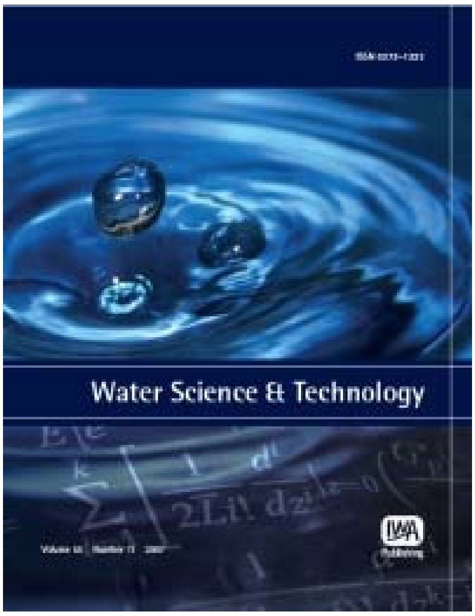
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Application of the SWAT model to the Xiangjiang river watershed in subtropical central China

Qiao Luo, Yong Li, Kelin Wang and Jinshui Wu

ABSTRACT

The Soil and Water Assessment Tool (SWAT) model was applied to simulate the water balance in the Xiangjiang river watershed for current and planning scenarios of land uses. The model was first calibrated for the period from 1998 to 2002 and then validated for the period from 2003 to 2007 using the observed stream flow data from four monitoring gages within the watershed. The determination coefficient of linear regression of the observed and simulated monthly stream flows (R^2) and their Nash–Sutcliffe Index (NSI) was used to evaluate model performance. All values of R^2 and NSI were above 0.8 and ranged from 0.82 to 0.92, which indicates that the SWAT model was capable of simulating the stream flow in the Xiangjiang river watershed. The calibrated and validated SWAT model was then applied to study the hydrological response of three land use change scenarios. Runoff was reduced by increasing the areas of forest and grassland while simultaneously decreasing the areas of agricultural and urban land. In the recent and future land use planning for the Xiangjiang river watershed, the hydrological effect should be considered in regional water management and erosion control.

Key words | land use, model, soil, stream flow, Xiangjiang river

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INTRODUCTION

Water quantity and quality have become serious issues for many regions around the world (Kundzewicz *et al.* 2007). Addressing these issues requires knowledge of how water resources are affected by changes of various aspects of the regional hydrological cycles (Guo *et al.* 2008). Changes in land use modify plant canopy interception and soil infiltration, which in turn affects surface runoff (e.g., Costa *et al.* 2003; Foley *et al.* 2005). The impact of land use patterns on surface runoff is closely dependent on specific study cases and differs at various spatial scales (Stehr *et al.* 2010). For instance, it was found that forest was no better than grassland in conserving water if the canopy cover of the forest was less than that of the grassland in the Loess Plateau of China (Huang *et al.* 1999; Li *et al.* 2009). Temporally, long-term impact of land use changes was more apparent on average annual runoff, whereas short-term impact was often observed for the peak runoff rate (Costa *et al.* 2003; Prowse 2006). Spatially, the land use impact on peak flows was generally most pronounced at a smaller scale, whereas the impact of land use change on the annual water balance was relatively small at larger catchment scales (Fohrer *et al.* 2001).

The Xiangjiang river watershed is located in the central part of China. It is generally rich in water resources, but the temporal distribution is exceptionally uneven during the year. Drought and floods have both occurred frequently in the watershed in recent decades. Between 1949 and 1998, in the middle and downstream watershed, 29 floods occurred, which represents an average of one every 1.7 years. However, the number of drought years, when the water level at the Changsha monitoring station was lower than 26 m, totaled 13 during the period of 1953–2008. For instance, the water level at a selected station declined to 25.15 m on December 14, 2007, which is the lowest level on record (Chen & Huang 2010). In general, the flood season in the Xiangjiang river watershed is from April to August, whereas the drought season starts in September and lasts until the next March. The surface runoff is believed to vary with the land use because of the impacts on evapotranspiration (ET), plant interception and soil water infiltration (Fohrer *et al.* 2001; Li *et al.* 2009). Therefore, a study of the runoff characteristics in the Xiangjiang river watershed is of great significance in optimizing land use

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planning and water resource management to achieve sustainable development and integrative management of the watershed.

