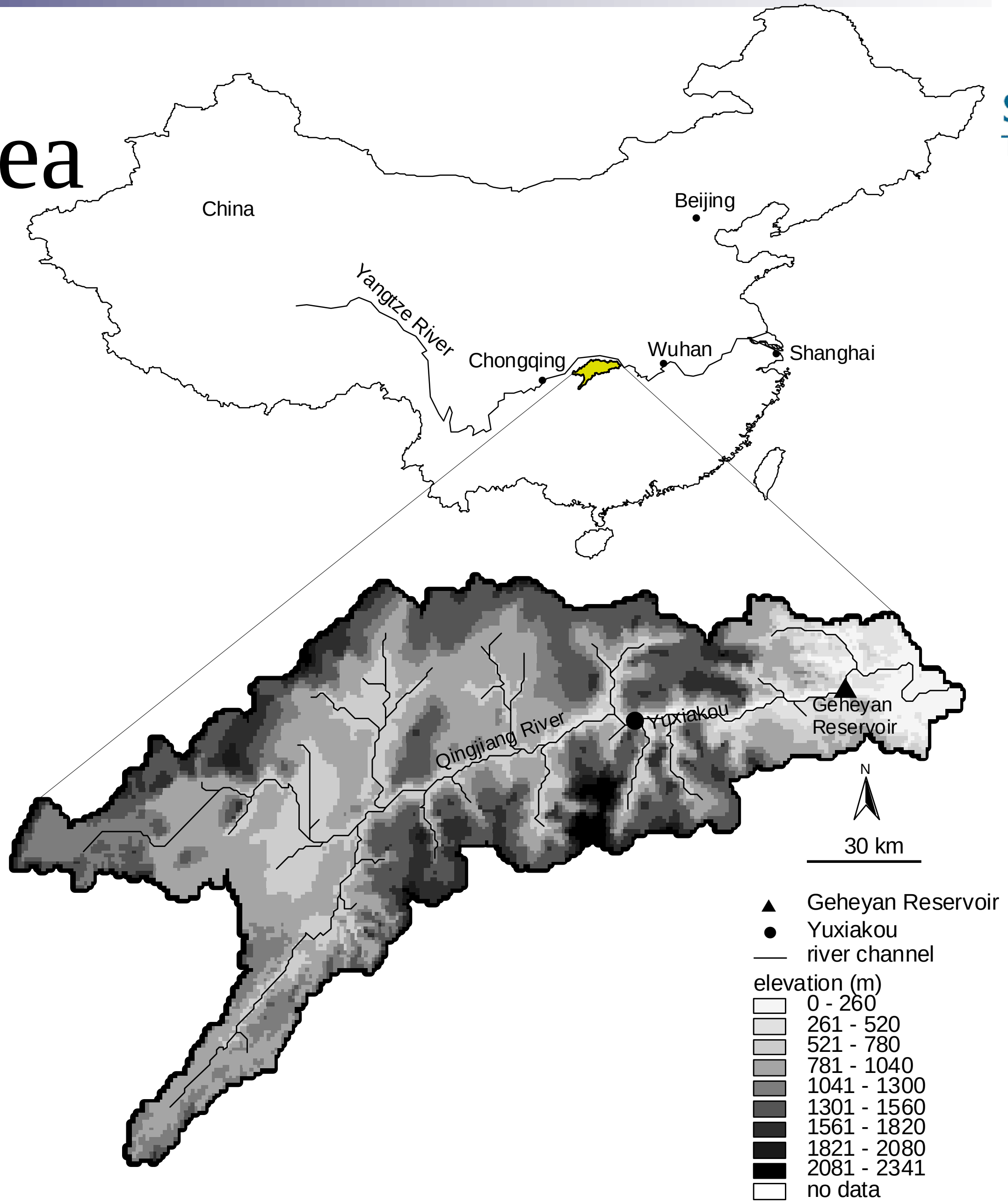
- For the hydrological simulation in North America, the attribute database in the model were originally designed to suit the situations there. However, to apply SWAT in China, the databases, have to be modified to be able to use Chinese data sets.

- This paper took Chinese Qingjiang river basin for case studying, discussed how to set up and modify the data sets, mainly the soil database and weather generator, to suit Chinese situation, and used the model to perform monthly and daily runoff simulations.

