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Hydrological Responses to Territorial Spatial Change in the Xitiaoxi River Basin: A Simulation Study Using the SWAT Model Driven by China Meteorological Assimilation Driving Datasets

Dongyan Kong [1], Huiguang Chen [2,*] and Kongsen Wu [1]

[1] College of Tourism, Henan Normal University, Xinxiang 453007, China; kongdongyan@htu.edu.cn (D.K.); wukongsen@htu.edu.cn (K.W.)
[2] College of Public Administration, Nanjing Agricultural University, Nanjing 210095, China
* Correspondence: chenhuiguang@njau.edu.cn

Abstract

The use of the Soil and Water Assessment Tool (SWAT) model driven by China Meteorological Assimilation Driving Datasets (CMADS) for runoff simulation research is of great significance for regional flood prevention and control. Therefore, from the perspective of production-living-ecological space, this article combined multi-source data such as DEM, soil texture and land use type, in order to construct scenarios of territorial spatial change (TSC) across distinct periods. Based on the CMADS-L40 data and the SWAT model, it simulated the runoff dynamics in the Xitiaoxi River Basin, and analyzed the hydrological response characteristics under different TSCs. The results showed that The SWAT model, driven by CMADS-L40 data, demonstrated robust performance in monthly runoff simulation. The coefficient of determination (R^2), Nash–Sutcliffe efficiency coefficient (NSE), and the absolute value of percentage bias (|PBIAS|) during the calibration and validation period all met the accuracy requirements of the model, which validated the applicability of CMADS-L40 data and the SWAT model for runoff simulation at the watershed scale. Changes in territorial spatial patterns are closely correlated with runoff variation. Changes in agricultural production space and forest ecological space show statistically significant negative correlation with runoff change, while industrial production space change exhibits a significant positive correlation with runoff change. The expansion of production space, particularly industrial production space, leads to increased runoff, whereas the enlargement of agricultural production space and forest ecological space can reduce runoff. This article contributes to highlighting the role of land use policy in hydrological regulation, providing a scientific basis for optimizing territorial spatial planning to mitigate flood risks and protect water resources.

Keywords: hydrological response; China Meteorological Assimilation Driving Datasets; territorial space; SWAT model; watershed management

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1. Introduction

The magnitude and perceived significance of land use's environmental impacts are probably far greater today than at any time in the past [1]. The impact of climate change and land use land cover change (LUCC) on rainfall and runoff is evident on a global scale [2]. With every change in land use, a series of new environmental impacts are released, while on a more local regional scale, a major change in land cover typically causes changes in hydrology and rates of soil erosion [1]. LUCC influences hydrological processes through

multiple pathways. On the one hand, it can be said that LUCC affects soil water infiltration and its redistribution process [3,4], which in turn affects the hydrological process. On the other hand, changes in land use structure have intensified peak discharge and stormwater flood volume by accelerating hydrological response, while significantly reducing the time of concentration [5]. These changes often extend beyond the directly affected areas and can trigger downstream flooding and siltation [1]. Consequently, research on the hydrological effect of LUCC has become a hot topic and an important component of hydrological process studies [6–8].

Extensive empirical evidence from China indicates that land use change caused by urbanization has a great impact on local climate and water resources [9], and urban green spaces play a valuable role in regulating and storing runoff [10], serving as a critical nature-based solution for urban flood mitigation. Precipitation, as the principal driving factor in hydrological process, exhibits the spatiotemporal heterogeneity that significantly influences runoff generation, confluence, and the parameter estimation of hydrological models [11–13]. Globally, most scholars believe that land use and land consolidation will affect the process of soil water infiltration and water redistribution, thereby affecting the hydrological process [14]. In-depth exploration in Germany has been conducted to find the impact of land consolidation measures on rural hydrology [14]. The flood flow of the Samoggia River Basin in Italy under diverse historical land use scenarios was investigated and analyzed in order to underscore the profound impact of land use changes on the basin's hydrological regime [15]. Climate and land use changes in 20 subsets of the Schijn River in Belgium had a significant impact on hydrological response [16].

Overall, studying the impact of land use change on hydrological processes is of great strategic significance for the scientific and rational utilization and development of watershed water resources, improving water resource management mechanisms, and ensuring the sustainable use of water resources [17,18]. Methodologically, scholars mostly use model simulation to analyze the hydrological response of LUCC [19–21]. In hydrological studies, various models have been used, such as the SWAT (USDA, Jeff Arnold, WA, USA) model [22,23], the SCS-CN model [24], and the TOPMODEL [25]. Notably, most studies on the impact of land use on hydrological processes are based on the SWAT model, which simulates watershed hydrological processes by designing different land use scenarios. SWAT dominates contemporary LUCC-hydrology studies due to its scenario-building flexibility, enabling multi-decadal simulations of land use policy impacts [21]. With the development of research, the available hydrological models are becoming increasingly diverse, and reasonable model selection has become one of the key issues in research.

Unlike the existing studies mentioned above, this article focuses on the shift from discussing the impact of land use change on hydrology to the impact of TSC on hydrology. To understand the shift, it is important to establish a conceptual foundation from land use change to TSC. For a country or region, territorial spatial planning integrates the two fundamental concepts of territory and space. It refers to the geographical space under the jurisdiction of national sovereignty and sovereign rights, encompassing land, inland waters, internal waters, territorial sea, and territorial airspace [26]. Territorial spatial planning possesses two key characteristics: territorial elements and spatial dimensions. Territorial elements refer to the land and marine elements influenced by human activities. Spatial dimensions emphasize the spatial boundaries of these territorial elements and the characteristics of their spatial relationships. In essence, based on this connotation, the land serves as the primary physical form and carrier of territorial space, with its fundamental manifestation being territory [27]. The utilization of different types of territorial space is realized on the carrier of land, manifested as land use and land cover types of different functions. Therefore, territorial spatial change mainly refers to changes in land use types,

including changes in quantity and spatial distribution. Therefore, LUCC is the foundation for understanding TSC (TSC). The focus of research has shifted from the hydrological response of LUCC to the hydrological response of TSC. This means that research has recognized that LUCC is the real foundation of TSC, and we must also pay attention to the impact of territorial spatial planning and its implementation at the same time.