Many computer models have been developed to simulate watershed hydrology and water quality processes. Among these models, the Soil and Water Assessment Tool (SWAT) model has been widely used to simulate the runoff, sediment and water quality of agricultural watersheds (Neitsch *et al.* 2005). SWAT is a physically based, semi-distributed, and continuous-time watershed model that is capable of assessing the impact of land use changes, population, agricultural activities and watershed development on water, sediment, and agricultural chemical yields in large complex watersheds with various soil types, land covers and management conditions over long periods (Arnold & Fohrer 2005). In China, SWAT has been applied to various watersheds for hydrological and non-point source pollution modeling. For example, the SWAT model was used to study hydrological responses to climate and land-cover changes in the Poyang lake watershed (Guo *et al.* 2008), the Zamu river (Wang *et al.* 2008) and the Loess plateau (Li *et al.* 2009). Other simulations with SWAT were performed in the Hei (He *et al.* 2008), Chaohe (Yang *et al.* 2007) and Huai (Zhang *et al.* 2010) rivers. However, very few SWAT applications have been reported for the Xiangjiang river watershed system. Lin *et al.* (2012) integrated SWAT with a simple export coefficient to simulate cadmium pollution in the Xiangjiang river basin in Zhuzhou, and He *et al.* (2007) modeled the effect of reservoirs on hydrological processes in the Zhengshui river watershed of the Xiangjiang river system. These studies only focused on a few segments of the Xiangjiang river watershed, and none examined the changing trends of the hydrological variables such as lateral flow and return flow, which tend to be difficult to observe under land use change scenarios at large spatial scales. In this paper, the SWAT model was applied to assess the impact of planned future land use changes on the hydrological processes in the Xiangjiang river watershed.

MATERIALS AND METHODS

Study area

The Xiangjiang river is the largest river in the Dongting lake stream network in subtropical central China (Figure 1). The river system covers an area of 94,660 km^2 and is approximately 856 km long. This area is dominated by a Pacific monsoon climate with an annual mean air temperature of 17.6 °C, an average annual precipitation of 1,400 mm, and an average annual evaporation rate of 1,200 mm (40 years). Because of the impact of high solar radiation and circulation of monsoon weather patterns, stream flow in the Xiangjiang river shows significant seasonal characteristics. As the precipitation in the watershed is usually maximal in May and June, accounting for about 40% of annual precipitation, the region is frequently threatened by storms and floods during this period each year. However, less precipitation occurs in late autumn and winter.

Input data

The SWAT model requires daily meteorological data, such as precipitation, maximum and minimum air temperature, wind speed, relative humidity and solar radiation. Spatial datasets, including a digital elevation model (DEM) map, land use map, and soil map are also required. Meteorological data were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). Within or surrounding the watershed, 17 weather stations were used for retrieving daily observations of maximum and minimum air temperature, sunshine hours, wind speed, relative humidity, and precipitation. Daily solar radiation was converted from the observed sunshine hours. Stream flow data were collected from four stream flow gages in the watershed (Xiangtan, Zhuzhou, Hengshan, and Hengyang). These data were obtained from the Hydrology and Water Resources Bureau of Hunan Province. The geographical locations of weather stations and stream flow gages are shown in Figure 1. DEM map data at a 90-m spatial resolution were acquired from http://srtm.csi.cgiar.org. The current land use map, at a spatial scale of 1:100,000, was obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The land use types were reclassified according to SWAT categories. The soil map, with a spatial scale of 1:1,000,000, was obtained from the Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn). The soil texture, organic matter content and other physical and chemical properties at soil depths of 0–20, 20–40, 40–60 and 60–100 cm were derived from the second National Soil Survey (Internal report, 1987, Department of Agriculture of Hunan Province), whereas soil hydraulic properties were estimated using pedo-transfer functions developed by Saxton & Rawls (2006).

