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Study on Interaction between Surface Water and Groundwater in Typical Reach of Xiaoqing River Based on WEP-L Model

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Abstract: Surface water and groundwater (SW-GW) are an inseparable whole, having a tightly coupled hydraulic relationship and frequent inter-transformation. As such, the quantitative calculation of water exchange between SW-GW is a difficult challenge. To address this issue, we propose the use of a physically based and distributed hydrological model, called WEP-L, in order to analyze the effects of the SW-GW interaction and its spatiotemporal variation characteristics in the Xiaoqing River basin. We demonstrate that the SW-GW interaction is significantly affected by season. The simulated annual average exchange volume of SW-GW above the control section of Huangtaiqiao Station from 1980 to 2020 is found to be 54.79 m^3/s. The exchange volumes of SW-GW in the wet and dry season are 28.69 m^3/s and 13.46 m^3/s, respectively, accounting for 48.75% and 22.87% of the whole year. In addition, considering two types of climate change scenarios, the exchange capacity of SW-GW increases by 0.42m^3/s when the rainfall increases by 5%, while the exchange capacity decreases by only 0.2 m^3/s when the temperature increases by 0.2 °C. This study provides insights for the quantification of the SW-GW interaction at the regional scale, which will benefit our understanding of the water cycle and evolution of water resources in Xiaoqing River basin.

Keywords: hydrological models; climate change; Xiaoqing River; surface water–groundwater interaction

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1. Introduction

Water resources are important for human survival. Along with social progress and economic development, the world's population has increased dramatically, and the consequently heightened impacts of human activities on water resources cannot be ignored. Human activities have led to environmental deterioration, water pollution, and serious waste, causing water resources to become increasingly scarce around the world. Surface water–groundwater (SW-GW) interaction is a common phenomenon observed in nature. The water exchange between surface water and groundwater is a complex process, affected by many factors such as topography and meteorology. Water exchange between the two is a hot issue of global concern, especially research on water exchange under the influence of climate change and human influences, which has attracted extensive attention from scholars both at home and abroad. Therefore, how to scientifically manage water resources and realize the sustainable utilization of water resources is a major challenge for human beings. Research has shown that the interaction between surface water and groundwater is affected by multiple factors, including climate change [1] and human activities [2,3]. At the same time, the interaction between surface water and groundwater also has a significant impact on other human production activities, such as the spatial distribution of pesticide metabolites in groundwater [4], lake conditions [5], water supply safety [6], irrigation projects [7], etc. Therefore, it is of great significance to study the interaction between surface water and groundwater.

There exist many methods to study the interaction between surface water and groundwater, such as the use of water chemistry information to explore the evolution of water chemistry under the interaction through various isotope tracers [8]. There are many types of isotopes used in hydrochemistry methods, such as natural uranium and strontium isotopes [9,10], ^{222}Rn, deuterium, and oxygen-18 [11]. The geothermal gradient causes a longitudinal difference between surface water and groundwater temperatures and, so, temperature can be used as a natural tracer. Temperature tracing technology can be used to determine abnormal areas, allowing for determination of the scope of groundwater discharge to the surface [12,13]. Yi Liu et al. (2011) [14] have proposed a trend outflow method to gain a better understanding of the interactions based on cumulated inflow and outflow data for any river reaches of interest. Researchers have recently analyzed the interactions between surface water and groundwater by measuring bacterial biomass and activity [15,16]. Aiping Zhu et al. (2020) [17] have integrated hydrochemical and biological approaches to investigate the surface water–groundwater interactions in the hyporheic zone of the Liuxi River basin, southern China. Isotope and temperature tracers are mostly used for qualitative and semi-quantitative studies and, so, there is a lack of quantitative studies on the surface water–groundwater interaction. In the 1970s, D.R. Lee developed a half-barrel osmotic flowmeter and applied it to the measurement of groundwater flow exchange with Lake Sully in Minnesota (MN), USA. Since then, osmotic flowmeters have been used in the study of water exchange under various hydrogeological conditions, and their accuracy and measurement range have been improved. However, this method is only suitable for point measurement, not for the calculation of catchment-scale exchange volume. As a result, large amounts of hydrological data have been collected, and models have been used to calculate the exchange between surface and groundwater. However, there is little research quantifying the interaction between surface water and groundwater by combining natural conditions and human water supply information. Many models have been used to simulate the interaction between surface and groundwater, such as SWAT, MODFLOW [18], STICS–EauDyssée coupled models [19], MIKE-SHE [20], STRIVE [21], AHF [22], HydroGeoSphere [23], and GSFLOW [24]. However, most studies on the SW-GW interaction have focused only on natural water cycles, and it is generally recognized that there is insufficient evidence quantifying the effect of human activities. Taking Xiaoqing River basin as an example, in this paper, we analyze the temporal and spatial variation of the exchange between surface water and groundwater in the region.

