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RESEARCH ARTICLE

Assessing effects of land use and land cover changes on hydrological processes and sediment yield in the Xunwu River watershed, Jiangxi Province, China

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Abstract The effects of land use and land cover changes on hydrological processes and sediment yield are important issues in regional hydrology. The Xunwu River catchment located in the red soil hilly region of southern China has experienced drastic land use changes in the past 30 years, with orchard increases of approximately 42% and forest decreases of approximately 40%. These changes have resulted in some alterations of runoff and sediment yield. This study aims to evaluate effects of land use/land cover on runoff and sediment yield in the Xunwu River catchment. The SWAT model (Soil and Water Assessment Tool) was used for runoff and sediment simulation, and the results met the requirements of the model acceptance based on evaluation statistics of R^2 (the coefficient of determination), *PBIAS* (percent bias), and *NSE* (Nash-Sutcliffe efficiency). Four land use scenarios representing the gradual expansion of orchards in the past 26 years were developed for assessment of hydrological processes and sediment yield simulation. As a result, both runoff and sediment yield were changed insignificantly with decrease rates of 1.84% and 5.29%, respectively. In addition, surface runoff accounts for the largest share of the runoff components, but the lateral flow changed more than other runoff components with a decrease rate of 10.96%. The results show that orchard expansion does not reveal severe water and soil loss. This study can contribute to the rational utilization of land and water resources in the red soil hilly area of southern Jiangxi Province.

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1 Introduction

Land use and land cover change (LUCC) is widely regarded as one of the most important factors leading to environmental change worldwide (Schmalz et al., 2015; Rafaai et al., 2020; Zhang et al., 2020a). Most areas of the world have experienced drastic land use/land cover change in recent years. These changes are the result of many causes including the natural evolution of vegetation and human activities such as afforestation/deforestation, agriculture, settlement, industry, etc. LUCC is one of the two foremost drivers for changes in hydrological processes and soil erosion, and the other one is climate change (Kundu et al., 2017; Shrestha et al., 2017; Liang et al., 2020). LUCC has significant impacts on water availability and runoff components, including surface runoff, groundwater flow, lateral flow, soil properties, evapotranspiration, etc. (Gashaw et al., 2018). Also, LUCC can alter soil erosion through vegetation cover and interception, especially at the plot or catchment scale, and it has a predominant influence on erosion rather than other environmental characteristics (Valentin et al., 2008). Although the loss of soil material from catchments may vary in different sites and situations, it will be several times greater under cultivation conditions than in natural conditions (Gafur et al., 2003). Removal of large areas of forest will have comprehensive impacts on the timing and volumes of water and sediment yield and lead to water and soil erosion problems in a region. The analysis of the influence of land use/land cover change on runoff and sediment yield and its driving factors can provide valuable information for governments to formulate strategies for water resources management and land use planning (Maalim et al., 2013).

In general, three methods are usually used for evaluating the effects of land use/land cover change on hydrological components and sediment yield, these are the paired catchment method, time series analysis method, and hydrological modeling method (Zuo et al., 2016; Zhang et al., 2020b). 1) The paired catchment method is used for two similar catchments with similar climate, areas, shapes, vegetation and soils. In the first three or four years, they remain the same (Bosch and Hewlett, 1982; Brown et al., 2005). Then, the land use/land cover is artificially changed such as afforestation or deforestation in one catchment, while the other catchment keeps the original condition. After some years, the runoff and sediment yield for both basins are compared to analyze the LUCC influence to hydrological processes and soil erosion/sediment yield. This method is generally regarded as the most accurate method to quantify the land use effects at a catchment scale. However, it is time-consuming and difficult to find two similar catchments. 2) The time series analysis method includes flow duration curves, double mass curves, redundancy analyses, multi-statistical regression models, and so on (Arrigoni et al., 2010; Li et al., 2012). This method is widely used in variation analyses of hydrological processes with highly applicable and simple forms. However, this method lacks consideration of a physical mechanisms; thus, it cannot be used to analyze the spatial heterogeneity of a catchment, the LUCC mechanisms, and the spatial variation of hydrological elements. 3) The hydrological modeling method is gradually emerging with development of computer science, GIS (Geographic Information System), and RS (Remote Sensing) technologies. Hydrological models provide useful tools to analyze the effects of the land use change on hydrological processes and soil erosion (Yang et al., 2020). Among them, distributed hydrological models such as SWAT (Soil and Water Assessment Tool) (Anand et al., 2018), TOPMODEL (TOPographic MODEL) (Gumindoga et al., 2011), SHE (Rujner et al., 2018), SVAT (Soil–Vegetation–Atmosphere–Transfer) (Olchev et al., 2008), WEPP (Water Erosion Prediction Project) (Nearing et al., 1989), HSPF (Hydrological Simulation Program-Fortran) (USEPA, 2014), and so on have been widely applied to watershed hydrology research because most of the model parameters are related with characteristics of catchment structure. The SWAT model is considered to be one of the most appropriate models for evaluating water quality and water quantity in watersheds with different land use, soils, and management measures (Gassman et al., 2007, 2014; Shrestha and Wang, 2018, 2020; Marin et al., 2020).

In China, with the rapid economic growth and accelerating urbanization in the past several decades, the underlying surface has changed dramatically resulting in a series of ecological and environmental problems, such as desertification, soil erosion, extreme hydrological disaster events, and water pollution problems (Borrelli et al., 2017). In the red soil hilly region of southern China, there is a special landscape of “Green hills in the distance, water losses and soil erosion nearby” due to the dual influence of natural and human activities (Zhang et al., 2014a; Li et al., 2020). On the one hand, the natural causes include the characteristics of red soil, high rainfall intensity, slope, etc. On the other hand, human activities involve excessive resource exploitation and dramatic changes in land management, such as aerial afforestation from the 1960s to the 1990s in the red soil hilly area of southern Jiangxi Province, China. In the 1990s, the area of woodland was more than 80% of the total area. However, the land use/land cover has changed dramatically in the past 30 years (Wang et al., 2009; Li et al., 2020). In the 1990s, the main land use type was forest. Then with the promotion of government policies, the area of orchards has expanded rapidly (Fig. 1). The orchard area increased from 9.77 km^2 in 1990 to 2200.34 km^2 in 2016. In addition, comparing the results of land use classification in 1990 and 2016, 87.23%, 11.08%, and 1.54% of the increased orchard area were derived from forest land, shrub land and arable land, respectively (Xu et al., 2018). In general, drastic land use changes will inevitably have a significant impact on hydrological characteristics of the basin, which have been proved by numerous studies. The phenomenon of large-scale conversion of forest land to orchard in the short-term is uncommon, and we assume that it will have an important impact on hydrological processes and sediment yield. Duan et al. (2021) found that orchard expansion at seedling stage as well as lack of terraces and surface coverage would aggravate the water and soil loss. In addition, soil and water loss decreases as the fruit trees mature, along with surface coverage increase and terraces construction.

Most of the existing studies have focused on the rainfall-runoff plot scale (Wang et al., 2011; Liu et al., 2016; Tang et al., 2021; Tu et al., 2021a). And terracing was confirmed to be effectively reduce the water and soil loss by runoff plots experiment. This method could provide information that is deemed important. However, it was only applied to a small watershed or a small-scale region due to the experimental site, conditions, and statistical material. Also, it inevitably involved considerable uncertainty and did not fully represent the efficacy of soil and water conservation measures on regional-scale (Niu et al., 2021). Moreover, it is necessary to assess the water and soil loss after decades of orchard development in southern Jiangxi. However, knowledge on the responses of hydrological processes and sediment yield to rapid orchard expansion and management practices remains scarce at the mesoscale catchment scale.