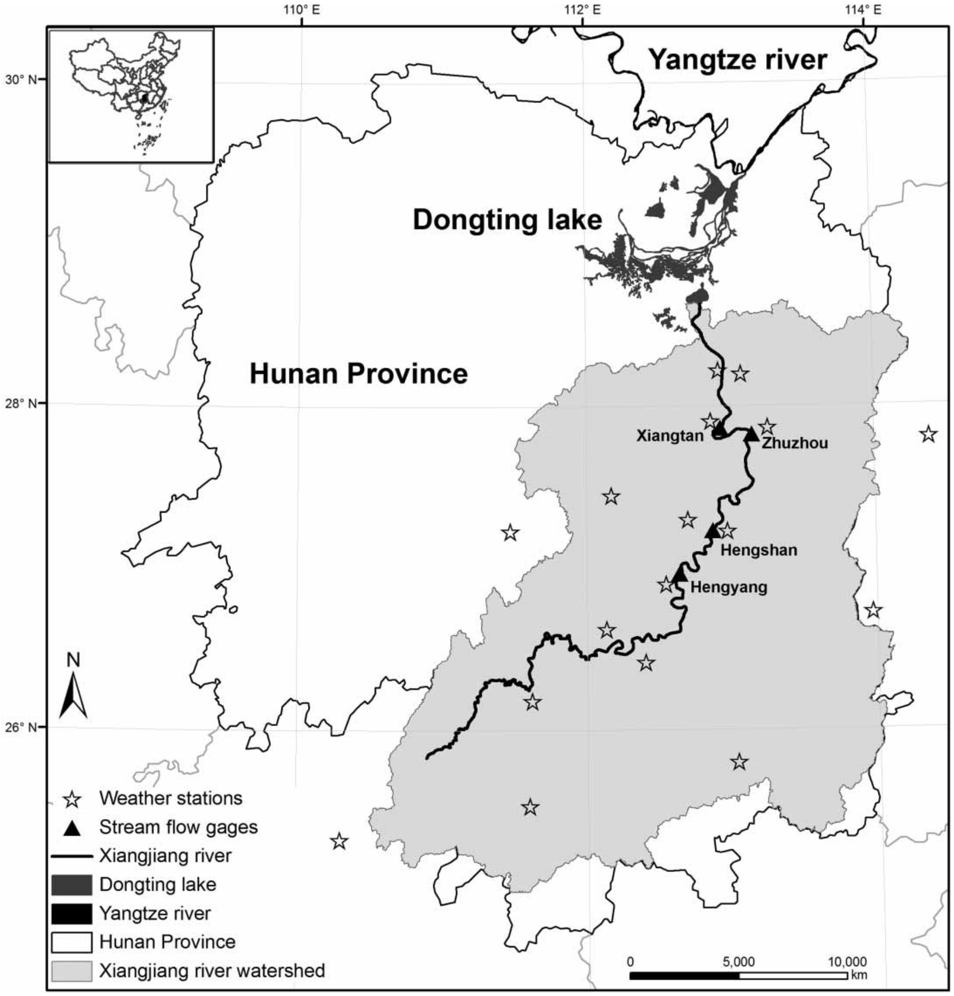

Figure 1 | Geographical locations of the Xiangjiang river watershed, weather stations and stream flow gages.

Model calibration and validation

Sensitivity analysis evaluates how model parameters influence model predictions. Parameters identified in sensitivity analysis that significantly influence predicted outputs are often used to calibrate a model. The Latin Hypercube–One Factor At a Time (LH–OAT) method was implemented in SWAT2005 for sensitivity analysis (Neitsch *et al.* 2005; Nossent & Bauwens 2012) and was used in this study with observed data for the Xiangjiang river watershed. Based on the sensitivity analysis, six parameters were chosen for the calibration of the model: (i) the Curve Number (CN) in the rainfall-runoff equation used in the SWAT model, (ii) the soil available water (SOL_AWC), (iii) the soil evaporation compensation factor (ESCO), (iv) the threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), (v) the groundwater re-evaporation coefficient (GW_REVAP), and (vi) the threshold depth of water in the shallow aquifer system for re-evaporation or percolation to the deep aquifer to occur (REVAPMN).

The SWAT model started first in 1997 with a warm-up period of 1 year. It was then calibrated for the period from 1998 to 2002 and validated for the period from 2003 to 2007 with the observed stream flow data from four national stream flow gages inside the watershed: Xiangtan, Zhuzhou, Hengshan, and Hengyang. The coefficient of determination (R^2) and the Nash–Sutcliffe Index (NSI) for the observation and the model prediction were used to assess the model performance. The R^2 value is an indicator of the statistical significance of relationships between the observed and simulated values, whereas the NSI value indicates how well the plot of the observed compared to the simulated values fits the 1:1 line. The NSI ranges from negative infinity ($-\infty$) to 1, with the highest value indicating a perfect 1:1 fit between the observed and simulated values. The model performance can be evaluated as ‘very good’ if the NSI ≥ 0.75 and 'satisfactory' if the NSI values range from 0.5 to 0.75. A negative NSI value indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Moriasi *et al.* 2007).