The main research schemes are as follows:

(1) Referring to the existing literature, we sort previous studies in the study area; collect measured land use, soil type, vegetation index, water supply, meteorology, and runoff data; and conduct data pre-treatment.
(2) We determine the simulation range and basin outlet, extract the simulated river network, divide the watershed, distribute the water supply information, and then construct the natural–societal dual water cycle simulation.
(3) According to the simulation results, the interannual and annual changes in exchange capacity between surface water and groundwater in the study area are analyzed. Meanwhile, the spatio-temporal changes in the interaction between the upper and lower reaches of the basin are also analyzed.
(4) Two climate change scenarios are considered: Rainfall increased by 5% and temperature increased by 0.2 °C. The change rules of runoff and the interaction between surface water and groundwater are analyzed under these change scenarios.

2. Materials and Methods

2.1. Study Area

This study considers the Xiaoqing River basin (37°16′09″N–37°21′02″, 118°52′27″E–119°07′29″E), located in the middle of Shandong Province (Figure 1). Xiaoqing River, the

Yellow River basin of the Bohai River system, originates from Yufu River and finally runs into Laizhou Bay, with a total length of 233 km and a basin area of 10,336 km^2. According to the statistics of the synchronous observation series from 1956 to 1979, the average annual precipitation in the Xiaoqing River basin is 640.4 mm, and the average annual runoff depth of the basin is 121 mm. The runoff of Xiaoqing River is mainly supplied by atmospheric precipitation, but the spring water supply is abundant. Therefore, the water situation of Xiaoqing River is stable, and the runoff is evenly distributed throughout the year. The main tributaries of the Xiaoqing River are the Juye River, Xinghua River, Xiaofu River, Zi River, etc., mainly distributed on the south bank of the Xiaoqing River. Xiaoqing River is in the warm temperate sub-humid continental climate zone, with hot and rainy summers and dry and cold winters. The average annual temperature of Xiaoqing River is 12–14 °C, and the average annual rainfall is about 640.4 mm. Xiaoqing River is the most important river channel in Jinan City, playing functions associated with flooding control, irrigation, and navigation.