Therefore, research on the effects of rapid orchard expansion on hydrological processes and sediment yield at a watershed scale is urgently needed in order to provide a scientific advice for local water and land resources management.

The purpose of this study is to evaluate the performance of SWAT and the responses of hydrology and sediment to land use/cover change in the red soil hilly area of southern China. The Xunwu River watershed was selected as a case study area. The objectives of the current study are as follows.

1) Analysis of the characteristics of orchard expansion over the past 30 years in the red soil hilly area of southern China.

2) Evaluation of the performance and the applicability of the SWAT model in simulating runoff and sediment yield in the Xunwu River watershed and assessment of the effects of orchard expansion on hydrological components and sediment yield under four land use scenarios.

3) Comparison of the difference of hydrological components including surface runoff, lateral flow, and groundwater flow among three land use types: orchard, forest, and arable land on the HRU (hydrological response unit) scale.

2 Materials and methods

2.1 Study area and characteristics

The Xunwu watershed (24°30′N–25°15′N, 115°20′E–115°60′E) is the main source of the East River watershed, which is the main tributary of the Pearl River, the second largest river in China according to runoff (Fig. 2(a)). Additionally, it is the source of drinking water for the residents of Hong Kong and Guangdong. The Xunwu River is 138 km long and covers an area of 1841 km^2. The Shuibei hydrological station monitors a drainage area of 995 km^2 and a river length of 86 km. The landforms of the basin mainly include mid-elevation and low mountains, low hills, deep river valleys, and high and steep terrain. The elevations range from 130 to 1493 m. The soil types in the Xunwu Basin are mainly red soil and yellow-red soil, which account for approximately 79% of the total based on the soil map (Fig. 2(b)). Soil types include Ferric Alisols, Ferric Alisols and Ferric Alisols according to the legend of world soil map published by FAO/UNESCO. The organic matter content of red soil is approximately 1%–5%. The soil is sticky and the water permeability is low. The soil is acidic or strongly acidic, and plants cannot grow well

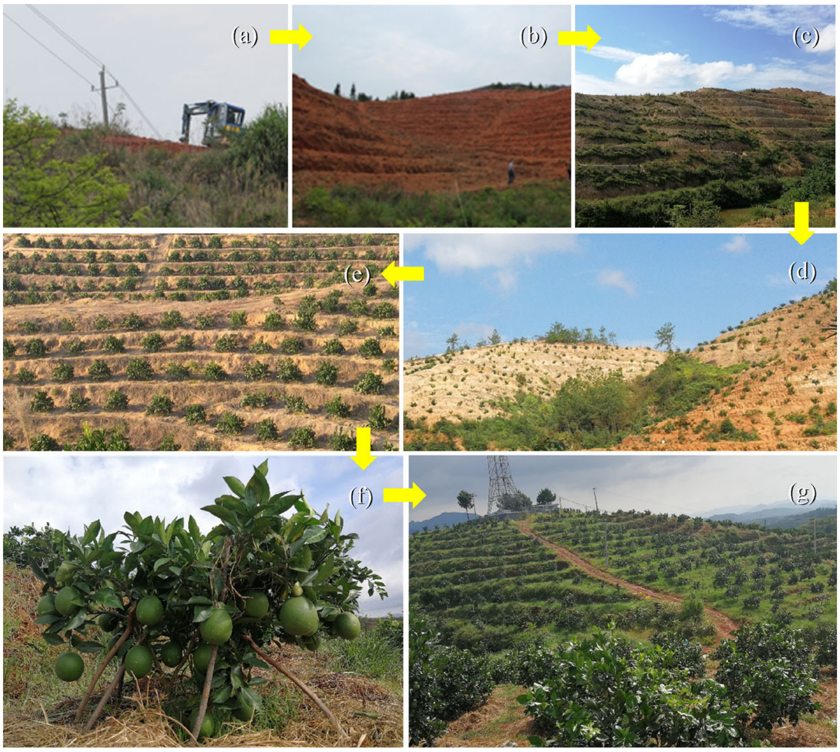
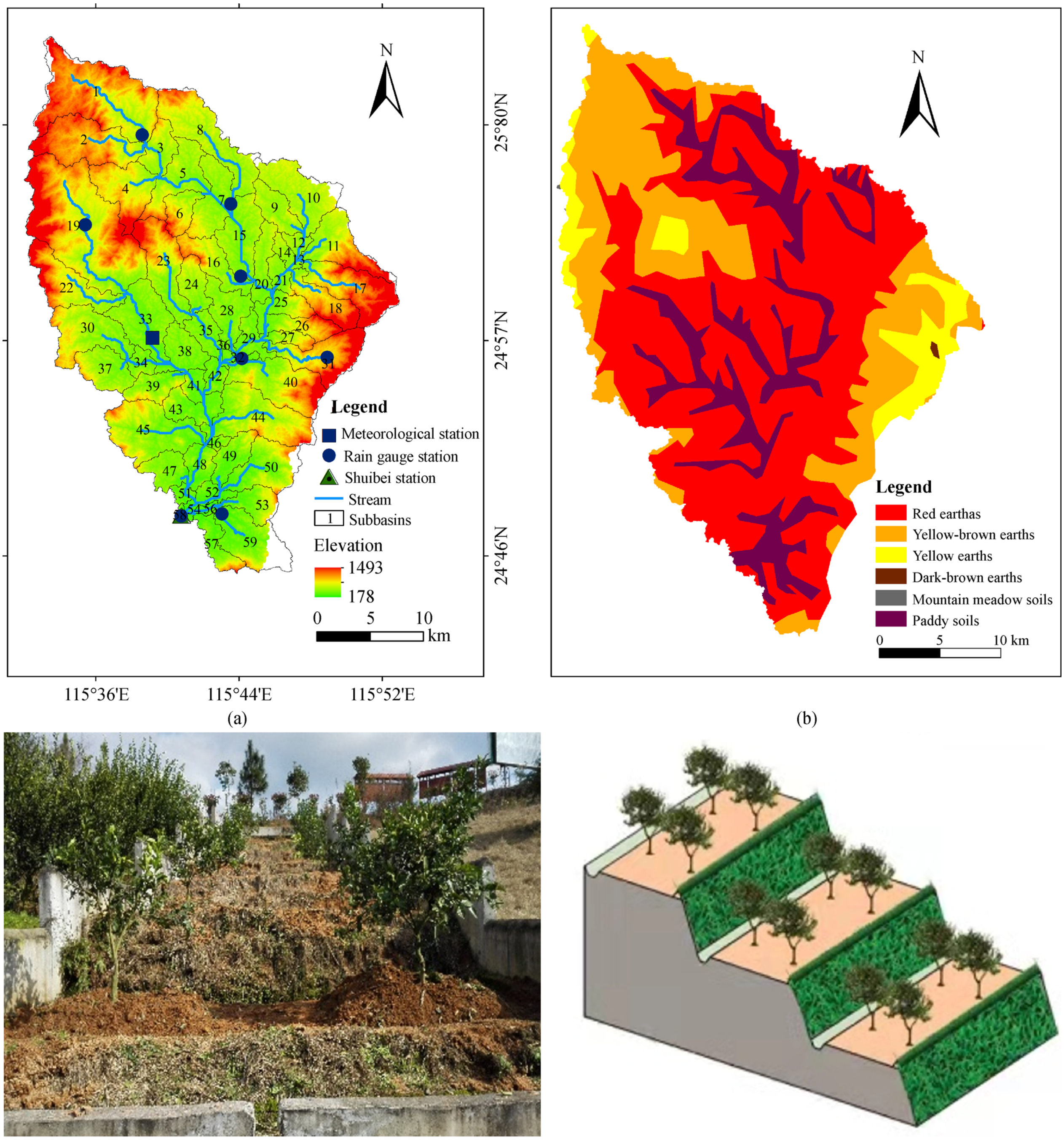