To investigate the hydrological response to the change of land use in the Xiangjiang river watershed, three hypothetical land use scenarios were designed according to the document *Comprehensive Land Use Planning of Hunan Province (2006–2020)* (normative document, the People's Government of Hunan Province). The first scenario was generated by transforming farmland with a slope of more than 15° into forest and that with a slope of 5°–15° into grassland, based on the policy of 'ecological restoration' in the planning. The second scenario was established by setting the forest with a slope of less than 5° in the upstream area into farmland but changing the farmland with a slope of less than 5° in the Changsha–Zhuzhou–Xiangtan urban area into construction land, as the plan proposes to 'increase farmland in the upstream area and reduce farmland in the Changsha–Zhuzhou–Xiangtan urban area'. The third scenario was established according to the 'moderate development of reserved resources of cultivated land', in which all unused land with a slope of less than 15° was set as farmland. Table 1 shows the proportions of land use changes under each scenario. The simulated average annual water yield (including runoff, lateral flow, and return flow) and ET of the three scenarios were compared with the original simulation. Paired-sample *t*-test was also performed to test the difference of water balance between the original simulation and the three scenarios on a monthly basis.

RESULTS AND DISCUSSION

Calibration and validation

The calibration and validation processes of SWAT worked well in the watershed. The observed and simulated stream flow for 1998–2007 on a monthly basis at the four monitoring gages is shown in Figure 2. Although the model underestimated stream flows at five points (Mar-98, Jun-98, Jun-01, Aug-02, and Jun-06), it performed well over the whole simulation period. Statistical indices for assessing the model performance at the four different monitoring gages are summarized in Table 2. The values of R^2 ranged from 0.88 to 0.90 during the calibration period, whereas they were between 0.84 and 0.92 during the validation period. The model performance on R^2 indicated that the model can explain at least 84% of the temporal variability of stream flows at any of the four monitoring gages. The values of NSI were all greater than 0.80 during the calibration and validation periods, and the highest NSI (0.90) was observed at Xiangtan stream flow gage during the validation period. Based on the NSI values, the model performance was categorized as 'very good'. Overall, the SWAT model was capable of simulating the stream flow in the Xiangjiang river watershed, and it can be used for further research simulations that relate to land use changes.

Table 1 | Land use changes for the three scenarios

Scenario		Area change (km^2)	Area change rate (%)
Scenario 1	Agriculture to forest	959	1.05
	Agriculture to grassland	5,143	5.61
Scenario 2	Forest to agriculture	8,174	8.92
	Agriculture to urban	338	0.37
Scenario 3	Bare land to agriculture	500	0.55

Response of water yield to land use changes

Because the ultimate aim of the SWAT model application in this study was to examine the hydrological response of the watershed to different land use change scenarios, the simulated annual average water yield, runoff, lateral flow, return flow for different scenarios including the original simulation are summarized in Table 3. It should be noted that the water yield in the SWAT model is composed of runoff, lateral flow and return flow.

Compared with the original simulations, surprisingly, the changes of the predicted average water yield were small on an annual basis (−0.04% to 0.33%) and were not significant on a monthly basis ($p > 0.05$) for all three scenarios (Table 3). According to Guo *et al.* (2008), returning partial or all agricultural lands to forest lands resulted in a small decrease of annual discharge in the Xinjiang river basin of China, and it was attributed to the fact that forest land has a higher rate of water loss by large ET compared to agricultural land. Therefore, the components of water yield as well as ET were analyzed to investigate the difference in water balance under the three scenarios.