2 Study Area



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2 Study Area

- The study area is the watershed upstream of Yuxiakou in Qingjiang River basin (Figure 1).

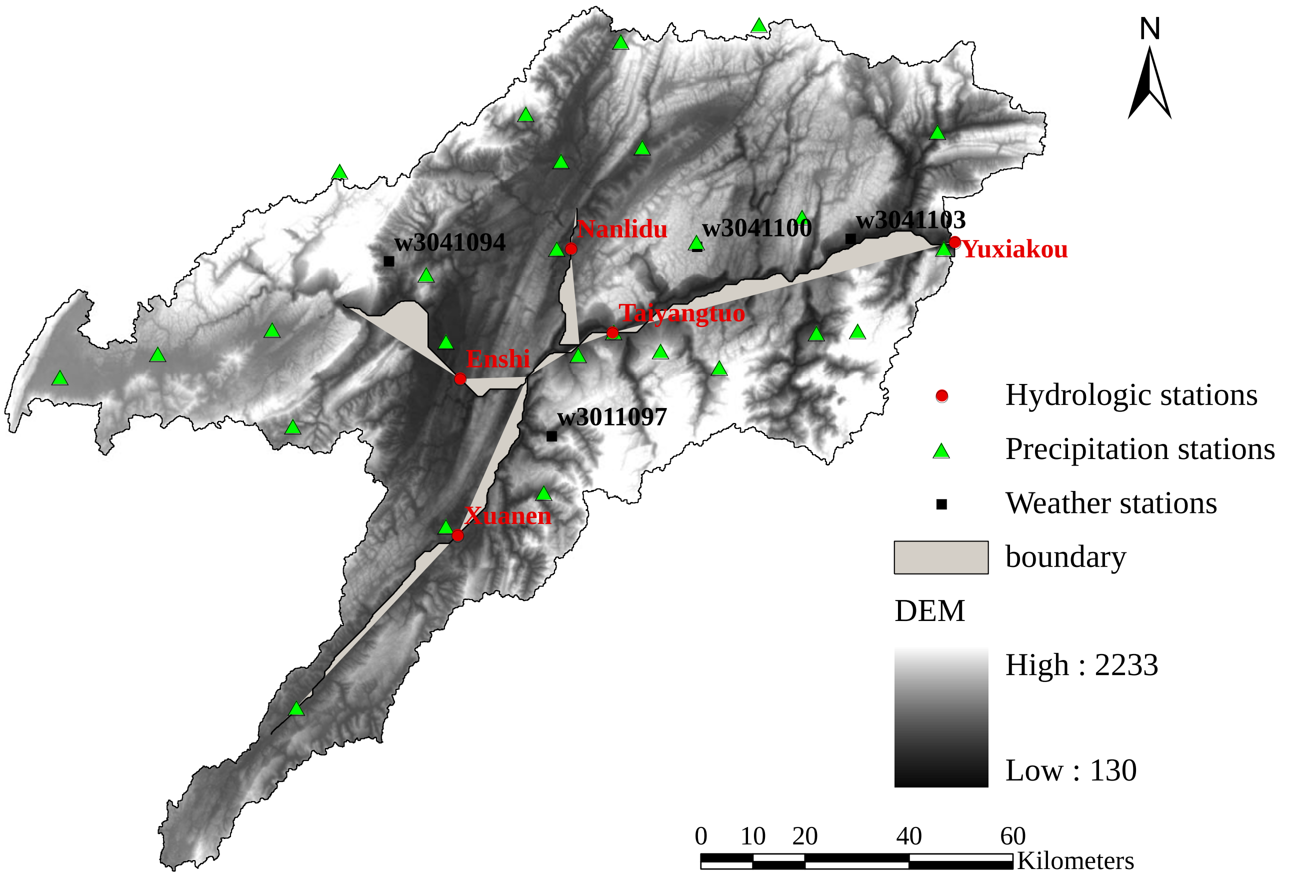

Figure 1. Riverbasin Upstream of Yuxiakou in Qingjiang River

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- The area of Qingjiang River basin is 17000km^2. It joins the Yangtze River about 100km downstream to the Three Gorges Dam.
- The length of the main river channel is 423km with a total water head of 1430m.
- Annual mean relative humidity is 70~80%.
- Annual mean precipitation is about 1460mm.
- Annual mean discharge at the outlet of the basin is 464m^3/s.
- Rainy season: April - September. The annual mean runoff of Qingjiang is 14.11 billion cubic meters, unevenly distributed over the year, 75% of the rainfall of a year is taking place in the rainy season.