In practice, territorial spatial data not only incorporates conventional land use categories (e.g., cropland, forestland, and construction land), but also integrates planning control elements such as the "Three Zones and Three Lines" (ecological conservation redlines, permanent basic farmland, and urban development boundaries). This enables more precise characterization of anthropogenic impacts on hydrological processes. Furthermore, territorial spatial data typically include annual land change surveys, offering higher temporal resolution than traditional LUCC data, which significantly improves the capacity to capture hydrological impacts from rapid urbanization. Therefore, compared to LUCC data, utilizing territorial spatial data offers distinct advantages for investigating hydrological responses to TSC.

Currently, the research on using production-living-ecological space, as a classification standard to establish various types of territorial space for runoff simulation, is still an undeveloped field. Based on the function orientation, the territorial space is included in the production-living-ecological space category. Specifically, the TSC has a more comprehensive significance than the planning vision and actual scene of LUCC. By comparing the hydrological responses to LUCC, the research on the hydrological process driven by TSC can uncover the significance of the implicit planning impact assessment. In addition, the meteorological data directly affects the hydrological cycle process and is one of the most crucial factors in the SWAT model. The quality of meteorological data affects the accuracy of simulation. Previous studies have shown that the China Meteorological Assimilation Driving Datasets can be used as the meteorological driving data for the SWAT model [28], with a time span of 1979–2018. However, there is currently relatively little research on applying this meteorological dataset to SWAT models. In existing research, short-term datasets from 2008 to 2018 are predominantly used, while long-term meteorological data input models are still scarce. But relatively few studies have applied this meteorological dataset to the SWAT model at present. In existing studies, short-term data such as 2008–2018 are mostly used, and long-term meteorological data input models are lacking. Therefore, this study attempts to use reanalysis data of CMADS-L 40 to drive the SWAT model, in order to make up for the shortcomings of the current research, and simulate the impact of TSCs on the regional hydrological processes.

The main purpose of this study is to identify the impact of changes in TSC on surface hydrological processes, and provide scientific decision-making basis for reducing the risk of flood disasters in the process of territorial spatial development. The remainder of this paper is organized as follows. In Section 2 we present the study area, study data, and research methodology. Section 3 presents the results of the construction of SWAT model and its sensitivity analysis. Section 4 discusses the scientificity of simulation results of hydrological processes, response of runoff to different territorial spatial structures, and the limitations of the study. Finally, the main conclusions of the study are discussed in Section 5.

2. Materials and Methods

2.1. Study Area

This study selects the Xitiaoxi River Basin as the study area, simulates runoff from the perspective of production-living-ecological space, and analyzes the hydrological response characteristics of TSC.

The Xitiaoxi River Basin is located in Huzhou City, Zhejiang Province, between 119°14′–120°29′ E and 30°23′–31°11′ N (the location of the study area is shown in Figure 1). It is an important inflow river in the upper reaches of the Taihu River Basin. The landform of the Xitiaoxi River Basin is mainly composed of mountains, hills and river network plains. The basin belongs to a typical humid subtropical monsoon climate. In summer, it is mainly affected by tropical oceanic air masses, with high temperature and rain. Generally, the flood season is from mid-April to mid-October. Due to the alternating influence of plum rains and typhoons, it is easy to form concentrated precipitation. This study has chosen the southwest upper part of the Gangkou hydrological station as the study area. The study area transitions from the upstream mountainous areas to middle and downstream hilly plains, covering an area of approximately 1828.82 km^2, accounting for approximately 80.42% of the Xitiaoxi River Basin.