Under Scenario 1, the average annual runoff decreased by 15.9 mm from the original simulation, corresponding to a reduction of 5.17% (Table 3). Such a decrease was expected to result from the change of 6,102 km^2 of

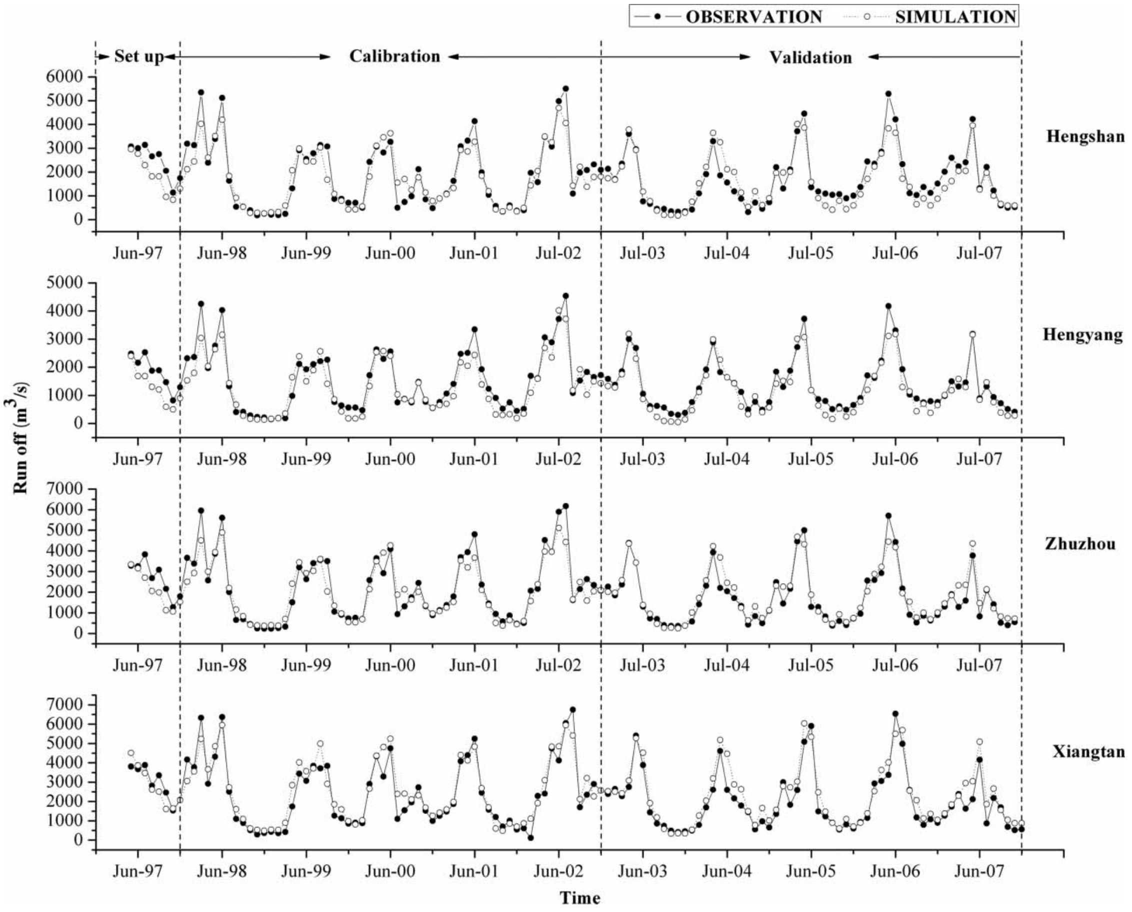

Figure 2 | Observed and simulated stream flows on a monthly basis at four stream flow gages: Xiangtan, Zhuzhou, Hengyang, and Hengshan (calibration: 1998–2002, validation: 2003–2007).

Table 2 | Statistical summary of the model performance at the four monitoring gages

	Calibration		Validation	
Station	R^2	**NSI**	R^2	**NSI**
Xiangtan	0.90	0.87	0.91	0.90
Zhuzhou	0.89	0.82	0.91	0.88
Hengshan	0.88	0.82	0.84	0.82
Hengyang	0.89	0.82	0.92	0.88

agricultural land to forest and grassland, which accounted for 6.66% of the total watershed area (see Table 1). At the same time, the average annual lateral flow and return flow increased approximately by 4.59 and 2.98%, respectively. On a monthly basis (data not shown), all three water components of this scenario were significantly different from the original simulation (Table 3), indicating a significant change of their monthly temporal patterns. Under Scenario 2, the average annual runoff increased by 15.6 mm, which corresponded to an increase of 5.07% (Table 3), resulting from 8,174 km^2 of the forest being reclaimed for agriculture in the upstream watershed and 338 km^2 of agricultural land being developed for urban area in the downstream watershed, accounting for 9.29% of the total watershed area (see Table 1), whereas the average annual lateral flow and return flow decreased by about 0.38 and 2.82%, respectively. Similar to Scenario 1, all three water components of this scenario were significantly different from the original simulation on a monthly basis (Table 3). Under Scenario 3, the average annual runoff increased by only 1.1 mm due to 500 km^2 of unused arable land being reclaimed for agriculture land (see Table 1), and such a small increase was also reflected by the insignificant difference from the original simulation on a monthly basis (Table 3). However, although the average annual lateral flow and return flow were decreased by only 0.09 and 0.32%, respectively, their monthly temporal patterns were significantly different from the original