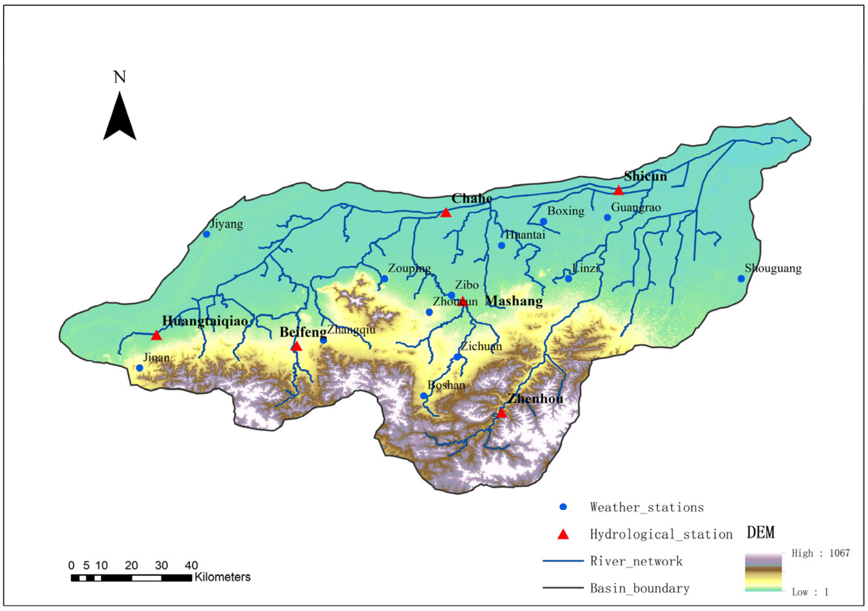
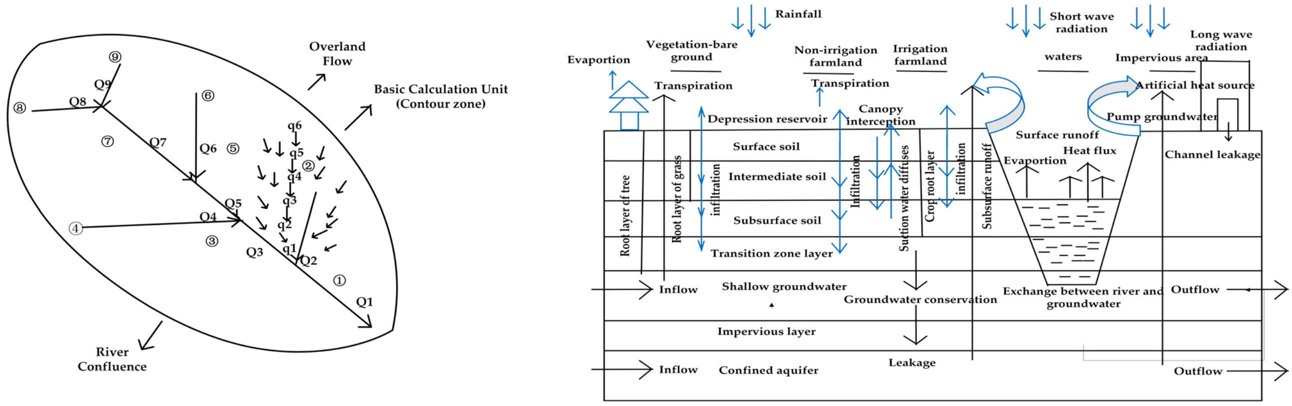


Figure 1. Location of the Xiaoqing River basin.

2.2. Model Development

The hydrological model employed for this study was the water and energy transfer process (WEP), which is a distributed hydrological model with a physical mechanism. This model integrates the advantages of distributed hydrological models and land surface process models, and allows for combined simulation of water cycle and energy exchange processes. The mosaic method was used to consider the diversity of land cover in the calculation unit, which not only allows for expression of the spatial variation characteristics of hydrological variables, but also improves the calculation efficiency of the model. According to the characteristics of the water cycle process, variable time step simulation was adopted, in order to ensure the realization of the water cycle dynamics mechanism.

The model uses sub-streams and contours as the basic calculation unit, thus effectively avoiding the "big basin coarse grid"-related distortion of water balance and flow path distortion, and the reasonable expression of hydrological variables is ensured through the space variation characteristic of the variable water (VSA) production flow theory, the implementation of river basin water, and process energy exchange coupling simulation. The horizontal and vertical structures of the model are shown in Figure 2. There are 10 types of underlying surface in the basic calculation unit: Water area, impervious area, forest land, grassland, bare land, irrigated farmland, non-irrigated farmland, sloping farmland, terraced fields, and dam land. The model is vertically divided into nine layers: Vegetation canopy, surface depression reservoir, the surface soil, the soil in the middle, the underlying soil, transition layer, shallow groundwater layer, difficult permeable layer, and confined aquifer [25].