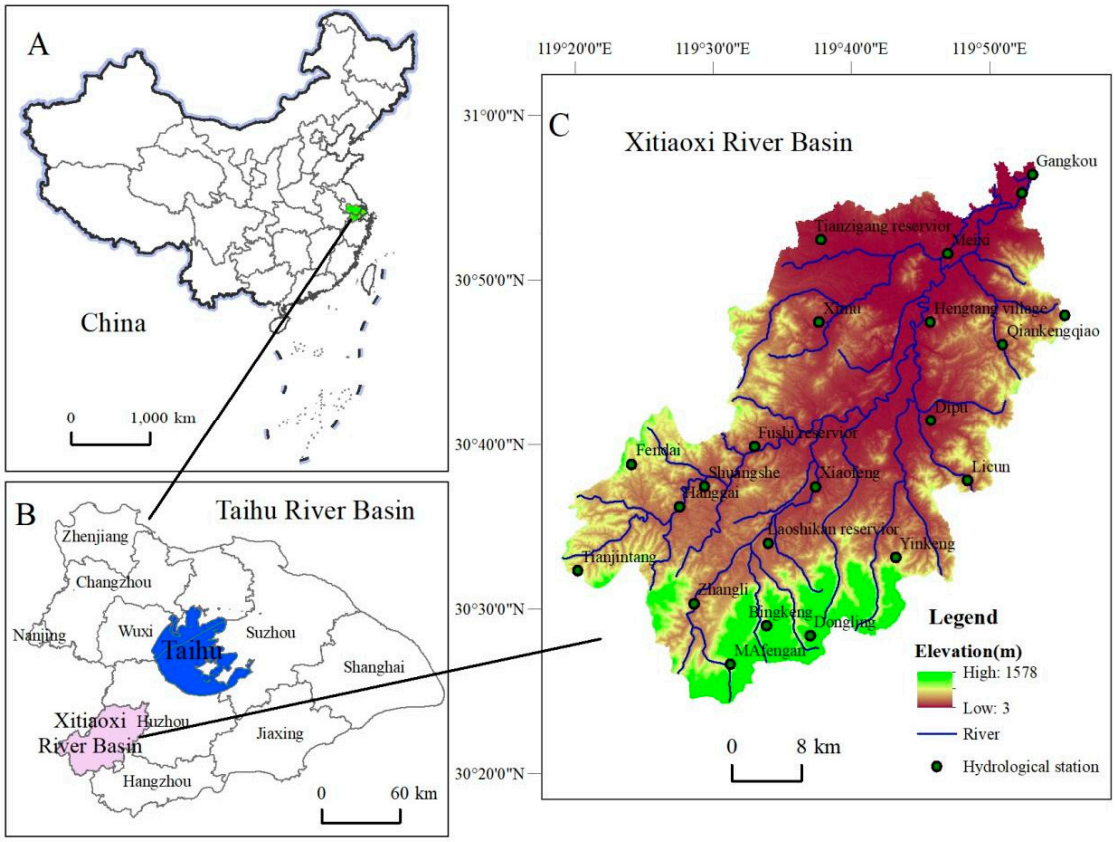

Figure 1. (**A**) the map of China; (**B**) location map of Taihu River Basin; (**C**) location map of the Xitiaoxi River Basin. Note: The elevation is extracted from DEM, which is derived from the Geospatial Data Cloud.

2.2. Data Sources

The data used in this study mostly included meteorological data from the China Meteorological Assimilation Driving Datasets for the SWAT Model (CMADS) [29], Digital Elevation Model (DEM) [30], land use data [31], soil type data from the Harmonized World Soil Database [32], and hydrological data.

2.2.1. CMADS

The meteorological data were sourced from the China Meteorological Assimilation Driving Datasets for the SWAT Model (CMADS). This study used the CMADS-L40-year reanalysis product. The dataset has high reliability, with a spatial resolution of 1/3°, a temporal resolution of one day, and a time span of 1979–2018. The data mainly include

daily accumulated precipitation, daily highest/lowest temperature, daily average relative humidity, daily average wind, and daily accumulated solar radiation. According to the study area, 16 meteorological stations were selected, which was much more numerous than the traditional meteorological stations.

2.2.2. Digital Elevation Model (DEM) and Hydrological Data

The DEM came from the Geospatial Data Cloud, and the spatial resolution is 30 m × 30 m. This study used ArcGIS 10.8 software to obtain the DEM of the study area after the acquired data were projection, splicing and tailoring. DEM data is the basic data in the SWAT model, which divides watershed boundaries, sub-basins, and water systems are based on the DEM. The hydrological data mainly came from the Water Resources of Huzhou Bureau and "Hydrological Yearbook of the People's Republic of China: Hydrological Data of the Yangtze River Basin", mostly including the monthly runoff data of the Gangkou, Hengtang Village and Fushi Reservoir from 1990 to 2018.

2.2.3. The Territorial Spatial Data

The land use raster data included four periods in 1990, 2000, 2010, and 2018, and were sourced from the Resource and Environmental Science Data Platform. The spatial resolution of the data is 30 m × 30 m. This study uses land use raster data as the basis of territorial spatial data. According to the secondary classification standards of the National Remote Sensing Monitoring Land Use/Cover Classification System, by distinguishing land use functions and land use types, and referring to existing research [33], the structure of production-living-ecological space corresponds to land use types. It mainly involves production space (including agriculture and industry), living space (including urban and rural areas), and ecological space (including forests, grasslands, water bodies, and other types).

2.2.4. The Soil Type Data

The soil type data came from the Harmonized World Soil Database (HWSD) published by the Food and Agriculture Organization of the United Nations (FAO), with a spatial resolution of 1 km × 1 km. It mainly consists of the soil type distribution map, the soil type index table, and soil database parameters. The soil database parameters provide a detailed description of the physical properties of the soil, which can affect the movement of water and gas within the soil profile. Therefore, soil data plays a key role in the early stage of SWAT model simulation, and it is the basic data for analyzing hydrological response units. In this article, the soil data parameters required for the user's soil database can be directly obtained from the HWSD for the physical attribute values of soil parameters, such as texture, drainage, and organic carbon content. In addition, some soil attribute values can be obtained by using SPAW 6.02.75 software and querying the soil hydrology groups.

2.3. Methodology

2.3.1. The SWAT Model

The SWAT model is a typical distributed watershed hydrological model developed by Dr. Jeff Amold based on the GIS platform for the United States Department of Agriculture (USDA). The model has a powerful physical mechanism and is mainly used to evaluate the impact of land use management on sediment production, pollutant migration, and watershed hydrological processes. The model comprehensively considers natural and social factors and can simulate long-term surface runoff in the watershed. The SWAT model mainly consists of the following steps. Firstly, this article divided the sub-basins by loading the DEM and river network. Secondly, hydrological response units (HRUs) were divided by adding land use, soil, and slope. HRU is a computational subunit characterized by unique

soil, territorial spatial, and slope combinations, representing areas with similar hydrologic behavior. Its fundamental premise is that uniform territorial spatial type, soil type, and slope characteristics within a given HRU result in consistent hydrologic responses [34,35]. Thirdly, meteorological elements were loaded after dividing the HRUs. Thirdly, we created model input files, built the model database, ran the model, and output the results. Finally, based on SWAT-CUP tool, hydrological data was used to conduct sensitivity analysis and validation of simulation results. The specific process is shown in Figure 2.