3 Soil Database Construction

- There are mainly two types of soil attribute data which are applied to the SWAT model:
- 1) Soil physical property (required) which determines the water and air movement in the soil profile, and plays an important role in modeling the water cycle processes in Hydrological Response Units (HRUs).
- 2) Soil chemical property (optional) mainly used to assign an initial value to the concentration of chemical substances contained in the soil.

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- This paper only carries out study on the runoff simulation, without consideration of water quality issues, therefore determining the soil physical property parameters is the primary mission when establishing the soil attribute database.
- The required data for soil physical property are listed in Table 1.

Table 1 Required data for soil physical property

NUMBER	NAME	DEFINITION
①	HYDGRP	Soil hydrological group
②	SOL_ZMX	Maximum rooting depth of soil profile
③	SOL_Z	Depth from soil surface to bottom of layer
④	SOL_BD	Moist bulk density
⑤	SOL_AWC	Available water capacity of the soil layer
⑥	SOL_K	Saturated hydraulic conductivity
⑦	SOL_CBN	Organic carbon content
⑧	CLAY	Clay content
⑨	SILT	Silt content
⑩	SAND	Sand content
⑪	ROCK	Rock fragment content
⑫	SOL_ALB	Moist soil albedo
⑬	USLE_K	USLE equation soil erodibility (K) factor

3.1 Data Preparation

- Soil information stems from the Harmony of the World Soil Database (HWSD).
- In HWSD, Chinese soil data were obtained in the second national land survey and is provided by Nanjing Institute of Soil Science (Nachtergaele et al., 2008) in maps at a scale of 1:1,000,000.

- In HWSD, soil is divided into two default layers:
- 1) Attribute field names beginning with T_ represents the soil properties at the top layer (0 to 30 cm).
- 2) Those start with the S_ represents the lower soil properties (30-100 cm).

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- The main attributes of soil in HSWD are listed in Table 2.

Table 2 The attributes of soil in HWSD

NUMBER	NAME	DEFINITION
(1)	SU_SYM90	The soil name in FAO90 classification system
(2)	T(S)_TEXTURE	Soil texture of the top (lower) layer
(3)	REF_DEPTH	Soil depth
(4)	AWC_CLASS	Available soil water
(5)	T(S)_GRAVEL	Gravel content of the top (lower) layer
(6)	T(S)_SAND	Sand content of the top (lower) layer
(7)	T(S)_SILT	Silt content of the top (lower) layer
(8)	T(S)_CLAY	Clay content of the top (lower) layer
(9)	REF_BULK	Bulk density of the top (lower) layer
(10)	T(S)_OC	Organic carbon content of the top (lower) layer

- The particle size grade of the HWSD is defined by United States Standard which is the same with the grading standards required in SWAT model. So the parameters ②, ③, ⑦ to ⑪ in Table 1 can be obtained easily from the HWSD.

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3.2 Soil Moisture Parameters

- Soil moisture parameters contain wilting point, the effective field capacity, saturated hydraulic conductivity and bulk density, which could be acquired by experimental method or could be calculated by using software like Soil-Plant-Air-Water (SPAW). Here the later is used.
- SPAW (Figure 2) was developed by the Washington State University.

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- Input the values of contents of clay, sand and organic matter into soil water characteristic (SWCT) module of SPAW software to calculate wilting point, field capacity, saturation, bulk density, saturated hydraulic conductivity and so on.

