

Hydrological behaviour and water balance analysis for Xitiaoxi catchment of Taihu Basin

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Abstract: With the rapid social and economic development of the Taihu region, Taihu Lake now faces an increasingly severe eutrophication problem. Pollution from surrounding catchments contributes greatly to the eutrophication of water bodies in the region. Investigation of surface flow and associated mass transport for the Xitiaoxi catchment is of a significant degree of importance as the Xitiaoxi catchment is one of the major catchments within the Taihu region. A SWAT-based distributed hydrological model was established for the Xitiaoxi catchment. The model was calibrated and verified using hydrometeorological data from 1988 to 2001. The results indicate that the modeled daily and annual stream flow match the observed data both in the calibration period and the verification period, with a linear regression coefficient R^2 and a coefficient e for modeled daily stream flow greater than 0.8 at Hengtangcun and Fanjiacun gauge stations. The results show that the runoff process in the Xitiaoxi catchment is affected both by rainfall and human activities (e.g., reservoirs and polder areas). Moreover, the human activities weaken flood peaks more noticeably during rainstorms. The water balance analysis reveals the percentages of precipitation made up by surface flow, evapotranspiration, groundwater recharge and the change of soil storage, all of which are considered useful to the further understanding of the hydrological processes in the Xitiaoxi catchment. This study provides a good base for further studies in mass transport modeling and comparison of modeling results from similar hydrological models.

Key words: *water balance analysis; distributed hydrological model; SWAT model; Xitiaoxi catchment; Taihu Lake*

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1 Introduction

The eutrophication of Taihu Lake has elicited domestic and international attention. For various reasons, water quality in the Taihu Basin has deteriorated, and eutrophication has developed in many areas of the lake. This is mainly due to the large amount of domestic pollution sources, agricultural non-point source pollution, animal pollution and industrial wastewater that discharge into the drainage network and the water bodies within the Taihu Lake drainage system. The Xitiaoxi River is one of the five major rivers flowing into Taihu Lake, and an important upstream tributary. The mean annual water quantity that discharges into Taihu Lake from the Xitiaoxi River is $26.8 \times 10^8 \text{ m}^3$, which accounts for 27.7% of the

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lake's total mean annual recharge. Meanwhile, it is also the area of the highest precipitation in the Taihu Basin, where surface runoff leads to soil erosion and severe loss of soil nutrition (Yu et al. 2003).

Several recent studies have focused on runoff simulation and other related research in the Xitiaoqi catchment. A surface runoff model was constructed for the Xitiaoqi catchment using a conceptual model, LASCAM. The model was well calibrated using daily runoff data from 1968 to 1988 from two monitoring stations within the catchment. The model indicated that saturation excess runoff was probably the dominant process for the catchment (Zhang et al. 2006; Xu et al. 2006). Flood events in the Xitiaoqi catchment were simulated with the distributed hydrological modeling system HEC-HMS. The findings illustrated that HEC-HMS can be used to simulate the impacts of land use change on hydrological regimes, such as floods (Wan et al. 2007). Based on cartographical modeling and water routing between grids using the PCRaster dynamic environmental modeling language, a hydrological model was developed for the Xitiaoqi catchment, with agreement between the measured and predicted values (Gao and Lu 2005). The SWAT model was used for preliminary simulation of nutrition transport from 1995 to 2002 in the Taihu Basin. The results indicated that the pollution source was mainly from the western part of Taihu Lake (Lai et al. 2005). However, most of the work in the runoff simulation is limited to the model calibration. There is a relative weakness in the water balance analysis, and the proportions of base flow and surface flow contributing to stream flow are not well known from previous studies. In addition, while parameter sensitivity analysis is an important way to validate the model and to evaluate the importance of the model parameters, it has not been conducted in the previous studies.

The purpose of this study was: (1) to separate stream flow into base flow and surface flow using the automated digital filter technique; (2) to analyze the hydrological behaviour in the Xitiaoqi catchment via a rainfall-runoff model based on SWAT; (3) to analyze the sensitivity of several model parameters and to summarize their influences on the modeling results; and (4) to evaluate annual water balance using the output from the model.