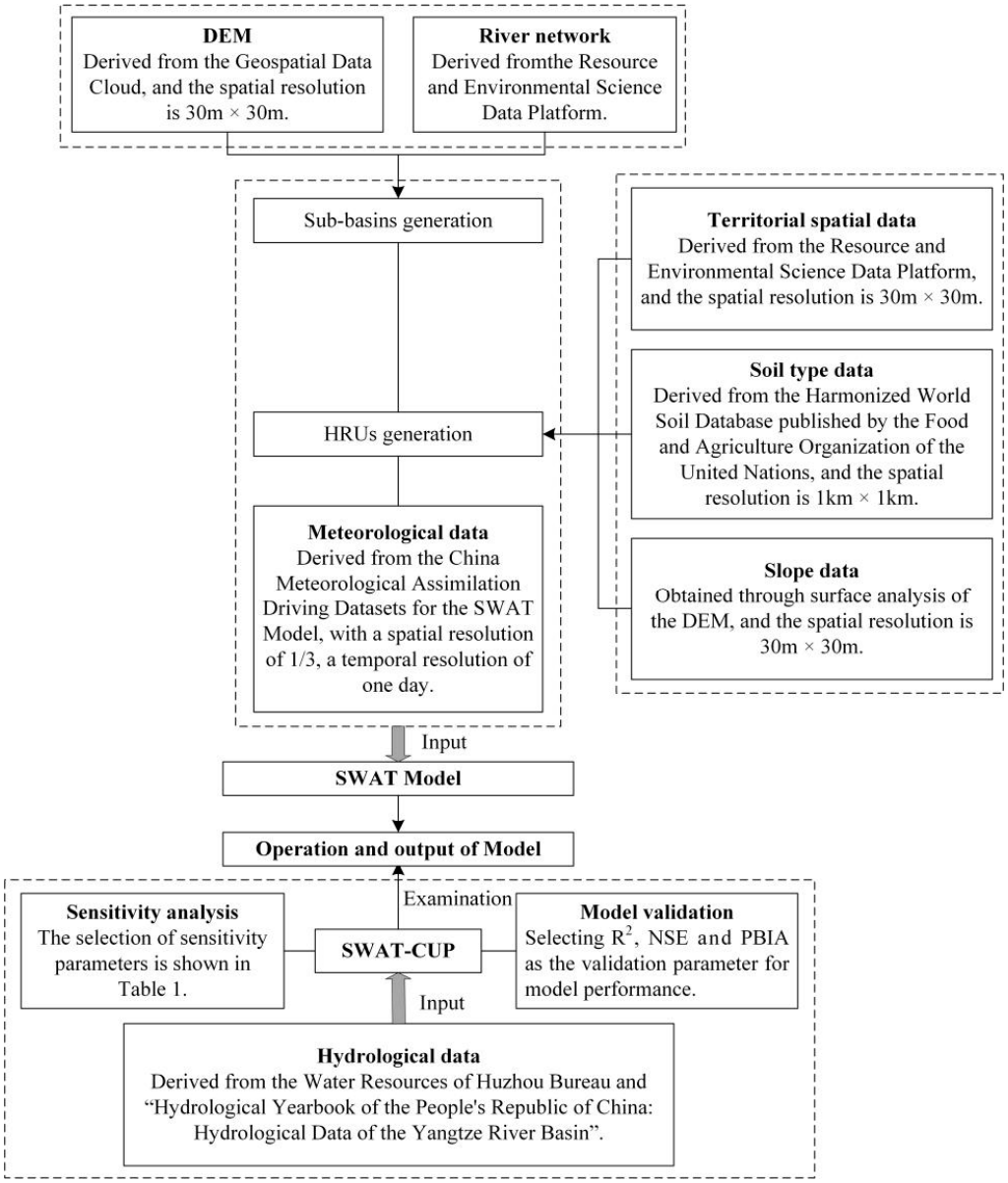

Figure 2. Flowchart for SWAT model construction and analysis.

2.3.2. Model Evaluation Index

This article conducted the sensitivity analysis, calibration, and validation of the simulation results of the SWAT model using the SWAT-CUP tool. SWAT-CUP was a freely accessible public program characterized by its simplicity, convenience, efficiency, diverse methods, and accurate results, which had led to its gradual widespread adoption [36]. Using SWAT-CUP 2019 5.2.1, the main process selected the SUFI-2 algorithm for multiple iterative fitting to determine the best parameters. The coefficient of determination (R^2), Nash–Suttcliffe efficiency (NSE), and standard bias (PBIAS) were selected to evaluate the

accuracy of the calibration and validation. The introduction and accuracy requirements of the indicators are shown in Table 1.

Table 1. The indicators of calibration and validation.

Indicator of Calibration and Validation	Description of the Relationship Between Indicators and Simulation Results	Accuracy Requirements for Indicators
The coefficient of determination (R^2)	The closer R^2 value is to 1, the higher the degree of fitting between the simulated value and the measured value, and the more accurate the simulated result.	The simulation results met the requirements when $R^2 > 0.6$, NSE > 0.5, and $\lvert PBIAS \rvert < 0.20$ [37], this result showed that the constructed SWAT model could accurately describe the runoff process in the study area.
Nash–Suttcliffe efficiency (NSE)	The closer NSE value is to 1, the higher the degree of fitting between the simulated value and the measured value, and the more accurate the simulated result.	
Standard bias (PBIAS)	The closer the PBIAS is to 0, the better the consistency between the simulation results and the observed values.	

2.3.3. The Change Rate of the Production-Living-Ecological Spatial Area and Runoff

The change rate of production-living-ecological spatial area in the article is calculated as

$$L_{i,j} = \frac{S_{i,j,n} - S_{i,j,n+1}}{S_i} \times 100\% \quad (1)$$

where n is period, $L_{i,j}$ is the area change rate of territorial spatial type j = 1 (agricultural production space), j = 2 (industrial production space), j = 3 (urban living space), j = 4 (rural living space), j = 5 (forest ecological space), j = 6 (grassland ecological space), j = 7 (water ecological space), j = 8 (other ecological space) in the sub-basin i (i = 1, 2, 3. . .. . .73) from period n to period $n + 1$. $S_{i,j,n}$ is the area of territorial spatial type j of the sub-basin i in period n, $S_{i,j,n+1}$ is the area of territorial spatial type j of the sub-basin i in period $n + 1$, S_i is the area of the sub-basin i.