Fig. 1 A general orchard development process in the red soil hilly area of southern China. (a) Removing native land cover (forest is the majority of the original land use); (b) bare land before orchard planting (although there are soil and water conservation measures, soil erosion is very serious); (c) newly planted orchard tree seedlings (grass began to grow at this stage); (d) one year old orchard trees (soil erosion remains severe); (e) two year old orchard trees; (f) three year old orchards trees with fruit (increased surface coverage and reduced soil erosion); (g) mature orchard (four or more years old, with only slight soil erosion).



(a)

(b)

(c)

Fig. 2 (a) Locations of the study area, climate stations, rainfall gauge stations, hydrological stations, and subbasins in the Xunwu River watershed; (b) soil map; (c) orchard terrace with grass planting in front ridge, back ditch and ladder wall (Duan et al., 2021).

resulting in infertile land (Ministry of Water Resources of China, 2010). A variety of measures have been undertaken to improve the soil in recent decades. The land use types are dominated by forests and orchards, which account for approximately 87.6% of the total based on the land use map of 2015. Additionally, the land uses include farmland, construction land, and water bodies.

The climate in the basin belongs to the south Asia mild and humid subtropical climate. The annual rainfall is 1600 mm. It is unevenly distributed throughout the year and is concentrated from March to September; this period accounts for approximately 81% of the annual rainfall. The annual temperature is 19.2°C. The extreme maximum temperature is 38.3°C and the extreme minimum temperature is −5.5°C (Ye et al., 2020). The rainstorms often occur from May to August, which are prone to floods and inundation disasters. In addition, the study area is subject to intense human activities and significant land use changes. One of the more significant activities is the development of orchards, which cause varying degrees of effects on water resources and sediment yield. Orchard plantation mainly refers to citrus trees (Tu et al., 2021b), including navel oranges, tangerines, grapefruits, etc., and navel oranges are absolutely dominant in the Xunwu River watershed. Gannan navel oranges are well known in China and abroad due to their good taste and appearance. Various terracing techniques have been widely used to reduce water and soil loss in the orchard area in recent years. And the orchard terrace with grass planting in front ridge, back ditch and ladder wall (Duan et al., 2021) was considered to be the most effective measure and has been widely applied to the red soil hilly region of southern China (Fig. 2(c)).

2.2 Model data input

The data involved in the SWAT model include spatial data, such as the digital elevation model (DEM), land use data, and soil type and physical property data (Table 1). The watershed DEM data were derived from ASTER GDEMV2 and downloaded from Geospatial Data Cloud website and the spatial resolution is 30 m × 30 m; the land use data were obtained by interpreting remote sensing TM (Thematic Mapper) images. The landscapes of the Xunwu watershed are divided into six types: forest land, orchard land, agricultural land, construction land, unused land, and water area; the soil data were divided into six soil types. It was extracted from the soil map (1:500000) of Jiangxi Province, which is based on the second national soil survey; the soil hydrological parameters of SOL_AWC (soil available water capacity), SOL_BD (soil bulk density), and SOL_K (soil saturated hydraulic conductivity) were calculated using the software of SPAW (Soil Plant Air Water), which was developed by the USDA (Rao and Saxton, 1995); the SNAM, SOL_ZMX, SOL_Z, and SOL_CRK parameters were obtained from field investigations and laboratory analysis; the SILT, ROCK, CLAY, and SAND parameters were calculated using the cubic spline interpolation method in MATLAB; SOL_CBN represented the values of the soil organic matter content and multiplied by 0.58; and SOL_ALB parameter was calculated using the equation of $0.2227 \times \mathrm{EXP}(-1.8672 \times \mathrm{SOL\_CBN})$; HYDGRP parameter was obtained from a table in the ArcSWAT documentation. The red earths, yellow earths, yellow-brown earths, and dark-brown earths belonged to B soil hydrological group according to the calculation results of the minimum infiltration rate. The paddy soils and mountain meadow soils were divided into C and D soil hydrological group; the default values were used for the parameters of SOL_EC, ANION_EXCL, and TEXTURE. The meteorological inputs driving the model, consisted of data from eight daily precipitation gauges (2007–2018) from the Jiangxi Provincial Meteorological Bureau, and data from one detailed weather element gauge (1980–2018) from the CMDC (China Meteorological Data Service Center). To calibrate the hydrological model, continuous daily runoff and daily sediment discharge records (2009–2018) at the Shuibei station (24.7988°N, 115.6783°E) were provided by the PHRSU (Provincial Hydrological Resources Survey Bureau) of Jiangxi and the Municipal Hydrology Bureau of Ganzhou city. The distribution of hydrological station and meteorological gauges is shown in Fig. 2. The data are listed in Table 1.

2.3 Model setup and parameter calibration

The SWAT model is a semidistributed hydrological model developed by the USDA-ARS (US Department of Agriculture, Agricultural Research Service), which operates on a daily time step (Arnold et al., 1998). It can estimate the effects of land use/land cover changes and human activities on the runoff elements, sediment transport, and agricultural pollutants in response to different soil types and diverse management conditions (Zhang et al., 2014b; Tan et al., 2020). Runoff components are calculated using the water balance equation, and sediment yield in each HRU (Hydrological Response Unit) is calculated using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975; Neitsch et al., 2011). The Xunwu River watershed was divided into 59 subbasins according to a convergence area of 1000 ha and 464 HRUs based on the land use, soil, and slope thresholds of 10%, 20%, and 20%, respectively. In addition, the slope was divided into 5 types based on the "Technical Regulations for Dynamic Monitoring of Regional Soil and Water Loss" promulgated by the General Office of the Ministry of Water Resources of China, with values of 0°–5°, 5°–8°, 8°–15°, 15°–25°, and ≥25°. In the red soil hilly area, agricultural activities are prohibited in areas with slopes greater than 25° to reduce soil erosion.

The land use classes were parameterized with their specific management scheme for the land management setup (Table 2). The effects of terraces and grass filter strips in orchard were considered through parameters of CN2, USLE_P, and OV_N. In particular, the USLE_P factor as support practice factor was adjusted in the model setup, thus it expresses the protective impact of terraces on erosion and is included in the calculation of soil loss. Also, the plantations were cultivated and harvested mainly by hand so that no severe soil compaction occurs, as is the case when using heavy machinery. The changed parameters were mainly in the orchard areas. In addition, the management parameters in croplands used default values due to the lack of detailed crop cultivation data. Additionally, default parameters also used in the forest area (Arnold et al., 2012).