2 Data and methods

The Xitiaoqi catchment is situated in Huzhou, a city in northern Zhejiang Province. The catchment covers an area of 2 274 km², accounting for 6% of the Taihu Basin (Figure 1). Generally speaking, the catchment slopes downward from southwest to northeast, and comprises mountains, hilly land and plains, with the elevation ranging from 2 m to 1 585 m. Hilly land, the main landform, is found in the north-central area (Li et al. 2005). The Xitiaoqi catchment has a

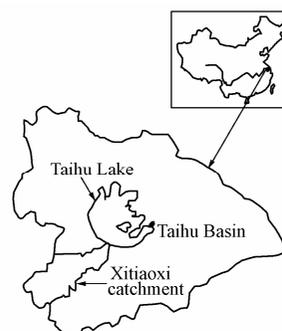


Figure 1 Location of Xitiaoqi catchment in Taihu Basin

subtropical monsoon climate, with a mean annual temperature of 15.5°C and about 241 frost-free days. Its mean annual precipitation is 1465.8 mm, and the spatio-temporal distribution is not well balanced, with about 75% of precipitation occurring in the flood season (from April to October) (Xue et al. 2006). The mean annual potential evaporation from free water surfaces ranges from 800 mm to 900 mm, with about 50% of evaporation occurring between May and August. The land use within the catchment is diversified: it is about 67% woodland and includes some other types, such as arable land, grassland, surface water, residential quarters, industrial or mining districts and non-exploited land. The soil types within the catchment are mainly red soil and yellow soil. The vegetation is subtropical evergreen broadleaf forest with different varieties, dominated by bamboo forest (Yu et al. 2003).

2.1 Model selection

Based on the comparison of advantages and disadvantages of several hydrological models, SWAT was selected for this study, with the following considerations:

(1) SWAT is capable of estimating the impacts of land management practices on water resources. It has proven to be an effective tool for assessing water resources at a wide range of scales under different conditions across the globe (Chanasyk et al. 2003).

(2) SWAT can simulate hydrological processes as well as associated mass transport. This enables us to perform mass transport modeling in future studies.

(3) SWAT is a spatially distributed model, which means that the impacts of spatially variable parameters can be easily modeled. Furthermore, the model is free to use and interfaces with ArcView software, which allows for easy pre- and post-processing of the input and output data (Romanowicz et al. 2005).

(4) The data collected in the Xitiaoxi catchment generally meet the requirements of the model.

2.2 Database setup

The model input data consists of climate, soils, land use and vegetation. Weather data from 1988 to 2001 were obtained from the Anji weather station. These data include daily precipitation, maximum/minimum daily temperature, daily potential evapotranspiration, and relative humidity. The missing daily climate values were filled in using the weather generator model WXGEN. Daily measurement data of ten precipitation stations from 1988 to 2001 were used.

It is well known that the accuracy of the digital elevation model (DEM) will have a strong influence on the final output of the hydrological model (Chaplot 2005). We used a 25-m resolution DEM available for the study area. The river network was recalculated from the DEM, and the length, steepness and cross sections of the channel reaches were automatically determined. Land use can significantly affect the water cycle. The influence of land use on these processes is a function of the density of plant cover and the morphology of the plant species. In this study we used a land cover map derived from Landsat TM/ETM

images from the year 2000. The original land use map consists of a geographical database describing vegetation and land use in 19 classes. A land use map of seven classes was finally derived from the 19-class one and recoded according to the SWAT land use database. The original soil map was also preprocessed in order to match classifications used in SWAT.

Based on a threshold area of 26km², the Xitiaoxi catchment was divided into 47 sub-catchments, which were then subdivided into 180 hydrological response units (HRU). Daily stream flow records were obtained from Hengtangcun and Fanjiacun gauge stations. Fanjiacun gauge station is close to the outlet of the catchment draining approximately 98% of this region. The river network and locations of hydrometeorological stations are shown in Figure 2.

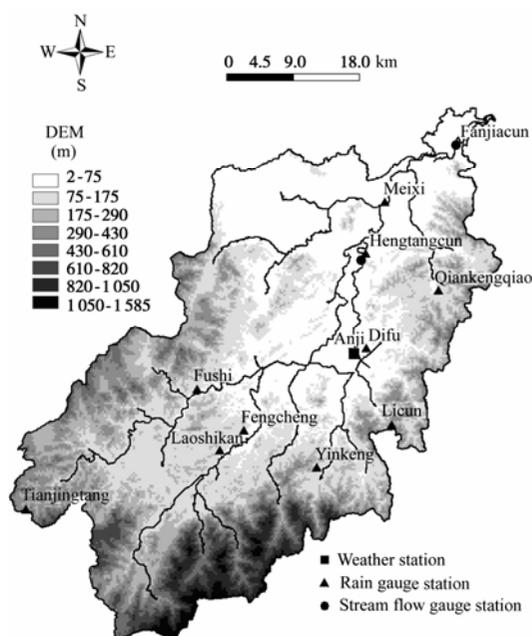


Figure 2 River network and locations of hydrometeorological stations in Xitiaoxi catchment