(**a**) (**b**)

Figure 2. Horizontal structure and vertical structure of WEP model: (**a**) Horizontal structure—the basic calculation unit is "isometric zone in sub-basin"; (**b**) vertical structure—this is divided into nine layers (from top to bottom: Vegetation canopy, surface depression reservoir, the surface soil, the soil in the middle, the underlying soil, transition layer, shallow groundwater layer, difficult permeable layer, and confined aquifer).

2.2.1. Model Evaluation Method

The relative error (Re), Nash efficiency coefficient (NSE), and coefficient of determination (R^2) were used to evaluate the simulation results of the model. The standard of model calibration was as follows:

(1) The relative error (Re) represents the deviation degree between simulated and measured values.
(2) The Nash–Sutcliffe efficiency coefficient (NSE) represents the degree of fitting between the actual and simulated values.
(3) The coefficient of determination (R^2) represents the consistency of the trend between the actual and simulated values.

The calculation formulas are as follows:

$$\mathrm{Re} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{Q}_{\mathrm{sim,i}} - \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{Q}_{\mathrm{obs,i}}}{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{Q}_{\mathrm{osb,i}}} \times 100\%, \tag{1}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \left(\mathrm{Q}_{\mathrm{sim,i}} - \mathrm{Q}_{\mathrm{obs,i}}\right)^2}{\sum_{\mathrm{i}=1}^{\mathrm{N}} \left(\mathrm{Q}_{\mathrm{obs,i}} - \overline{\mathrm{Q}}_{\mathrm{obs,i}}\right)^2}, \tag{2}$$

$$R^2 = \frac{\left[\sum_{i=1}^{N} \left(Q_{obs,i} - \overline{Q}_{obs,i}\right)\left(Q_{sim,i} - \overline{Q}_{sim,i}\right)\right]^2}{\sum_{i=1}^{N} \left(Q_{obs,i} - \overline{Q}_{obs,i}\right)^2 \sum_{i=1}^{n} \left(Q_{sim,i} - \overline{Q}_{sim,i}\right)^2}, \tag{3}$$

where $Q_{sim,i}$ and $Q_{obs,i}$ are the monthly runoff simulation and site observation results ($m^3 \cdot s^{-1}$), respectively; N is the number of months; and $\overline{Q}_{\mathrm{sim},i}$ and $\overline{Q}_{obs,i}$ are the monthly averages of simulated flow and observed flow ($m^3 \cdot s^{-1}$), respectively.

2.2.2. Data Sources

The distributed hydrological model of Xiaoqing River basin includes the following six types of basic data: (1) Hydrometeorological data; (2) geographic elevation and topographic data; (3) river network data; (4) soil and hydrogeological data; and (5) land use and vegetation cover data. Data descriptions and sources are provided in Table 1.

Table 1. Data description and source summary table, including data start and end times, accuracy, and data source.

Terms	Data Description	Time	The Data Source
Meteorological Data	Diurnal scale data sets	1980–2020 (There are some missing years)	Dataset of daily surface climatological data for China
runoff	Month	1980–2020 (There are some missing years)	Shandong Hydrology Bureau
DEM	Geographic digital elevation, precision 30×30 m		Geospatial data cloud
LUCC	1 km grid, class 22	1980, 1990, 1995, 2000, 2010, 2013, 2015, 2018, 2020	Interpreted by Institute of Geography, Chinese Academy of Sciences
Soil type	According to national standards, it is divided into four major categories	2004	Chinese Academy of Sciences Resource Cloud platform
Leaf area index	Month	2001–2020	MODIS Global Product
Vegetation coverage	Month	2001–2020	MODIS Global Product

The digital elevation map, soil type map, land use map, and site distribution map of Xiaoqing River basin are presented in Figure 3.