The period of 2009–2011 was used for model calibration, 2012–2014 was used for model validation on monthly scale, and 2008 was the model warm-up period. For

Table 1 The data sets used in the SWAT model for the Xunwu River watershed

Name	Spatial/Temporal resolution	Source
DEM	30 m	ASTER GDEM
Land use	30 m (1990–2016)	Downloaded from the National Earth System Science Data Center website
Soil	30 m	Obtained from 1:500000 soil vector maps of Jiangxi Province
Climate	Daily (1980–2018)	China Meteorological Data Service Center (CMDC)
Rainfall	Daily (1980–2018)	Jiangxi Provincial Meteorological Bureau
Runoff	Daily (1980–1992, 2009–2018)	Jiangxi Provincial Hydrological Resources Survey Bureau and Ganzhou Hydrology Bureau
Sediment	Daily (2009–2018)	Jiangxi Provincial Hydrological Resources Survey Bureau and Ganzhou Hydrology Bureau

Table 2 The land management setup in the SWAT model in the Xunwu River watershed

Name	Areal percentage/%	Date	Operation	Comment
ORCD	39.22	1st March	Fertilization	NPK 15-15-15
		1st July	Fertilization	NPK 15-15-15
		15th August	Fertilization	Elemental N
		15th December	Harvest Bench Terraces & filter strips	
FRST	51.83	default	default	
AGRL	7.70	default	default	
URHD	1.21	default	default	
WATR	0.04	default	default	

Notes: ORCD, FRST, AGRL, URHD, and WATR represented orchard, forest, cropland, constructed land, and water, respectively. NPK 15-15-15 represented the same ratio of *N*, *P* and *K*, and Elemental *N* means only nitrogen fertilizer was applied.

parameter calibration, first, the hydrological parameters were calibrated. Then, sediment calibration was done based on the best runoff simulation. When the model evaluation index values were satisfactory, the model parameter calibration process was complete. Afterwards, the calibrated parameters are used as simulation parameters to modify the model. The “sensitivity analysis” tool of arcswat2009 was used to fix and rank the main sensitive parameters (Table 3). Then their values were calibrated by the “manual calibration helper” tool and “edit sub-basin inputs” tool. The relatively sensitive parameters for the runoff were CN2, RCHRG_DP, ESCO, GWQMN, CH_K2, REVAPMN, GW_REVAP, ALPHA_BF, SOL_AWC, SOL_Z, SURLAG, SLSUBBSN, and SLOPE. Following runoff calibration, sediment calibration was done using the SPEXP, SPCON, USLE_P, USLE_K, and PRF parameters (Table 3).

2.4 Performance evaluation coefficients for SWAT

Several coefficients including the R^2 (coefficient of determination), *NSE* (Nash-Sutcliffe efficiency) and *PBIAS* (percent bias) were selected to evaluate the model performance in the calibration and validation periods (Moriasi et al., 2007; Ma et al., 2019).

Generally, the values of the criteria for evaluating the model performance can be divided into 4 groups based on previous studies: very good performance ($0.8 < R^2 \leqslant 1$, $0.75 < NSE \leqslant 1$ and $|PBIAS| \leqslant 10$), good performance ($0.7 < R^2 \leqslant 0.8$, $0.65 < NSE \leqslant 0.75$ and $10 < |PBIAS| \leqslant 15$), satisfactory performance ($0.5 < R^2 \leqslant 0.7$, $0.5 < NSE \leqslant 0.65$ and $15 < |PBIAS| \leqslant 25$) and unsatisfactory performance ($R^2 \leqslant 0.5$, $NSE \leqslant 0.5$ and $|PBIAS| \geq 25$).

2.5 The interannual variation characteristics

Several coefficients including the C_v (Coefficient of variation), *K* (Absolute variability ratio), and *A* (Inter-annual nonuniform coefficient) were selected to analyze the interannual variation characteristics of hydrometeorological data (Li et al., 2004).

The C_v is estimated as

$$C_\mathrm{v} = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(R_i - R_\mathrm{m})^2}}{R_\mathrm{m}}, \tag{1}$$

where R_i, R_m are observed and mean observed value (rainfall, runoff, or sediment yeild), respectively. And N is the total number of data records. C_v value ranges from 0 to 1 and the optimal value of is 0.

The *K* is estimated as

Table 3 Model parameters, the order of parameter sensitivity, the range and fitted values during the final iteration of the calibration process

Rank	Parameters*	File	Definition	Range	Fitted value
1	*m*_CN2	.mgt	SCS runoff curve number	35–98	0.08
2	*r*_SURLAG	.bsn	Surface runoff lag time	0.05–24	2
3	*r*_USLE_P	.mgt	USLE equation support practices (P) factor	0–1	0.13
4	*r*_CH_N2	.rte	Manning's "*n*" value for the main channel	0–0.3	0.26
5	*a*_SLOPE	.hru	Mean slope within the HRU	0–0.6	0.02
6	*r*_ESCO	.hru	Soil evaporation compensation factor	0–1	0.48
7	*r*_SPCON	.bsn	Linear parameters for sediment	0.0001–0.01	0.0001
8	*a*_SOL_Z	.sol	Depth from soil surface to bottom of layer	0–3500	−50
9	*r*_ALPHA_BF	.gw	Baseflow alpha factor	0–1	0.04
10	*r*_GWQMN	.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	0–5000	4908
11	*r*_CH_K2	.rte	Effective hydraulic conductivity in main channel alluvium	0–500	146
12	*m*_SLSUBBSN	.hru	Average slope length	10–150	0.14
13	*m*_SOL_AWC	.sol	Available water capacity of the soil layer	0–1	0.11
14	*r*_SPEXP	.bsn	Exponent parameter for sediment re-entrainment	1–1.5	1.3
15	*r*_REVAPMN	.gw	Threshold depth of water in the shallow aquifer for "revap" to occur	0–500	9.57
16	*r*_GW_REVAP	.gw	Groundwater "revap" coefficient	0.02–0.2	0.1
17	*r*_RCHRG_DP	.gw	Deep aquifer percolation fraction	0–1	0.8
18	*r*_USLE_K	.sol	USLE equation soil erodibility (K) factor	0–0.65	0.2
19	*r*_OV_N	.hru	Manning's "*n*" value for overland flow	0.01–30	18.5
20	*r*_PRF	.bsn	Peak rate adjustment factor for sediment routing in the main channel	0–2	1.5

Notes: *The initials represent the methods used to fix the values of the parameters; *m* = multiply default value by fitted value (1 + fitted value), *r* = replacement of default value, *a* = add the fitted value to default value.

$$K = \frac{R_{\max}}{R_{\min}}, \tag{2}$$

where $R_{\max}$, $R_{\min}$ are the maximum and minimum values. The larger the value, the greater the variation of the sequence data.

The A is estimated as

$$A = \frac{R_{\mathrm{m}}}{R_{\max}}. \tag{3}$$

The optimal value of is 1. When A approaches 1, it means more uniform variation.