2.3 Model calibration

The calibration method was as follows (Zhu et al. 2006): First of all, the overall water balance was considered, then the hydrological process. Second, surface flow was considered, then soil water, evapotranspiration and base flow, in that order. Base flow was regarded as the groundwater contribution to the stream flow. Estimates of the amount of base flow and surface flow can be derived from stream flow records. Such estimates are critical in the assessment of flow characteristics of streams used in water supply and water management. Initially, base flow and surface flow were separated from observed stream flow using an automated digital filter technique (Zhang et al. 2003; Arnold et al. 1995). With the observed stream flow included, the program was started by typing the execution file *bflow.exe* on the DOS command line. Daily base flow, the fraction of stream flow contributed by base flow Fr , the base flow recession constant $ALPHA_BF$, and the number of days from the start of base flow recession were printed out (Yang et al. 2003). The base flow and surface flow obtained from this technique were used to calibrate the simulated ones in SWAT. In addition, the separation of observed stream flow records into base flow and surface flow greatly saved parameter calibration time.

The steps of the SWAT calibration process took place in the following order: the annual stream flow was calibrated first; then the daily stream flow was calibrated when the simulated annual surface flow, base flow and evapotranspiration data matched the annual observed data.

During the process of runoff calibration, the SCS runoff curve number for moisture condition II (CN₂) was top-priority as it is the most important parameter for hydrological analysis. The available water capacity of the soil layer (SOL_AWC) was calibrated in the process of soil water simulation. Base flow parameters including ALPHA_BF, the groundwater revap coefficient (GW_REVAP) (Chen and Scott 2004), and the threshold water level in a shallow aquifer for base flow (GWQMN) were all adjusted from the initial estimates to better fit the recession portion of the hydrograph. The soil evaporation compensation factor (ESCO) was also validated in order to simulate soil evaporation. The calibration was performed for the period from January 1988 to December 1995 at Hengtangcun and Fanjiacun gauge stations. Calibrated parameter values are shown in Table 1.

Table 1 Calibrated parameters

Item	CN ₂	SOL_AWC(mm/mm)	ESCO	ALPHA_BF(d)	GW_REVAP	GWQMN(mm)
Range	-8-+8	0-1	0-1	0-1	0-1	0-5 000
Value	-2.0	0.025	0.1	0.16	0.1	200

The validation was carried out for the six years from January 1996 to December 2001 at the same two stations. In the validation process, the model was run with parameters obtained in the calibration process. Statistical values were derived, including the linear regression coefficient R^2 and efficiency e ($e=1-V_{\text{arr}} / V_{\text{aro}}$, where V_{arr} is the variance between observed and simulated values of stream flow and V_{aro} is the variance of observed values) (Zhang et al. 2006). If e values were close to $-\infty$, the model performance was considered unacceptable or poor. If the values were equal to 1, the model prediction was considered perfect.

3 Simulated results and discussion

The simulation was analyzed by comparing the daily and annual observed stream flow with the simulated ones at Hengtangcun and Fanjiacun stations, as shown in Figures 3 through 5. On average, the modeled daily and annual stream flow matched the observed data both in the calibration period and verification period. R^2 and e for the daily stream flow during the calibration period of 1988-1995 were 0.86 and 0.81, respectively, at Hengtangcun, and 0.88 and 0.84, respectively, at Fanjiacun. During the verification period of 1996-2001, R^2 and e for the daily stream flow were 0.89 and 0.85, respectively, at Hengtangcun, and 0.90 and 0.87, respectively, at Fanjiacun. However, compared to the validation results from the two gauge stations, the calibration results seemed to be less accurate, which may have been caused by the fact that reservoirs and other polder areas played an important role in the redistribution of flood discharge. Even though SWAT is capable of representing the influence of reservoirs, two large-scale reservoirs (Fushi and Laoshikan reservoirs) and many other small-scale reservoirs in the upstream Xitiaoxi catchment were not taken into consideration due to the lack of detailed data (storage, leakage, etc.). For example, the impact of large amounts of precipitation from August 31 to September 4, 1990 and from June 20 to 24, 1995 on the simulated flood peak values increased as the influence of reservoirs was not taken into account