2.2.3. River Network Extraction

The WEP river network includes an actual river network and virtual river network. The actual river network was obtained by measurement, and the extraction of the virtual river network mainly involved the following steps: Cutting, full classification, and filling of DEM. According to the measured river network, the DEM elevation was lowered. We calculated the "flow direction" and "sink", determined the water threshold, determined the location of the basin reservoir, lake, and basin outlet, defined segmentation points, and, finally, extracted and calculated the virtual river network. The virtual river network of Xiaoqing River basin is shown in Figure 4.

2.2.4. Division of Basic Calculation Unit

To not only meet the requirements of vertical zone simulation and analysis, but to also avoid excessive calculation burden, the 10,336 km^2 area of the Xiaoqinghe River Basin was divided into 123 sub-basins with topological relations, which were then sub-divided into 1244 basic calculation units, according to the contour zone division rules of WEP. The sub-basin unit division of the Xiaoqinghe River basin is shown in Figure 5.

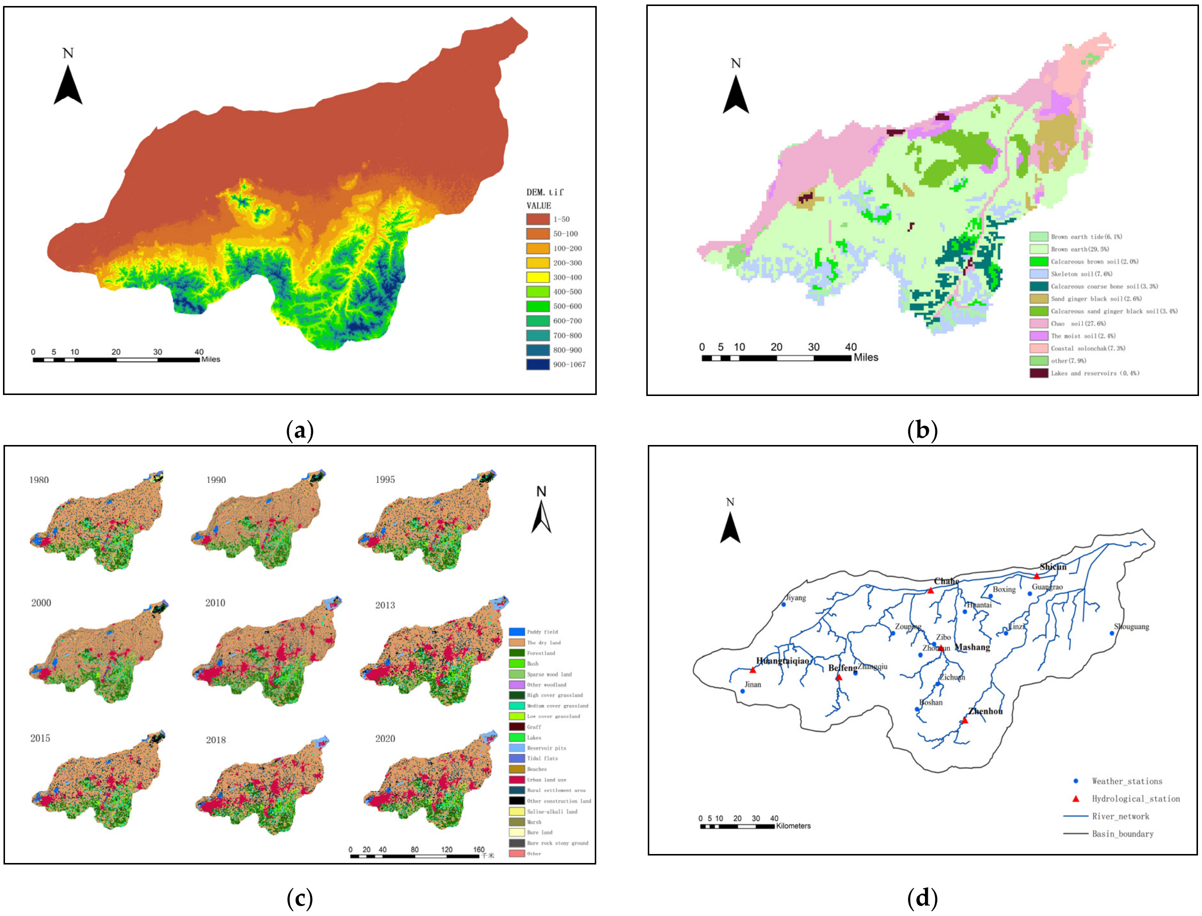


Figure 3. Basic hydrological data of Xiaoqing River basin: (**a**) Digital elevation map reflecting the topography of the study area; (**b**) soil type map, divided into 12 categories; (**c**) land use type map, divided into 22 categories; and (**d**) distribution of hydrological and meteorological stations, including 6 hydrological stations and 12 meteorological stations.

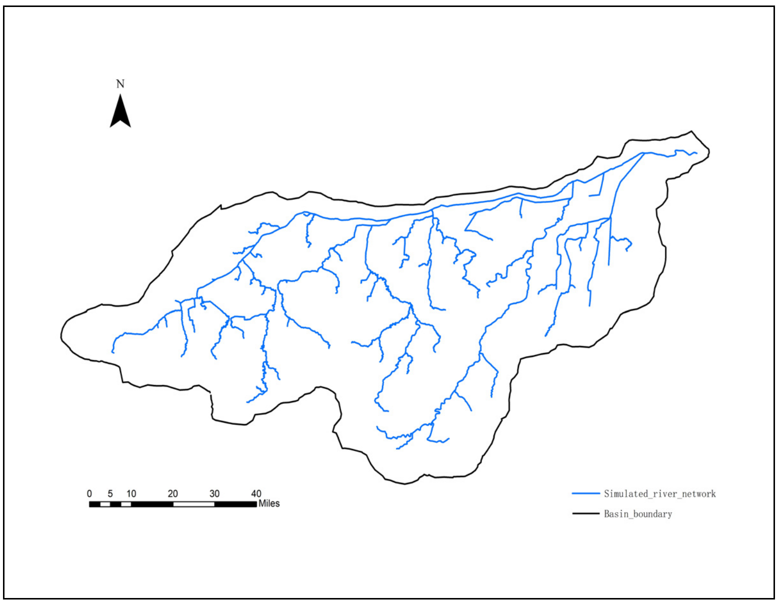


Figure 4. Virtual water system extracted based on WEP.

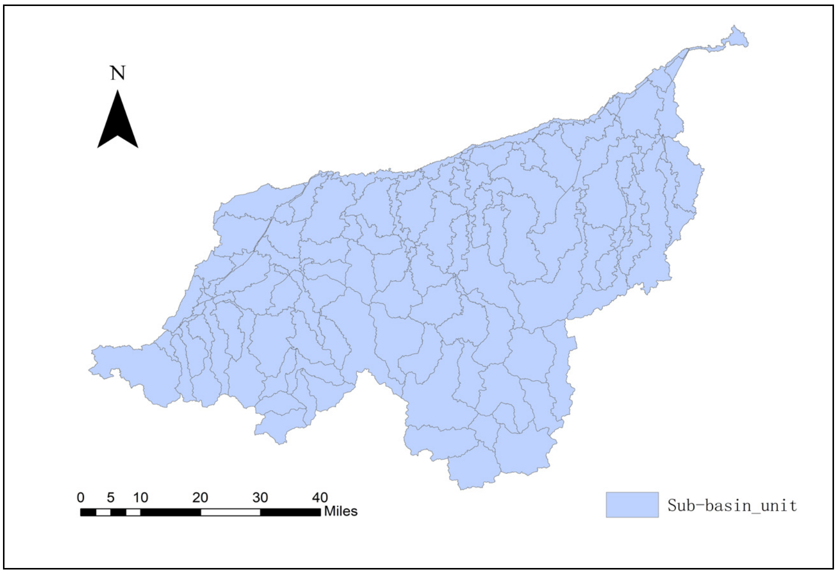


Figure 5. Sub-basin unit map (minimum catchment area threshold, 50 km^2).