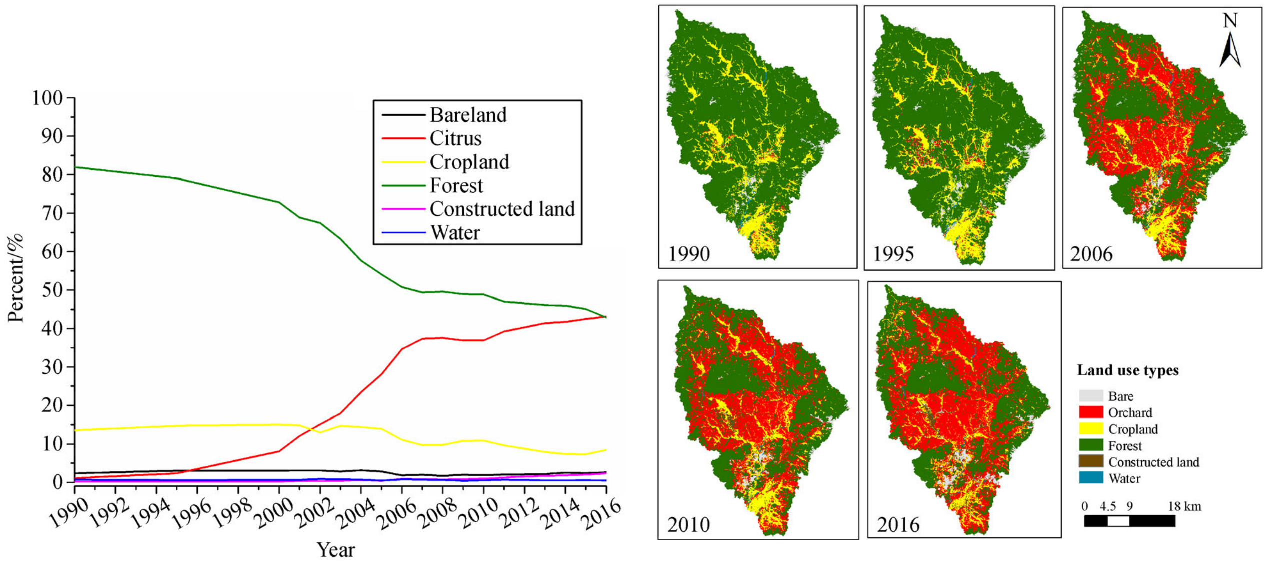
3 Results

3.1 Orchard development

Orchard cultivation started in the 1990s. In the past ten years in particular, orchard development has been especially rapid (Fig. 3). Additionally, the growth in the area of orchards has mainly been derived from the conversion of forestland. The 18 land use maps from 1990 to 2016 were used for analysis, including maps from 1990, 1995, and 2000–2016 (except 2012). The orchard area increased from 1.2% of the total area to 43.1%, while the forest area decreased from 82.0% to 42.9%. The areas of other land types did not change significantly. Additionally, the orchard area increased rapidly during 1990–2006, with an increase rate of 33.5%, while the forest experienced a reduction rate of 31.2%. Since 2007, the growth rate of the orchard area has slowed down. Severe land use changes will inevitably have significant impacts on the hydrological elements of the Xunwu River watershed.

3.2 Hydrometeorological data analysis

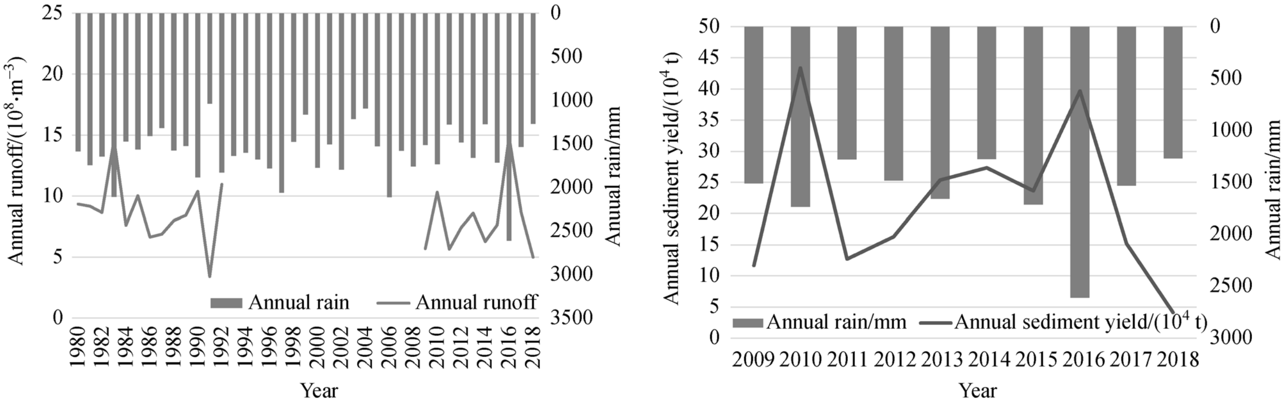
Based on the analysis of the interannual variation characteristics of the hydrometeorological data at the gauge station (Fig. 4), the annual rainfall and runoff decreased during 1980–1992, while they increased during 2009–2018. The correlation coefficients of rainfall and runoff in the two periods were 0.91 and 0.89, respectively. In contrast, the annual sediment yield decreased during 2009–2018. The correlation coefficients between sediment yield and rainfall and between sediment and runoff were 0.47 and 0.64, respectively. These results suggest that runoff was mainly affected by rainfall both during 1980–



(a)

(b)

Fig. 3 Land use changes during 1990–2016. (a) Percent of various land use types; (b) distribution characteristics of different land use types.



(a)

(b)

Fig. 4 Interannual variation characteristics of hydrometeorological data in the Xunwu River watershed: (a) variation trend of rainfall and runoff (1980–2018, runoff data missing during 1993–2008); (b) variation trend of sediment yield (2009–2018).

1992 and during 2009–2018. The reasons for sediment yield change include rainfall, runoff, and other reasons.

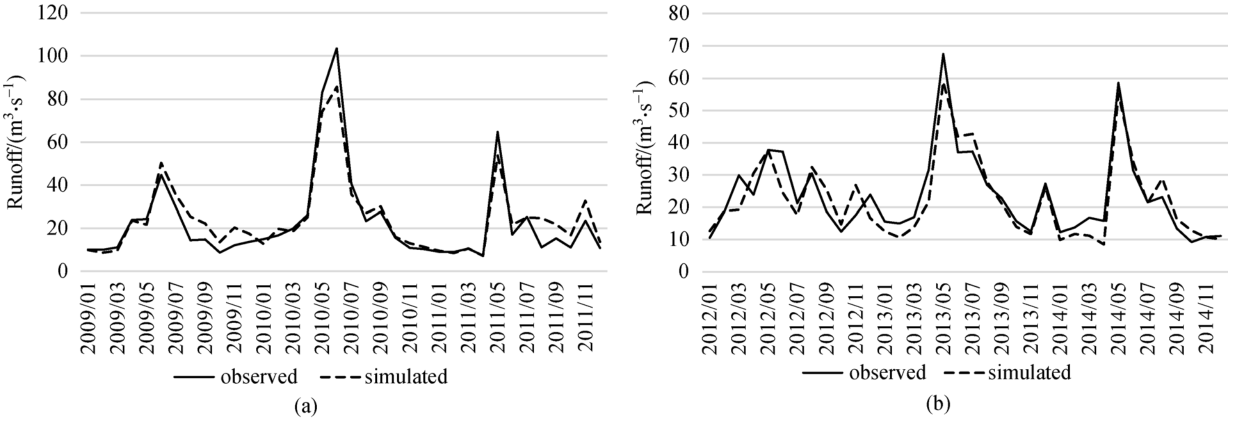
Based on the analysis of variations in the characteristic parameters of rainfall, runoff, and sediment yield (Table 4), in general, the changes in rainfall and runoff during 2009–2018 were larger than those during 1980–1992. However, the changes in rainfall and runoff were similar and insignificant. In contrast, the sediment yield changed substantially, and the *K* (Absolute Variability Ratio) value reached 10.5, which suggests that the maximum sediment yield was more than ten times the minimum value during 2009–2018.