This article simulates the runoff of territorial spatial utilization in different periods for the Xitiaoxi River Basin by fixing meteorological conditions from 1979 to 2018, using the same soil type, the parameters of regular rate, and validation. On this basis, we explored the change in runoff under the change in territorial spatial type in different periods. The change rate of runoff in different periods is calculated as

$$P_i = \frac{Z_{i,n+1} - Z_{i,n}}{Z_{i,year\ 1}} \times 100\% \quad (2)$$

where n is period, P_i is the change rate of runoff in the sub-basin i (i = 1, 2, 3. . .. . . 73) under the condition of territorial spatial type from period n to period $n + 1$. $Z_{i,n}$ is the runoff in the sub-basin i under the condition of territorial spatial type in period n. $Z_{i,n+1}$ is the runoff in the sub-basin i under the condition of territorial spatial type in period $n + 1$.

3. Results

3.1. Construction of SWAT Model

The division of sub-basin is the foundation and important link of SWAT model operation. The number of sub-basins can reflect the spatial heterogeneity in the Xitiaoxi River Basin. The more sub-basins there are, the more accurate it is to reflect the complex situation of the underlying surface. However, the running time of the model will increase with the number of sub-basins, and too many sub-basins will affect the efficiency of the model's

operation. Therefore, the number of sub-basins should not be too high or too low. In the SWAT model, river networks can be generated based on DEM data. Based on DEM data and actual water systems as auxiliary data, hydrological elements were extracted using the ArcSWAT model to obtain the basin division map of Xitiaoxi. Finally, the Xitiaoxi River Basin was divided into 73 sub-basins (Figure 3).

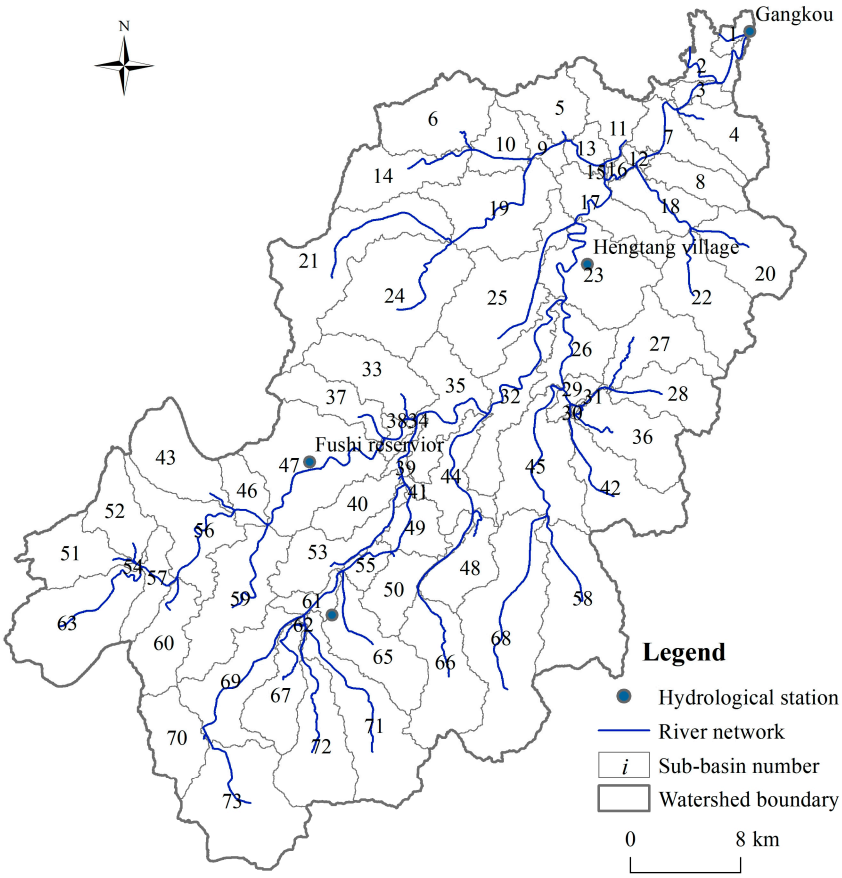

Figure 3. The results of the river network and sub-basin division in the Xitiaoxi River Basin.

HRU is a spatial combination of soil type, territorial spatial type, and slope with consistent hydrological characteristics, which can better reflect the differences in underlying surfaces and hydrological cycles, thereby improving the accuracy of the SWAT model. The production of HRUs involves stacking three layers: territorial space, soil distribution, and slope. This process requires completing the reclassification of territorial space, soil and slope, establishing the corresponding txt index files, and finally delineating regions with the same territorial spatial type, soil type, and slope into individual HRUs. Due to the small study area in this article, the impact of TSC on runoff was mainly analyzed. Therefore, when generating HRUs, the exclusion thresholds for territorial space, soil type, and slope ratio were set to zero. With other parameters unchanged, the territorial space data for 1990, 2000, 2010, and 2018 were replaced to generate 3427 HRUs, 3403 HRUs, 3680 HRUs, and 3782 HRUs in sequence.

After HRU analysis, the CMADS meteorological data from 1979 to 2018 were inputted, and mainly related meteorological data were collected using TXT files to complete the SWAT model's reading of meteorological data.