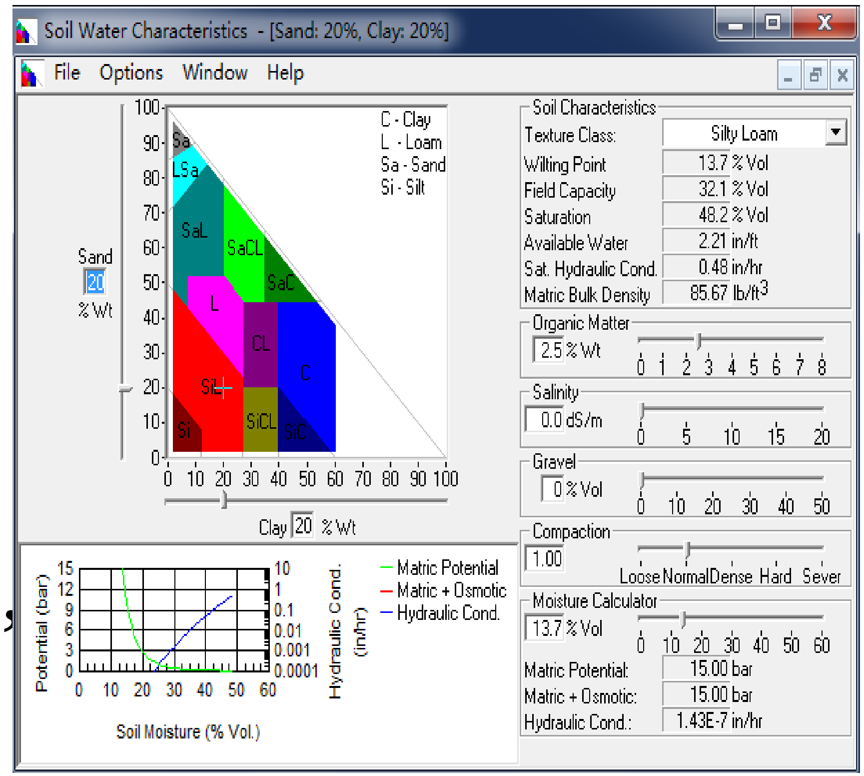

Figure 2. SPAW interface

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- Parameter ⑤ could be obtained:

SOL_AWC=Field capacity-Wilting point

- The units of some variables calculated by

SPAW were inconsistent with SWAT model, such as ④ and ⑥. They should be transformed before input intg the database:

$$SOL\_BD\left(g/cm^3\right) = 0.016 \times Bulk\ Density\left(lb/\ ft^3\right)$$

$$SOL\_K\left(mm/hr\right) = 25.4 \times Sat.Hydraulic\ Cond\left(in/hr\right)$$

3.3 Soil Hydrological Group

- The SCS curve method is used to estimate the runoff from each HRU, which needs to classify the soil into different categories.
- Soil was classified into four groups based on the infiltration rate (Neitsch et al., 2004), as seen in Table 3.

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Table 3 Soil hydrological group definition

Hydrologic Soil Group	Hydrological properties	Infiltration rate(mm/hr)
A	Low runoff potential; High rate of water transmission; Consisting chiefly of sands or gravel that are deep and well to excessively drained.	7.6-11.4
B	Moderate runoff potential and rate of water transmission;	3.8-7.6
C	High runoff potential; Slow rate of water transmission; Having slow infiltration rates when thoroughly wetted, chiefly with a layer that impedes the downward movement of water or of moderately fine to fine texture.	1.3-3.8
D	Slow rate of transmission; Having very slow infiltration rates when thoroughly wetted, chiefly clay soils with a high swelling potential.	0-1.3

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- Che (1995) used the correlation between the average particle diameter and soil permeability to estimate the soil permeability coefficient, and then put forward empirical formulae of infiltration rate:

$$X = (20Y)^{1.8}$$

Where:

$$Y = \frac{Scp}{10} \times 0.03 + 0.002$$

X is the permeability coefficient; Y is the soil particle diameter; and Scp is the percentage of sand content (%).

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- According to the range of infiltration rate in Table 3 (the values of which are calculated by empirical formulas), the soil could be classified into four groups, and the group number is given to parameter ① (HYDGRP).

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3.4 Moist Soil Albedo

- The moist soil albedo (⑫ SOL_ALB) varies with different natural conditions. Certain studies transformed the soil spectrum into 14 kinds, then took advantage of spectrum differential technology and stepwise regression analysis method to research the relationship between soil albedo and soil organic matter. The results show that the albedo value is sensitive to the content of soil organic matter (He, et al., 2006).

- Taking this relationship into account, this paper offered exponential regression analysis between SOL_ALB and SOL_CBN based on the data from the SWAT original database.