3.3 Runoff simulation

Based on the calibrated parameters, the SWAT model was used for runoff and sediment yield simulations during 2008–2014. The warm-up period, calibration period, and validation period of the model were 2008, 2009–2011, and 2012–2014, respectively. The curve fitting of the observed and simulated runoff worked well in both the calibration and validation periods at the Shuibei station of the Xunwu River watershed (Fig. 5). The R^2, *PBIAS*, and *NSE* values in the calibration periods are 0.94, 0.06, and 0.92, respectively, while they are 0.84, −0.04, and 0.91,

Table 4 Variations in the characteristic parameters of rainfall, runoff and sediment yield at Shuibei station

Period Parameter	1980–1992		2009–2018		
	Rainfall	Runoff	Rainfall	Runoff	Sediment
Coefficient of variation (C_v)	0.16	0.29	0.23	0.35	0.54
Absolute variability ratio (*K*)	2.03	4.28	2.06	2.97	10.5
Interannual nonuniform coefficient (*A*)	0.75	0.6	0.62	0.54	0.51



(a) (b)

Fig. 5 Temporal variability of observed and simulated monthly runoff at Shuibei station during 2009–2014: (a) calibration period; (b) validation period.

respectively in the validation periods (Table 5). According to the model evaluation statistics, the simulated results can be considered as "very good" both in the calibration and validation periods.

3.4 Sediment yield simulation

Based on the model evaluation statistics (Table 5), the R^2, *PBIAS*, and *NSE* values in the calibration periods are 0.78, 0.20, and 0.73, respectively, while in the validation periods they are 0.82, -0.02, and 0.74, respectively. The simulated results can be rated as "satisfactory." These results indicate that the SWAT model is suitable for sediment yield simulation in the Xunwu River watershed. The model–simulated results for sediment are shown in Fig. 6. The simulated and observed values of sediment yield match well except for the peak values.

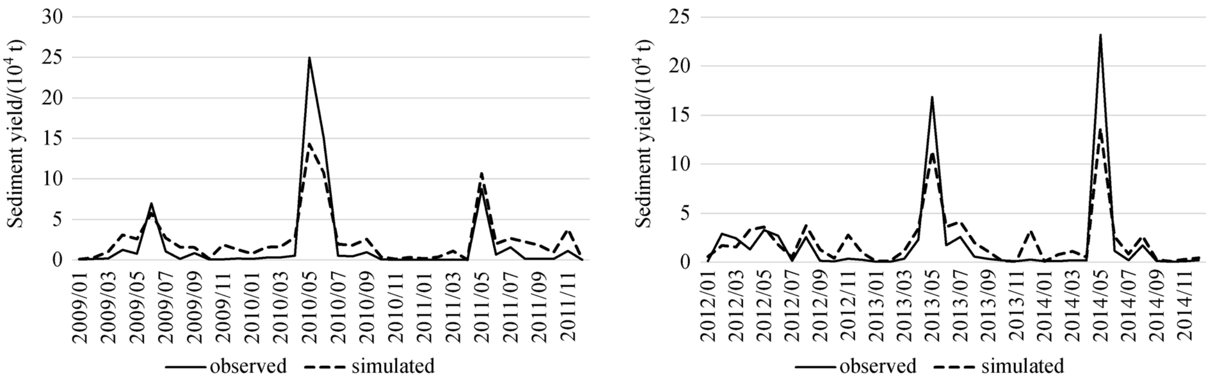
3.5 Annual runoff and sediment yield under different scenarios

The land use maps of 1990, 1995, 2006, and 2016, which are shown in Fig. 3, were selected for scenario analysis. For example, the lucc1990 was used as scenario 1 (S1), the lucc1995, lucc2006 and lucc2016 were used as scenario 2 (S2), scenario 3 (S3) and scenario 4 (S4), respectively. In the past 30 years, the main land use change in the study area has been the conversion of forestland to orchards. Therefore, it is suitable to select land use maps as scenarios for model simulation. The simulated runoff and sediment yield under different scenarios at the gauging station are shown in Fig. 7. The simulated runoff changed slightly under drastic land use changes. The runoff decreased by 1.84% from 1990 to 2016, while it decreased the most during 1995–2006, with a minimum of 2.04% (Table 6). In fact, there are three development stages for the orchards in the study area: these are the period of rapid expansion of the orchard area (1990–2008), the period of basically unchanged conditions (2009–2010), and the period of slow growth (2011–2016). Therefore, it can be concluded that the conversion of a large area of forest to orchards in a short time can cause a slight decrease in annual runoff. Some researchers have shown that annual runoff is mainly affected by rainfall, especially in humid areas (Gao et al., 2014).

The period of 2009–2018 was selected to analyze the

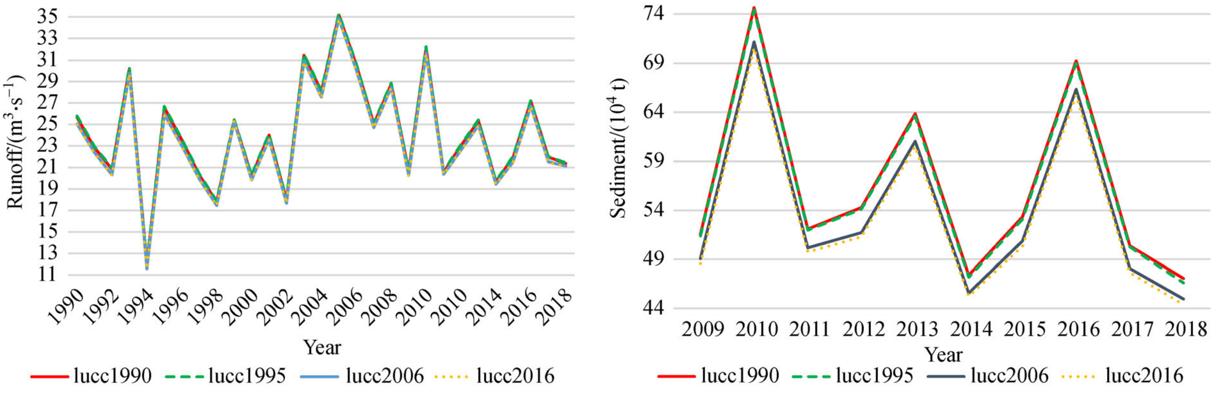
Table 5 Model evaluation statistics for monthly runoff and sediment yield during the calibration (2009–2011) and validation (2012–2014) periods

Model evaluation statistics	Calibration period (2009–2011)		Validation period (2012–2014)	
	Runoff/($m^3 \cdot s^{-1}$)	Sediment/t	Runoff/($m^3 \cdot s^{-1}$)	Sediment/t
R^2	0.94	0.78	0.84	0.82
PBIAS	5.88	20.26	−3.51	−2.36
NSE	0.92	0.73	0.91	0.74



(a) (b)

Fig. 6 Temporal variability of observed and simulated values of monthly sediment yield during 2009–2014: (a) calibration period; (b) validation period.



(a) (b)

Fig. 7 Interannual variation in (a) annual runoff and (b) sediment yield under different simulated LUCC scenarios.

Table 6 Statistics of runoff and sediment under different scenarios

	S1	S2	S3	S4	S1 vs. S2 Change/%	S2 vs. S3 Change/%	S3 vs. S4 Change/%	S1 vs. S4 Change/%
Runoff/($m^3 \cdot s^{-1}$)	24.14	24.24	23.75	23.70	0.41	−2.04	−0.20	−1.84
Sediment/(10^4 t)	56.38	56.16	53.90	53.40	−0.40	−4.03	−0.91	−5.29

sediment change under different scenarios because the observed sediment yield data were only available during 2009–2018. The sediment yield decreased slightly when a large part of the forest area was converted into orchards (Fig. 7). Similar to the runoff change, the sediment decreased by 4.03% under S3 compared with S2, which is the largest decrease. These results suggest that the conversion of forest to orchards caused a small decrease in sediment delivery. However, the decreasing trend is not obvious.