Table 3 | Simulated average annual water components under the three scenarios

Scenario	Water yield (mm)	Runoff (mm)	Lateral flow (mm)	Return flow (mm)	ET (mm)
Original simulation	851.4	307.8	106.7	436.9	757.3
Scenario 1	853.4 (0.23^a, 0.186^b)	291.9 (−5.17, 0.004)	111.6 (4.59, 0.000)	449.9 (2.98, 0.000)	753.8 (−0.46, 0.052)
Scenario 2	854.2 (0.33, 0.115)	323.4 (5.07, 0.008)	106.3 (−0.38, 0.000)	424.6 (−2.82, 0.000)	755.3 (−0.26, 0.427)
Scenario 3	851.1 (−0.04, 0.203)	308.9 (0.36, 0.545)	106.6 (−0.09, 0.017)	435.5 (−0.32, 0.000)	757.7 (0.05, 0.004)

[a] Relative changes (%) compared with original simulation on an annual basis.

[b] *p* value of the paired-sample *t*-test on a monthly basis, with a value <0.05 indicating a statistically significant difference compared with original simulation.

simulation (Table 3). For the simulated ET, it was interesting to observe that its average annual amount under Scenario 3 was increased by only 0.05% compared with the original simulation (much smaller than those of the other two scenarios, see Table 3). But, its average monthly amounts were tested significantly different from the original simulation, which were not shown under Scenarios 2 and 3.

It is worth mentioning that the runoff was negatively related to the lateral flow and the return flow for Scenarios 1 and 2. Under Scenario 1, the runoff was reduced, whilst the lateral flow and the return flow were increased. Such a result might be explained by the increase of forest and grassland and its impact on the character of land surface, thus affecting the concentration time of the quick runoff component and increasing internal water storage and the water loss to deep groundwater, and vice versa for Scenario 2. In other words, the changes in lateral flow and return flow, which also contribute to stream flow but are hard to observe, may compromise the change of runoff due to the land use change. Our results were consistent with the findings by Fohrer *et al.* (2005), which revealed that an increasing peak flow rate could be observed under the situation of deforestation. Furthermore, it was expected that the runoff was reduced when steeper agricultural land changed to forest (>15°) and grassland (5°–15°). Fohrer *et al.* (2005) also found that catchments with steeper slopes were particularly susceptible to land use change, where a significant increase in quick runoff components due to deforestation was displayed.

The small variation of runoff under Scenario 3 can probably be explained by the limited change of land uses. Li *et al.* (2007) reported that there was no significant impact on the water yield and river discharge when the deforestation percentage was below 50% or the overgrazing percentage below 70% for savanna and 80% for grassland areas in West Africa. Stednick (1996) suggested that as little as 15% of the catchment area could be harvested for a measurable increase in annual water yield at the catchment level in the Rocky Mountain region. Nevertheless, the specific value of the threshold was of no concern here, as Scenario 3 was based on the policy of the 'moderate development of reserved resources of cultivated land', in which all unused land with a slope of less than 15° is set to farmland to produce more grains. ET increased because crops were grown on the unused land, and lateral flow and return flow decreased consequently.

CONCLUSIONS

The SWAT model performed well in simulating the general trends of monthly stream flows at the four stream flow monitoring gages. With the further simulations for the three land use change scenarios, not the total water yield but its components such as runoff, lateral flow, and return flow were susceptible to the planned land use changes.

From a hydrological point of view, however, changes in land use proposed by *Comprehensive Land Use Planning of Hunan Province (2006–2020)* should be fully studied, as the simulated runoff was reduced by increasing the areas of the forest and grassland (Scenario 1) and was increased by increasing the areas of agricultural land and urban areas (Scenario 2). Such changes in runoff would, in general, be indicative for regional water management and erosion control.

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