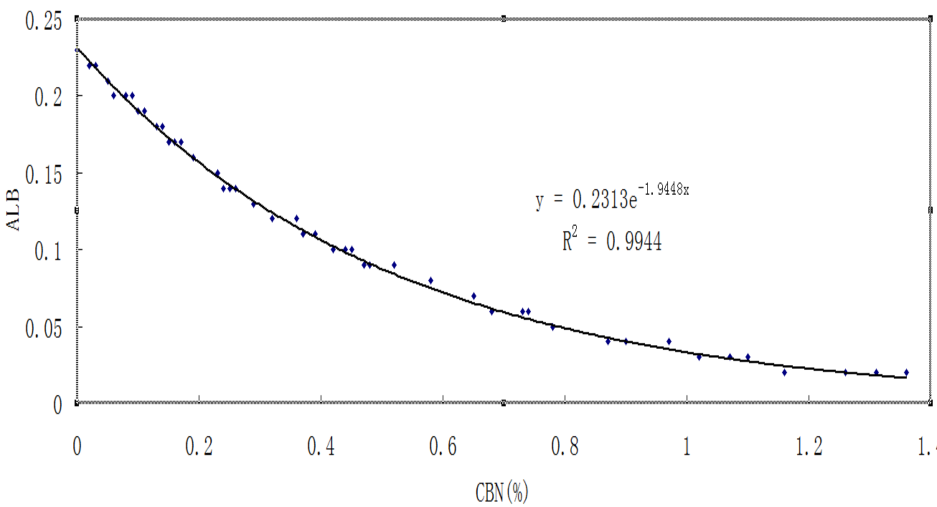

Figure 3. ALB-CBN Regression Analysis

- Figure 3 is the picture of analysis, showing the correlation coefficient r^2= 0.9944. The average error is 2.3%.

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- Empirical formula is as follows:

$$SOL\_ALB = 0.2313 \times EXP\left(-1.9448 \times SOL\_CBN\right)$$

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3.5 Soil Erodibility Factor

- Soil erodibility factor (⑬ USLE_K) is defined as the soil loss rate per erosion index unit for a specified soil as measured on a unit plot.
- Direct measurement of the erodibility factor is time consuming and costly. Equations were developed to calculate the soil erodibility factor (Williams,1995).

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$$USLE_K = f_{csand} \cdot f_{cl-si} \cdot f_{orgc} \cdot f_{hisand}$$

Where, $USLE_K$ is the soil erodibility factor, f_{csand} is the coarse sand soil erosion factor; f_{cl-si} is the clay loam soil erosion factor; f_{orgc} is the soil organic matter factor; f_{hisand} is the factor of soil erosion in high sandy.

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Where:

$$f_{csand} = 0.2 + 0.3 \cdot \exp\left[-0.256 \cdot m_s \cdot \left(1 - \frac{m_{silt}}{100}\right)\right]$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3}$$

$$f_{orgc} = 1 - \frac{0.25 \cdot orgC}{orgC + \exp(3.72 - 2.95 \cdot orgC)}$$

$$f_{hisand} = 1 - \frac{0.7 \cdot \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51 + 22.9 \cdot \left(1 - \frac{m_s}{100}\right)\right]}$$

m_s is the content of sand with particle size of 0.05-2.00mm;

m_{silt} is the content of sediment with particle size of 0.002-0.05mm;

m_c is the content of clay with particle size less than 0.002 mm;

$orgC$ is the organic carbon content in the soil layer (%).

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4 Weather Generator Establishment

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- The main parameters for weather generator are:

mean daily maximum / minimum temperature for month (TMPMX/TMPMN),

standard deviation for daily maximum / minimum temperature in month (TMPSTDMX/TMPSTDMN),

average total monthly precipitation (PCPMM),

standard deviation for daily precipitation in month (PCPSTD),

daily precipitation skew coefficient in month (PCPSKW),

- probability of a wet day following a dry day in the month (PR_W1),
- probability of a wet day following a wet day in the month (PR_W2),
- average number of precipitation days in month (PCPD), average daily solar radiation for month (SOLARAV), average daily dew point temperature in month (DEWPT) and average daily wind speed in month (WNDAV).

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- Among these parameters, the value of rainfall factors (PR_W1, PR_W2, PCPD) and DEWPT are difficult to calculate for the lack of original data.
- Liersch (2003) has developed PcpSTAT, which uses the daily observed precipitation to calculate the values of rainfall factors, and Dew/Dew02 program to calculate the dew point temperatures.
- The results are presented in Table 4.