3.6 Effects of land use change on runoff components and evapotranspiration

Although the rapid increase in the orchard area has little effect on the annual runoff in the Xunwu River watershed, land use change may have significant effects on evapotranspiration as well as hydrological elements, such as surface runoff, groundwater, and lateral flow. Subbasin 45 was chosen to compare the differences in every runoff component under different land use types because it is large enough, consists entirely of red soil, and includes the land use types of land, forest, farmland, and orchard. In addition, it is located close to the gauging station. Specifically, as part of Subbasin 45, HRU320, HRU321, and HRU324, which represent orchards, arable land, and forest, respectively, were selected to calculate runoff component changes under different land use types (Fig. 8, Table 7). These HRUs cover the same soil types and slopes. The mean water yield (WYLD) and surface

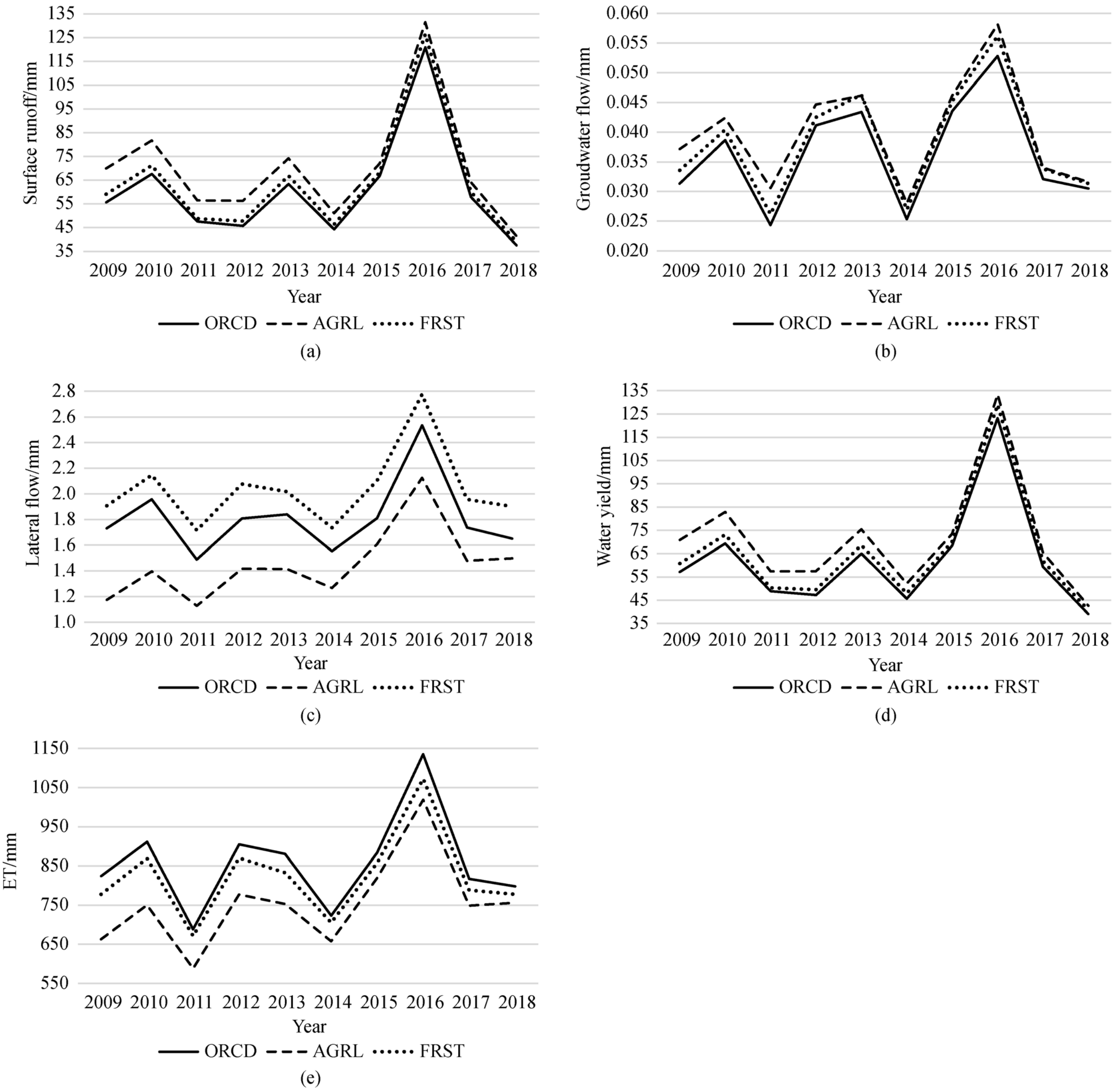


Fig. 8 Annual runoff components. (a) Surface runoff, (b) lateral flow, (c) groundwater flow, (d) water yield, and (e) evapotranspiration of HRU 320, HRU 321, and HRU 324 within Subbasin 45 under LUCC 2016 during 2009–2018.

Table 7 The mean values of the runoff components (SURQ, GWQ, LATQ, and WYLD) under LUCC 2016 in HRU 320, HRU 321, and HRU 324 of subbasin 45 during 2009–2018

HRU	Type	Soil	Slope/(°)	SURQ/mm	GWQ/mm	LATQ/mm	WYLD/mm	ET/mm
320	ORCD	Red soil	15 – 25	60.70	0.036	1.81	62.37	856.73
321	AGRL			69.83	0.040	1.45	71.12	753.3
324	FRST			63.35	0.038	2.03	65.24	822.3

runoff (SURQ) values ranged between 62 and 72 mm/yy and 60 – 70 mm/yy, respectively. Both runoff components decreased in this order: AGRL > FRST > ORCD. WYLD is defined as the sum of surface runoff and lateral, and groundwater flow. SURQ represents approximately 97% of WYLD in the selected HRUs. The mean values of lateral flow (LATQ) ranged from 1 to 3 mm/yy and were ranked as follows: FRST > ORCD > AGRL. Mean values of groundwater flow (GWQ) ranged from 0.03 to 0.04 mm/yy and decreased in the order of AGRL > FRST > ORCD. Mean values of evapotranspiration (ET) ranged from 588.47 to 1135.06 mm/yy and decreased in the order of FRST > ORCD > AGRL. In general, compared with FRST, the WYLD value in the orchard area decreased by 4.4%. In detail, the SURQ, GWQ, and LATQ decreased by 4.19%, 5.03% and 10.96%, respectively. The LATQ change was the largest, while the SURQ and GWQ changes were not significant. However, compared with FRST, the ET increased by 4.19%.

4 Discussion

4.1 Discussion on the model limitations and uncertainties

It has been proved that SWAT model is suitable for runoff simulation and sediment yield simulation. However, there also were periods when the fitting of the model was not ideal, such as in the dry season and the flood season. For example, the simulation of extreme hydrological events was poor in June 2010, and the simulated runoff value was much lower than the observed runoff. To some extent, it is related to the structural principle of the model itself (Bieger et al., 2014). Also, there may be many other reasons for the mismatch between observed data and simulated values of sediment yield, especially in flood periods (Cao et al., 2006).