The files required for the SWAT model simulation are written to the database through Write Input Tables, and the model is run and saved. The SWAT model does not impose strict requirements on the length of the regular rates and validation periods, so the regular rates and validation periods are randomly selected. This article ran the SWAT model by

setting the warm-up period from 1985 to 1989, the regular rate period from 1990 to 2005, and the verification period from 2006 to 2018. After the model was successfully run, the summary file of simulation results was saved.

3.2. Sensitivity Analysis and Regular Rate of the SWAT Model

The selection of parameters has a direct impact on both the accuracy and efficiency of the model's simulations. Sensitivity analysis of SWAT-CUP 2012 tool helps to identify key parameters, which can then be adjusted to effectively calibrate and validate the operational results of the SWAT model. In the SWAT-CUP, *p*-Value and *t*-Stat can measure the sensitivity of parameters. *p*-Value represents the significance of sensitivity, with the value closer to 0 indicating greater significance. *T*-Stat represents the degree of sensitivity, and the larger the absolute value is, the more sensitive it is. According to sensitivity analysis, the 25 parameters that exhibit a higher degree of sensitivity to the model output have been identified and selected for further adjustment. The ranges of the selected parameters, optimal parameter values, and rankings are listed in Table 2. The most sensitive parameter was CH_N2, followed by ALPHA_BNK, HRU_SLP, EPCO, etc. Based on this, the simulation process of runoff in the Xitiaoxi River Basin is studied.

Table 2. Results of sensitivity analysis and regular rate.

Rank	Parameter	Description	Parameter Range	Rate Value	t-Stat	*p*-Value
1	V__CH_N2.rte	Manning's *n* value for main channel	(−0.01, 0.3)	0.017840	−16.8048	0.0000
2	V__ALPHA_BNK.rte	Base flow alpha factor for bank storage	(0.0, 1.0)	0.056741	−13.6155	0.0000
3	R__HRU_SLP.hru	Average slope steepness	(−0.5, 0.5)	−0.420013	−12.8899	0.0000
4	V__EPCO.hru	Plant uptake compensation factor	(0.0, 1.0)	0.017689	−12.8084	0.0000
5	R__SOL_AWC ( ).sol	Available water capacity of the soil layer	(−0.2, 0.4)	0.072698	−8.9173	0.0000
6	V__CANMX.hru	Maximum canopy storage	(0.0, 100.0)	0.462685	−8.1778	0.0000
7	R__CN2.mgt	SCS runoff curve number	(−0.2, 0.2)	−0.052725	−3.7211	0.0002
8	V__ESCO.hru	Soil evaporation compensation factor	(0.0, 1.0)	0.997933	3.1444	0.0018
9	V__CH_K2.rte	Effective hydraulic conductivity in the main channel	(−0.01, 500.0)	75.039429	−1.8856	0.0600
10	V__GWQMN.gw	Threshold depth of water in shallow aquifer for return flow to occur	(0.0, 5000.0)	1417.180298	−1.7316	0.0840
11	V__TIMP.bsn	Snowpack temperature lag factor	(0.0, 1.0)	0.953033	−1.6147	0.1070
12	V__SFTMP.bsn	Snowfall temperature	(−5.0, 5.0)	−4.939772	−1.3025	0.1934
13	V__RCHRG_DP.gw	Deep aquifer percolation fraction	(0.0, 1.0)	0.087207	1.2484	0.2125
14	R__SOL_K ( ).sol	Saturated hydraulic conductivity	(−0.8, 0.8)	−0.755703	−1.0056	0.3151
15	V__GW_DELAY.gw	Groundwater delay time	(0.0, 500.0)	303.878967	−0.8540	0.3935
16	V__SLSUBBSN.hru	Average slope length (m)	(10.0, 150.0)	104.545128	0.8514	0.3950
17	V__SURLAG.bsn	Surface runoff lag time	(0.05, 24.0)	11.667909	0.7858	0.4324
18	V__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur	(0.0, 500.0)	156.044724	0.7563	0.4498
19	V__OV_N.hru	Manning's *n* value for overland flow	(0.01, 30.0)	29.390974	0.7028	0.4825
20	V__DEP_IMP.hru	Depth to impervious layer for modeling perched water tables	(0.0, 6000.0)	251.831955	0.6508	0.5155
21	R__SOL_BD ( ).sol	Moist bulk density of first soil layer	(−0.5, 0.6)	0.351647	−0.5465	0.5850
22	V__SMFMX.bsn	Maximum melt rate for snow during year	(0.0, 20.0)	7.120377	0.4648	0.6423
23	V__ALPHA_BF.gw	Base flow alpha factor	(0.0, 1.0)	0.403756	0.2039	0.8385
24	V__GW_REVAP.gw	Groundwater "revap" coefficient	(0.02, 0.2)	0.132085	0.1904	0.8490
25	R__SOL_ALB ( ).sol	Moist soil albedo	(0.0, 0.25)	0.164555	−0.0435	0.8490

4. Discussion

4.1. Evaluation of Simulation Results

This article mainly selected monthly runoff observation data from three hydrological stations in the upstream, middle, and downstream sections of the research area, namely, Fushi Reservoir, Hengtang Village, and Gangkou, to calibrate and verify the simulation results of the SWAT model. In other words, meteorological conditions from 1979 to 2018 were held constant, with calibration performed using territorial space simulation results from the year 2000 (calibration period) and validation conducted using results from 2010 (validation period). The results are shown in Table 3. R^2 was greater than 0.7, and NSE and |PBIAS| also met the accuracy requirements of the model for the monthly runoff in the Xitiaoxi River Basin. From the above analysis, it can be seen that the SWAT model fully considers soil conditions, land use types, climatic conditions, and underlying surface factors and can simulate the runoff process in the watershed. The hydrological effects of urbanization in the Xitiaoxi River Basin were studied based on the SWAT model, indicating that the model was applicable to the Xitiaoxi River Basin. Therefore, this article used the SWAT model to accurately simulate the monthly runoff process.