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Table 4 rainfall factors and dew point temperature in basin

STA	PAR	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
w1097	PR_W1	0.33	0.38	0.41	0.47	0.43	0.5	0.59	0.46	0.34	0.31	0.28	0.24
w1094		0.34	0.39	0.42	0.49	0.42	0.47	0.62	0.52	0.39	0.31	0.31	0.27
w1100		0.31	0.34	0.39	0.46	0.41	0.43	0.58	0.45	0.33	0.3	0.29	0.24
w1103		0.29	0.34	0.39	0.5	0.43	0.47	0.6	0.43	0.32	0.28	0.27	0.24
w1097	PR_W2	0.68	0.69	0.75	0.73	0.76	0.75	0.86	0.85	0.75	0.71	0.7	0.68
w1094		0.66	0.67	0.71	0.73	0.76	0.77	0.88	0.86	0.76	0.75	0.7	0.64
w1100		0.63	0.66	0.71	0.72	0.74	0.75	0.87	0.86	0.75	0.71	0.67	0.63
w1103		0.65	0.66	0.72	0.72	0.75	0.76	0.88	0.88	0.79	0.72	0.68	0.62
w1097	PCPD	16.16	16.19	19.97	20.09	20.75	20.59	26.13	24.78	18.59	17.13	15.06	14.03
w1094		15.78	15.97	19.19	20.31	20.94	21	26.84	25.91	19.78	18.59	15.88	13.91
w1100		14.47	14.75	18.56	19.69	20.06	20.06	26.34	24.94	18.28	16.75	14.38	12.63
w1103		14.31	14.81	18.91	20.09	20.78	20.84	26.81	26.03	19.16	16.72	14.34	12.56
w1097	DEWPT	0.96	2.43	6.08	11.35	15.37	18.6	20.91	20.42	16.75	11.98	7.25	2.53
w1094		1.23	2.76	6.43	11.58	15.54	18.76	21.17	20.69	16.94	12.14	7.39	2.71
w1100		0.31	1.94	5.65	10.92	14.94	18.18	20.67	20.06	16.24	11.36	6.61	1.89
w1103		-0.28	1.36	5.18	10.58	14.59	17.86	20.46	19.69	15.81	10.9	6.23	1.41

5 Application

- DEM is used to abstract slope direction, slope length, river network and watershed boundary. Also, the studied basin is divided into 5 subbasins and 52 hydrological response units based on the DEM data layer. Daily rainfall from 26 precipitation stations, daily maximum/ minimum temperature, relative humidity, wind speed and solar radiation from 4 meteorological stations in the basin are also used in Qingjiang SWAT model (Figure 1).

5.1 Calibration and Validation

- In early running of the model, some variables, such as the soil water content, the initial value of which was set to be zero, which has a big influence on the results of simulation. Therefore, it is necessary to take the initial stage as the warming up period so that reasonable values of these variables could be identified.

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- Monthly average flow data from 1989 to 1995 were used for monthly simulation, whereas the data from 1989 was taken for model warming up to produce the initial conditions, the data from 1990 to 1992 were used for calibration and the data from 1993 to 1995 were used for validation.
- Daily simulations were performed by using daily flow data from 1997 to 1999. The Year 1997 was taken as the warm-up year, the year 1998 as the calibration year, and 1999 as the validation year.

- Figure 4 shows the monthly simulation results, while the observed and simulated process in daily simulation results can be seen in Figure 5.