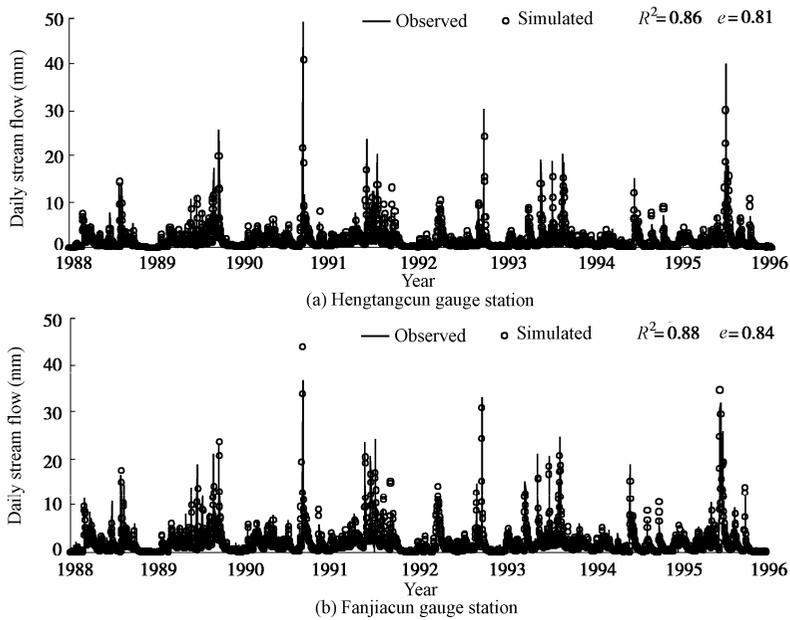


Figure 3 Observed and simulated daily stream flow for calibration period of 1988-1995

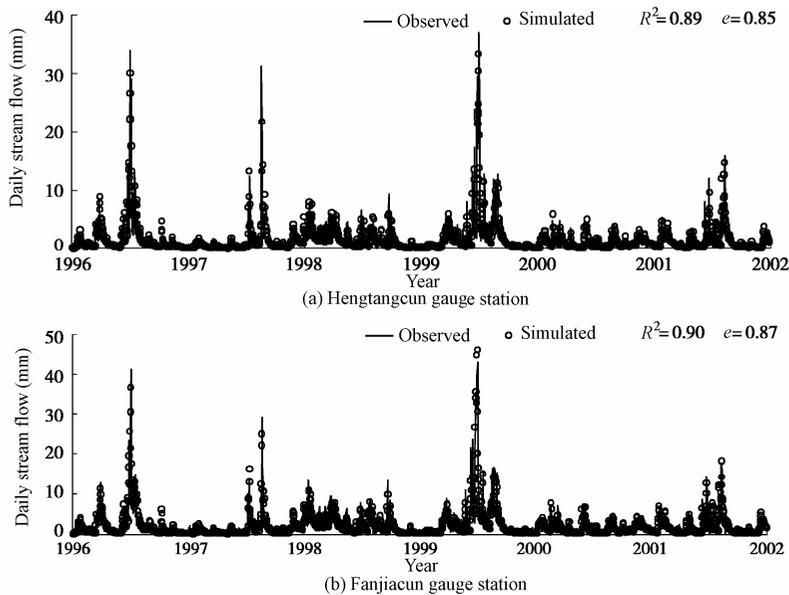


Figure 4 Observed and simulated daily stream flow for verification period of 1996-2001

(Xu 2000). The analysis above indicates that there were some system errors in the simulation, demonstrating that reservoirs and polder areas have a significant effect on the modeled runoff, especially when rainstorms are occurring.

4 Sensitivity analysis

Sensitivity analysis can be used to evaluate the importance of various parameters in a

hydrological model. The three most important parameters selected in this study were CN_2 , SOL_AWC , and $ESCO$. Lenhart et al. (2002) came up with a simple method for sensitivity analysis:

$$I = \frac{(y_2 - y_1)/y_0}{2\Delta x/x_0} \quad (1)$$

This expression is numerically approximated with a finite difference method: I is the sensitivity index and y_0 is the model output calculated with an initial value x_0 of the parameter x . This initial parameter value is varied by $\pm \Delta x$, yielding $x_1 = x_0 - \Delta x$ and $x_2 = x_0 + \Delta x$ with corresponding values y_1 and y_2 . The computation results were $I_{CN_2} = 0.24$, $I_{SOL_AWC} = -0.21$ and $I_{ESCO} = 0.13$. To assess the calculated sensitivity, indices were ranked in four classes (Table 2).