Table 3. Calibration and validation results of the SWAT model for monthly runoff.

	Gangkou		**Hengtang Village**		**Fushi Reservoir**	
	Calibration Period	**Validation Period**	**Calibration Period**	**Validation Period**	**Calibration Period**	**Validation Period**
R^2	0.83	0.71	0.79	0.74	0.72	0.71
NSE	0.80	0.69	0.78	0.73	0.71	0.67
PBIAS (%)	−12.9	5.7	−6.1	−2.3	−2.6	11.6

The reanalysis product based on CMADS-L40 has been utilized to provide detailed, long-term, and continuous high-resolution meteorological data for the SWAT model simulation of the Xitiaoxi River Basin. The simulation results accurately reflect the hydrological processes in the basin, providing a reference for hydrological analysis in other basins with relatively insufficient meteorological stations. However, there are still some shortcomings. This article chooses the SWAT model to simulate surface runoff in different periods. Although it can accurately simulate the overall trend of surface runoff in a large range, runoff simulation is influenced by natural factors such as climate, as well as human factors such as policies and engineering measures for returning farmland to forests, making it a complex process. Although agricultural activities may not alter soil types in the short term, they can modify soil permeability by influencing the composition and structure of soil particles, thereby increasing or decreasing surface runoff. Engineering projects, particularly water conservancy projects, can directly affect surface runoff processes. For instance, reservoirs and dams regulate the timing of runoff, reducing peak flows but potentially altering natural hydrological regimes downstream. Urban drainage systems accelerate stormwater discharge, which may transfer flood risks to downstream areas. Additionally, water resource management, ecological policies, and improper urban planning can all influence runoff generation and concentration processes, ultimately affecting the entire surface hydrological cycle. Therefore, integrating and optimizing the model, including human factors into the surface runoff simulation process, as well as conducting multi-scenario simulations, are important entry points for improving research accuracy in the future.

4.2. Response of Runoff to Different Territorial Spatial Structures

4.2.1. Influence of Single Territorial Spatial Type on Runoff

This article employs an extreme territorial spatial scenario to study the impact of a single territorial spatial type on runoff. Specifically, after reclassifying the territorial space data for the study area, we applied regular rate parameters and substituted the single territorial spatial type into the SWAT model to analyze its impact on runoff. The area of the territorial spatial type in the study area examined in this article is relatively large. It is generally believed that territorial spatial types with significant impact on runoff have been simulated. The results are shown in Table 4. When considering a single territorial spatial type, various territorial spatial types exert different impacts on runoff, with the promoting effects, ranging from strong to weak, being industrial production space, agricultural production space, urban living space, forest ecological space, grassland ecological space, and rural living space. The results indicate that the industrial production space and urban living space, as the main types of construction land, are the main carriers of impermeable surface, and farming on the agricultural production land increases soil hardness to a certain extent, which can increase surface runoff. The ecological space of forest and grassland, as the permeable surface of the basin, can absorb a large amount of rainfall and reduce surface runoff.

Table 4. The runoff of different territorial spatial types.

Territorial Spatial Type	Agricultural Production Space	Industrial Production Space	Urban Living Space	Rural Living Space	Forest Ecological Space	Grassland Ecological Space
Runoff (m^3/s)	6.828	8.112	6.570	5.979	6.546	6.345

4.2.2. Change in Production-Living-Ecological Space Type and Runoff in Different Periods

The overall change rates of different territorial spatial types in different periods are shown in Table 5. However, other ecological spaces in the Xitiaoxi River Basin were relatively small and almost constant, so they were not included in this analysis. Moreover, the SWAT model was used to simulate the monthly runoff of the territorial space in 1990, 2000, 2010, and 2018. The overall change rates of runoff in different periods are shown in Table 5, and the impact of seven types of territorial space change on the runoff change rate in different periods was analyzed, as shown in Table 6. Due to the different territorial spatial types and combinations in different periods, the results of runoff simulation vary, resulting in different rates of runoff change. The specific analysis is as follows.

Table 5. Variations in production-living-ecological spaces and runoff in different periods.

Period	Runoff (%)	Agricultural Production Space (%)	Industrial Production Space (%)	Urban Living Space (%)	Rural Living Space (%)	Forest Ecological Space (%)	Grassland Ecological Space (%)	Water Ecological Space (%)
1990–2000	−0.037	−0.029	0.064	0.488	0.038	0.012	−0.063	0.000
2000–2010	0.201	−0.051	6.315	1.504	0.448	−0.009	0.009	0.118
2010–2018	0.326	−0.049	1.088	0.437	0.170	−0.007	0.023	−0.030
1990–2018	0.492	−0.123	15.247	4.355	0.758	−0.004	−0.033	0.085

During the period of 1990–2000, excluding the reductions observed in agricultural production space and grassland ecological space, all other types of territorial spatial shown an increasing trend in the Xitiaoxi River Basin. Meanwhile, an overall declining trend was observed in the runoff in the Xitiaoxi River Basin. The correlation analysis revealed significant negative relationship between changes in forest ecological space and runoff

change. Theoretically, the forest ecological space has the function of conserving water sources and preventing soil erosion. The interception effect of forest land is significant, with a large amount infiltration, ultimately leading to the decrease in surface runoff. Thus, the expansion of forest ecological space constitutes the primary driver behind increased runoff in the Xitiaoxi River Basin during the period of 1990–2000.

Table 6. Correlation analysis of the change in production-living-ecological space type and runoff.