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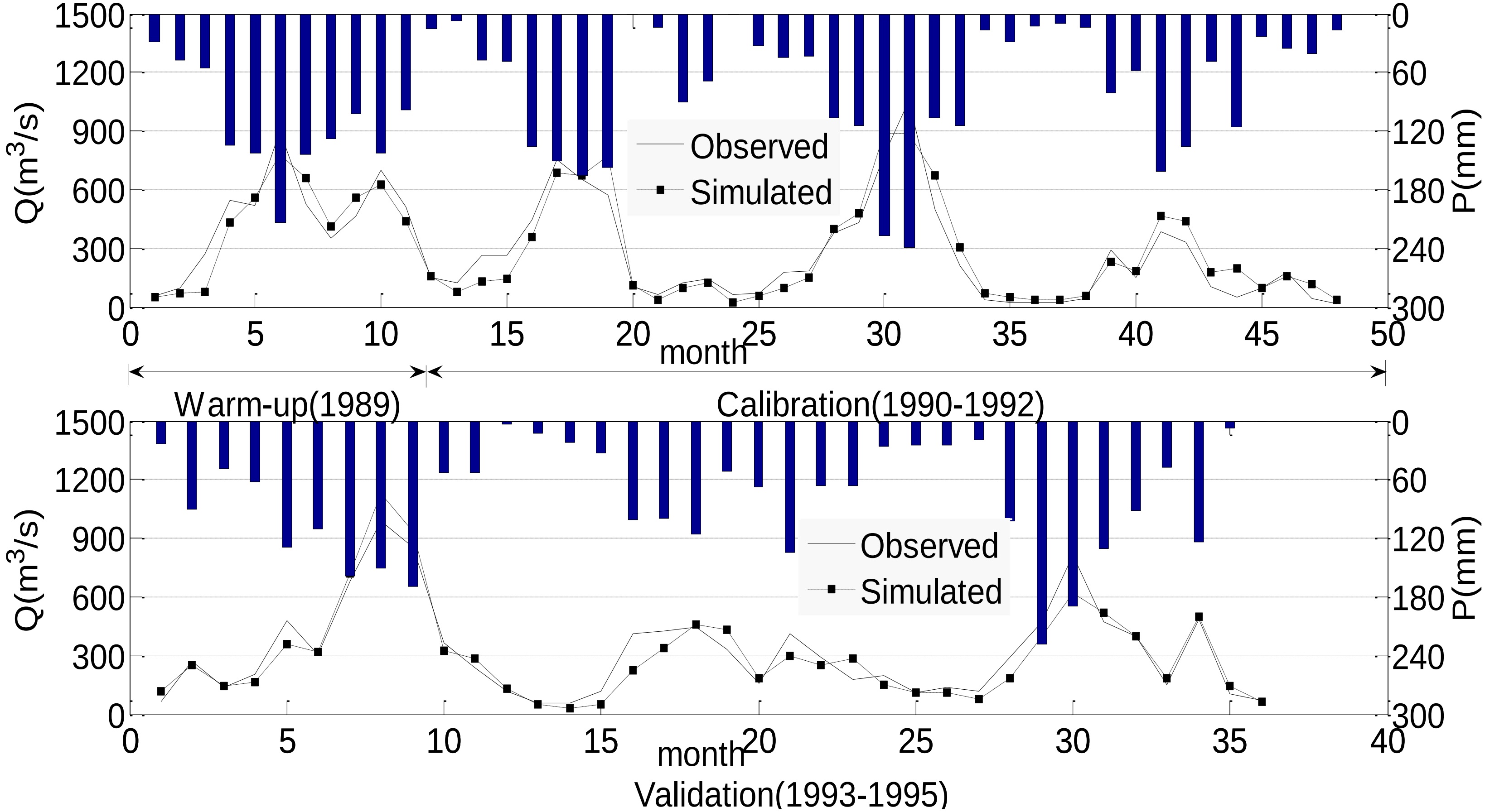