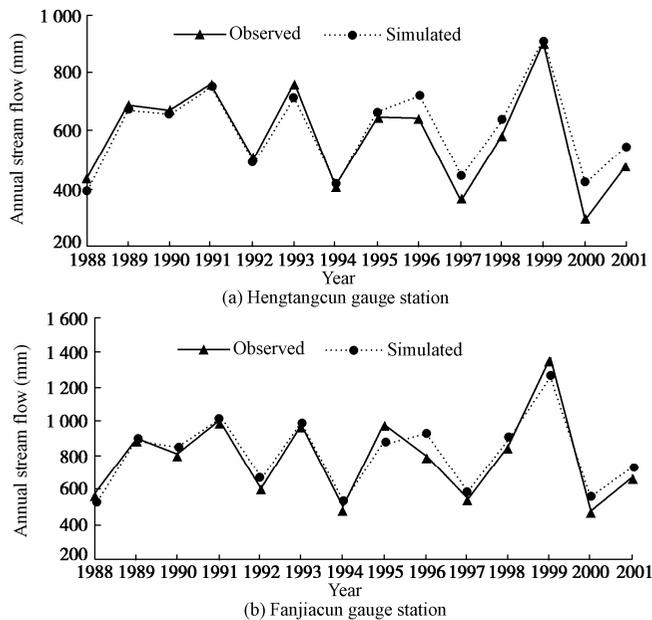


Figure 5 Observed and simulated annual stream flow for the period of 1988-2001

Table 2 Sensitivity classes

Parameter	Class	Sensitivity	Index
	I	Small to negligible	$0.00 \leq I < 0.05$
ESCO	II	Medium	$0.05 \leq I < 0.20$
CN_2 , SOL_AWC	III	High	$0.20 \leq I < 1.00$
	IV	Very high	$ I \geq 1.00$

Plant-specific parameters such as the curve number and physical soil properties such as available water capacity showed a high sensitivity. Runoff was more sensitive to CN_2 than to other parameters. The evaporation compensation factor showed a medium sensitivity. Runoff from the basin will increase with the rise of CN_2 and $ESCO$, and decrease with the rise of SOL_AWC (Saleh et al. 2000; Srinivasan et al. 1998).

5 Water balance analysis

In addition to the comparison of stream flow hydrographs, a reasonable water balance result can further validate the model. The water budget for a basin can be stated as

$$P - E_s - R_{\text{suf}} - R_{\text{pc}} = \Delta S \quad (2)$$

$$R_{\text{pc}} - R_{\text{bf}} - E_g - R_d = \Delta S_{\text{gw}} \quad (3)$$

$$R_{\text{suf}} + R_{\text{bf}} = R_{\text{stf}} \quad (4)$$

where P is precipitation, E_s is evapotranspiration including surface water evapotranspiration and soil evapotranspiration, R_{suf} is surface flow, R_{pc} is groundwater recharge, ΔS is the change in soil storage, R_{bf} is base flow, E_g is shallow groundwater evapotranspiration, R_d is deep groundwater recharge, ΔS_{gw} is the change of shallow groundwater storage, and R_{stf} is stream flow. According to the modeling results, the water budget from 1988 to 2001 was calculated, and it is plotted in Figure 6.

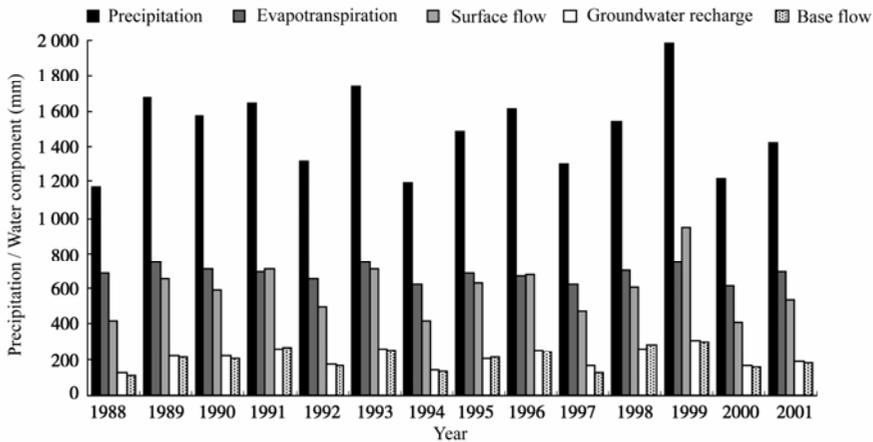


Figure 6 Annual water balance in Xitiaoxi catchment from 1988 to 2001

The results of the water balance analysis are as follows:

(1) The precipitation balance analysis (Eq. (2)) shows that mean annual evapotranspiration and surface flow are 45.9% and 39.7% of mean annual precipitation, respectively. Mean annual groundwater recharge is 14.2% of mean annual precipitation. Groundwater recharge is strongly affected by precipitation and determines the amount of base flow. Besides, mean annual soil water storage change is just 0.2% of precipitation.