Period	Agricultural Production Space	Industrial Production Space	Urban Living Space	Rural Living Space	Forest Ecological Space	Grassland Ecological Space	Water Ecological Space
Correlation coefficient	−0.116	0.716	−0.082	−0.058	−0.193	−0.051	−0.046
p-Value	0.048	0.000	0.162	0.322	0.001	0.386	0.429

Across the consecutive temporal intervals 2000–2010 and 2010–2018, industrial production space, urban living space, rural living spaces, and grassland ecological space all exhibited expansion trends in the Xitiaoxi River Basin, whereas agricultural production space and forest ecological space experienced contraction. The runoff mainly increased in the Xitiaoxi River Basin. Industrial production space change exhibited a significant positive correlation with runoff change. It is generally believed that the type of construction land, particularly industrial production space, has a significant impact on the increase in runoff. This is mainly due to the expansion of the impervious surface area, which greatly reduces infiltration and increases surface runoff. Forest ecological space change and agricultural production space change exhibited significant negative correlation with runoff change. The reduction in both agricultural production space and forest ecological space leads to increased runoff. Consequently, the combined effects of industrial production space expansion and reduction in both agricultural production space and forest ecological space have contributed to an overall increasing trend in runoff from 2000 to 2018 in the Xitiaoxi River Basin.

During the period of 1990–2018, industrial production space, urban living space, rural living spaces, and water ecological space all exhibited expansion trends in the Xitiaoxi River Basin, whereas agricultural production space, forest ecological space, and grassland ecological space experienced contraction. Forest ecological space change and agricultural production space change exhibited significant negative correlation with runoff change, while industrial production space change exhibited a significant positive correlation with runoff change, while industrial production space change exhibited a significant positive correlation with runoff change. Thus, the contraction of agricultural production space and forest ecological space, coupled with industrial production space expansion, constitutes the primary drivers of increased surface runoff in the Xitiaoxi Basin during the period of 1990–2018.

The above analysis shows that the change in runoff is closely related to the type and area of territorial space. The expansion of production space, particularly industrial production space, leads to increased runoff, whereas the increase in agricultural production space can reduce runoff. Conversely, the increase in ecological spaces, especially forest ecological space, results in decreased runoff.

4.3. The Limitations of the Study and Future Research

Although the hydrological simulation results in the study area meet the accuracy requirements of the SWAT model, they still warrant further discussion. The CMADS-L40 dataset exhibits certain limitations. While its current spatial resolution (1/3°) is suitable

for hydrological process simulations in plain areas, its performance in regions with micro-topography (e.g., valleys, urban heat islands) requires further improvement. Additionally, in regions with inadequate meteorological coverage, particularly western plateaus and rugged highlands, the dataset's reliance on reanalysis data introduces systematic errors. Given the rugged and complex mountainous terrain in the upstream study area, the accuracy of hydrological process simulations using this dataset has been somewhat compromised. Furthermore, the complex terrain introduces errors in the DEM data, particularly in vertical errors. Vertical errors lead to inaccurate slope calculations, which subsequently affect the extraction of parameters such as watershed area and sub-basin delineation. For example, such errors may cause slope values to deviate from actual conditions, thereby impacting the determination of flow accumulation paths and drainage area division. These factors collectively impact the accuracy of simulation results. Therefore, employing higher-resolution data to improve the accuracy of hydrological process simulations in the study area will be the focus of our future work.

The territorial spatial type, soil type, topography, and climate are interrelated to some extent. While this study has predominantly focused on the impacts of territorial spatial changes on hydrology, it has paid insufficient attention to other elements and their interactions. Investigating the coupled effects of these multi-element interactions on hydrological processes should be a key focus in future research. We employed the threshold method to delineate HRUs. In the threshold method, the assigned thresholds for territorial spatial type, soil type, and slope classification directly influence simulation accuracy. While the SWAT model typically employs default thresholds of 5–20%, this highly homogeneous thresholding approach, despite its simplicity, may compromise modeling precision to some extent. Therefore, comparative analyses using multiple thresholds within a reasonable range should be attempted in future studies to enhance simulation accuracy.

5. Conclusions

This article selected the Xitiaoxi River Basin as the study area. Using the SWAT model alongside the 40-year CMADS-L reanalysis dataset, combined with multi-source data such as DEM, soil type, and territorial spatial type, surface runoff within the basin was simulated from the perspective of production-living-ecological space under different TSCs. Moreover, hydrological response characteristics under varying TSCs were analyzed. Therefore, the conclusions are as follows.

(1) The SWAT model, driven by CMADS, and supported by multi-source data, is robust in monthly runoff simulation. The integrated CMADS-L40/SWAT framework demonstrates high reliability for monthly runoff simulation in the data-scarce basin ($R^2 > 0.70$, NSE > 0.50, |PBIAS| < 20%), indicating that the model meets the accuracy standards of the SWAT model. Although our simulation results meet the accuracy requirements of the SWAT model, further validation of uncertainties remains necessary. The rugged mountainous terrain in the upstream study area inevitably introduces errors in DEM generation, which affects the accuracy of sub-basin delineation and consequently influences the entire hydrological process simulation. Currently, the CMADS dataset provides higher-precision meteorological data (with a spatial resolution of $1/16^\circ$ and hourly temporal resolution), demonstrating superior accuracy compared to the data used in this study. Therefore, our forthcoming work will employ higher-resolution meteorological and topographic data to implement multi-model (SWAT, SCS-CN, TOPMODEL, etc.) simulations of hydrological processes in the study area, followed by comparative analysis of modeling results to reduce uncertainties in SWAT-based hydrological assessments.

(2) Significant linkages exist between territorial spatial change and runoff change. Changes in agricultural production space and forest ecological space showed statistically

significant negative correlation with runoff change, while industrial production space change exhibited significant positive correlation with runoff change. The expansion of production space, particularly industrial production space, leads to increased runoff, whereas the enlargement of agricultural production space can reduce runoff. The increase in ecological spaces, especially forest ecological space, results in decreased runoff. Changes in agricultural production space, industrial production space, and forest ecological space during the study period constitute the primary drivers of runoff change in the Xitiaoxi River Basin.

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