Figure 4. Monthly average runoff simulation

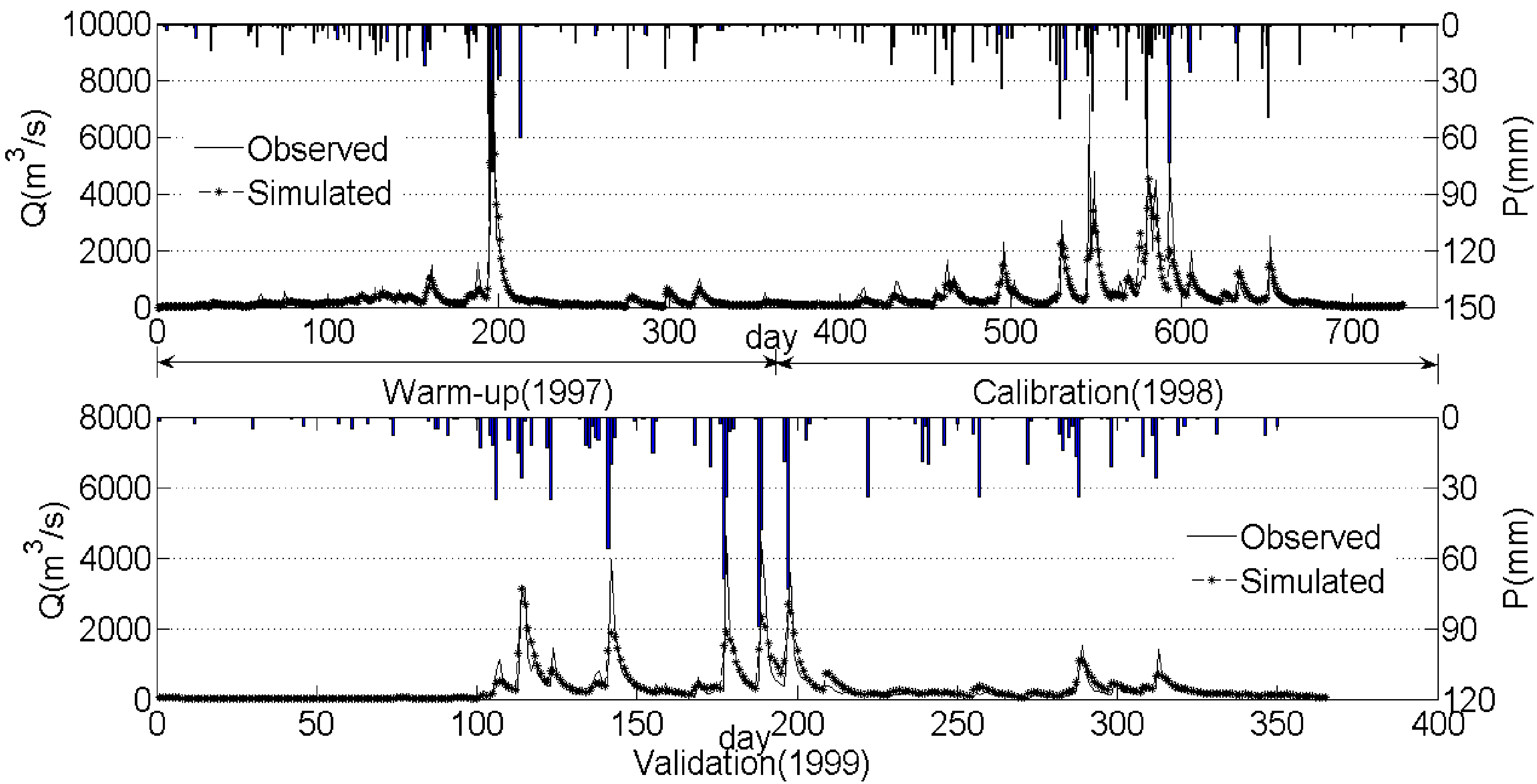

Figure 5. Daily average runoff simulation

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- Nash-Sutcliffe efficiency coefficient (E_{NS}) and correlation coefficient (R) were used to evaluate the accuracy of simulations.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{o,i} - Q_{s,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{o,i} - \overline{Q_o}\right)^2}$$

$$R = \frac{\sum_{i=1}^{n}\left(Q_{o,i} - \overline{Q_o}\right)\left(Q_{s,i} - \overline{Q_s}\right)}{\sqrt{\sum_{i=1}^{n}\left(Q_{o,i} - \overline{Q_o}\right)^2 \sum_{i=1}^{n}\left(Q_{s,i} - \overline{Q_s}\right)^2}}$$

- The E_{NS} and R values in calibration and validation periods are displayed in Table 5.

Table 5 Simulation Results

Period	Monthly simulation		Daily simulation	
	E_{NS}	R	E_{NS}	R
Calibration	0.89	0.95	0.77	0.88
Validation	0.89	0.95	0.73	0.86

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6 Conclusions

- The SWAT model was adapted to be applied in Chinese Qingjiang river to perform runoff simulations.
- The adaptation mainly focused on soil database and weather generator, so that the model could be modified to suit Chinese situation, in which programs like SPAW, PcpSTAT, Dew02, etc. were adopted to perform the necessary modification.
- Flow simulations were carried out on monthly and daily time steps, the validation accuracies (in terms of E_{NS} values) of which can reach 0.89 and 0.73 respectedly.

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Thank you!

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