Previous studies have shown that many factors can affect runoff and sediment yield, such as soil properties, vegetation coverage, terrace structure, rainfall intensity and duration, etc. (Wang et al., 2011; Liu et al., 2021). The influence of these factors was not fully reflected in the model. For one thing, the values of some parameters in the model were not very accurate, such as USLE_K, USLE_C, and USLE_P. For example, in the red soil hilly area, there are large orchard areas with terraces. The terrace effect on runoff and sediment yield has been simulated in the SWAT model. However, the simulation of terraces in the SWAT model relies on empirical approaches involving the adjustment of key input variables, including CN2, USLE_P, and USLE_K (Shao et al., 2013). In addition, the terraces were assumed in good shape, correctly constructed, well planned, and have fine soil and water conservation capacity in the SWAT model. In the actual situation, some terraces were damaged to some extent or left abandoned which led to the mismatch between some simulated and observed values (Liu et al., 2021). In addition, the slope factor is oversimplified in the SWAT model (Bieger et al., 2014, 2015; Pang et al., 2020). Moreover, farmland plots in the study area are relatively small and some land use types are not involved in running the model (Ongley et al., 2010; Shen et al., 2012). At last, high rainfall intensity has an important influence on sediment yield. The RAINHHMX parameter represented the effect of rainfall intensity (Pang et al., 2020).

The reasons also include the limited number of studies on soil erosion in orchard area (Niu et al., 2021), the scale coupling problem from field to watershed scale, etc. These limitations may result in some uncertainties.

However, no method is perfect. The model is a generalized expression of the real world, and it can be used if the model performance meets the requirements of the evaluation coefficients. Thus, the SWAT model is still suitable for sediment yield simulation. It can be used for runoff and sediment yield simulation in the Xunwu River watershed. In addition, the combination of hydrological model and field experiment is a new attempt on soil and water conservation research under regional orchard expansion.

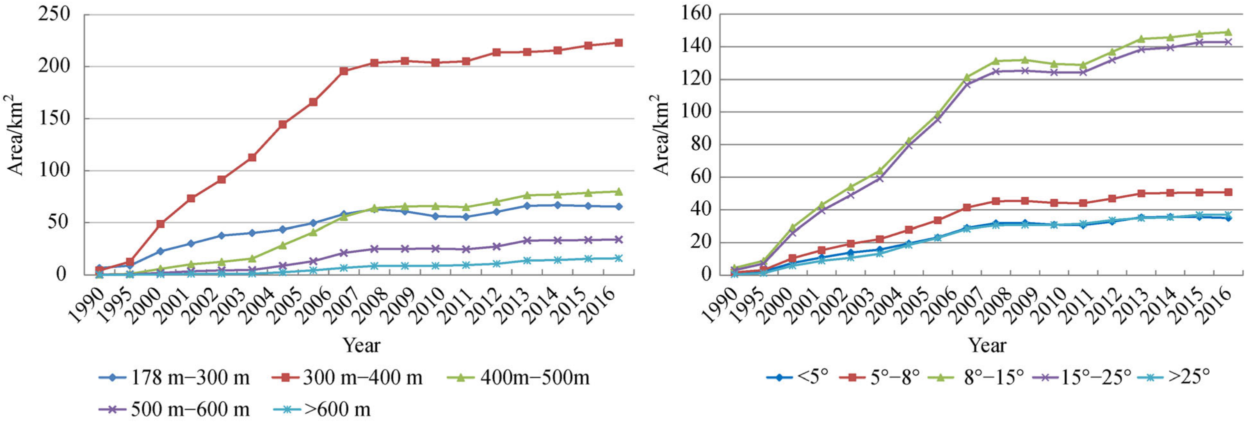
4.2 Effects of land use change on annual runoff and sediment yield

In the study area, no precious research has been focused on the impacts of converting forestland to orchards on runoff and sediment yield. The characteristics of the orchard distribution based on elevation and slope were selected for analysis to identify the causes of runoff and sediment changes (Fig. 9). The orchard area increased slowly from 1990 to 1995 and then increased sharply from 1995 to 2006. In addition, most of the newly increased area was mainly distributed at elevation range from 300 to 400 m in areas with slopes of 8°–15° and 15°–25°. The area of orchards at elevations between 300 and 400 m accounted for 58% of the total area in 2006, which was 14 times greater than that in 1995. The 300–400 m elevation area is suitable for orchard growth due to favorable conditions such as good drainage effects, so the area of orchards within this range increases the fastest and the most. Additionally, the area of orchards with slopes among 8°–25° accounted for 71% of the total in 2006, which increased by approximately 10 times compared with that in 1995. Some researchers (Duan et al., 2020) suggested that orchard planting areas comply with relevant soil and water conservation regulations, which can effectively reduce soil erosion. Therefore, this may explain why the soil erosion caused by orchard expansion is not as serious as expected.

Also, the construction of terraces effectively reduced water and soil loss caused by the conversion effects from forest to orchard, which is also proved (Ricci et al., 2020; Duan et al., 2021).

4.3 Effects of land use change on runoff components and evapotranspiration

Based on the analysis of land use change effect on runoff components, the LATQ change was larger than the SURQ and GWQ changes. This might be attributed to the effects of terrace in the orchard area, such as the reduction of surface roughness, weaken of buffering effects of unders-



(a) (b)

Fig. 9 Elevation and slope distribution of orchards in the Xunwu River watershed during 1990–2016.

tory plants and litter layers (Ricci et al., 2020). These effects can result in a reduction of rainfall infiltration as well as the LATQ (Liu et al., 2020). Also, the enlarged tree canopy of orchard will lead to the increase of rainfall interception to some extent which was equivalent to the reduced LATQ. In addition, the evapotranspiration of orchard area was higher than that in forest because the plant transpiration and soil evaporation of orchard are greater than those of artificial forest land (Dong, 2009).

5 Conclusions

This study analyzed the rapid growth of orchard areas and the effects of growth on runoff components and sediment in the red soil hilly region of southern China. The following conclusions can be drawn from this study.

1) Land use change was relatively simple. Most of the orchard area was converted from forest. Orchard area increased by about 42% of the entire catchment from 1990 to 2016, while forest area decreased by about 40% of the entire catchment.

2) Both rainfall and runoff decreased during 1980–1992 while increased during 2009–2018. However, the changes were not obvious. In contrast, the sediment changed considerably.

3) In general, the SWAT model was proved to be a useful tool for runoff and sediment yield simulation for the Xunwu River watershed.

4) The water and sediment yield both decreased slightly with the rapid expansion of the orchard area, which was attributed to the elevation and slope distribution of the newly planted orchard area, as well as the construction of terraces. In contrast, some of the runoff components changed considerably under significant orchard expansion such as the lateral flow. This was attributed to the reduction of rainfall infiltration and increase in evapotranspiration.

In general, the analysis of orchard expansion and its effects on runoff components and sediment yield shows that if there are appropriate land management measures, drastic orchard expansion does not lead to severe sediment yield change. However, there are also some other aspects should be considered to make land policies, such as farmers' input and output. It requires particular investments in terrace construction while the profit can be earned from about 3–6 years after orchard trees implantation. It may not find agreement among farmers in some areas. Therefore, both the soil and water conservation effectiveness and economic subsidies should be considered to make regional land strategies. This study can provide scientific suggestions for the sustainable use of land and water resources in the red soil hilly area of China.

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