(2) In groundwater recharge analysis (Eq. (3)), ΔS_{gw} is assumed to be 0, since there is no output of change of shallow groundwater storage in SWAT. Base flow accounts for 97.2% of the groundwater recharge, which demonstrates that most of the water that percolates into the shallow groundwater later recharges surface water bodies. Deep groundwater recharge and groundwater evapotranspiration are only 2.8% of the total groundwater recharge.

(3) The stream flow analysis (Eq. (4)) indicates that surface flow and base flow are, respectively, 74.1% and 25.9% of stream flow. The surface flow fluctuates with the variation of precipitation. For instance, the lowest recorded annual precipitation value was 1173.16 mm in

1988, and the surface flow that year was 418.22 mm. The highest recorded annual precipitation value was 1980.0 mm in 1999, and the surface flow that year was 941.07 mm. The simulated average daily base flow over the whole Xitiaoxi catchment during the simulation period was 0.74 mm. Figure 7 shows the average daily base flow distribution in the Xitiaoxi catchment. In the northwest plain area, base flow is much greater than that in other areas. In the eastern mountainous area, base flow is less than that in the southern mountainous area. As riverbed elevation, riverbed slope and water table are not considered in the SWAT model, the simulated base flow results cannot be as exact as those obtained by coupled surface water and groundwater models.

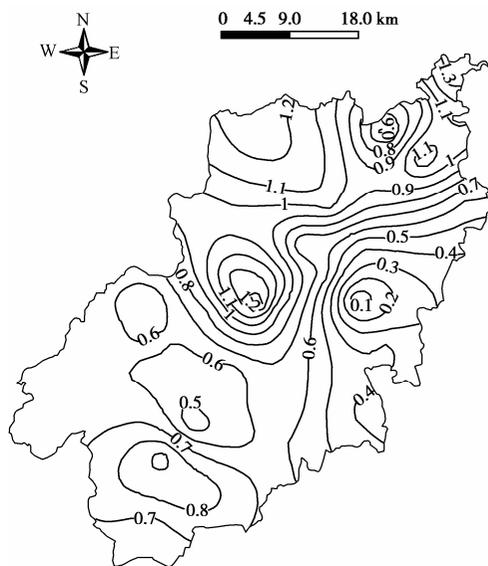


Figure 7 Average daily base flow distribution over Xitiaoxi catchment from 1988 to 2001 (Unit: mm)

6 Conclusions

(1) This paper presents the details of a distributed hydrological model for predicting the daily and annual stream flow in the Xitiaoxi catchment. Calibration and verification of the model against the observed data indicates accurate prediction of total stream flow. The linear regression coefficient R^2 and the efficiency e for the daily stream flow modeled at Hengtangcun and Fanjiacun gauge stations are greater than 0.81 during the calibration period (1988-1995), and greater than 0.85 during the verification period (1996-2001). The outcome of this investigation helps broaden the understanding of dynamic changes of hydrological processes and water quality in Taihu Lake, and is also useful to similar research on other catchments of the Taihu Basin.

(2) The water balance analysis reveals the percentage of precipitation made up by surface flow, evapotranspiration, groundwater recharge, and the change of soil storage: the mean annual evapotranspiration is 45.9%, surface flow represents 39.7% and responds to changes in annual precipitation, and the mean annual groundwater recharge and soil water storage change make up 14.2% and 0.2%, respectively. Base flow accounts for 97.2% of the groundwater recharge, which demonstrates that most of the water that percolates into the groundwater later recharges surface water bodies. Surface flow and base flow are, respectively, 74.1% and 25.9% of stream flow.

(3) A sensitivity analysis was performed for several important parameters. Results indicate that the most sensitive parameters are the SCS runoff curve number for moisture condition II(CN₂), the available water capacity of the soil layer (SOL_AWC), and the soil

evaporation compensation factor (ESCO).

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