3. Results

3.1. Model Calibration and Verification

The parameters of the WEP model are mainly divided into four categories: Underlying surface and water system parameters, vegetation parameters, soil parameters, and aquifer parameters. All parameters have physical significance and can be estimated from observed or remote sensing data. The sensitivities of the above four types of parameters were analyzed and, according to their sensitivity, these parameters were divided into three levels: High, medium, or low sensitivity. The highly sensitive parameters included soil thickness, soil saturated water conductivity, and bed material permeability. Highly sensitive parameters were selected for model calibration, conducted according to the measured runoff data. The results of parameter calibration are shown in Table 2, while the simulation effect evaluation of cross-section discharge in the Xiaoqing River basin is shown in Table 3. The permeability coefficient of the soil layer used in the model was 0.648 m/d, that for the sand and gravel layer was 4.32 m/d, and that for the riverbed material was about 5.18 m/d. The soil layer thickness for the top isometric zone, middle isometric zone, and river valley or plain was 0.4 m, 0.6 m, and 1.0 m, respectively.

Table 2. Calibration results of WEP model parameters (the value ranges and final values of the parameter are described in this section).

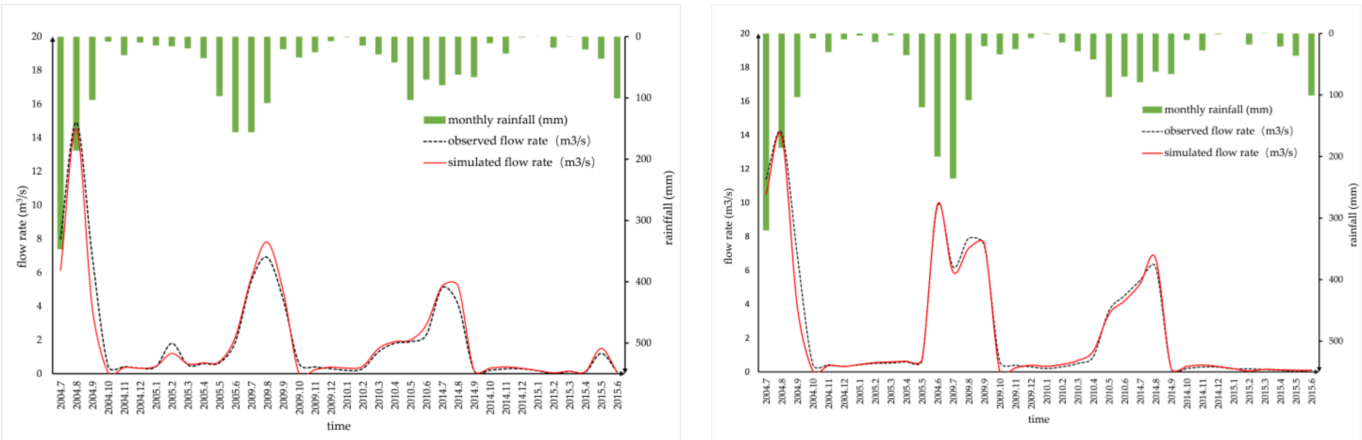
Parameters	Value Range	Value
Aquifer thickness correction factor	0.1–20	1
Soil thickness of the first layer (m)	0.1–0.8	0.2
Soil thickness of the second layer (m)	0.2–2.0	0.6
Soil thickness of the third layer (m)	0.3–4.0	1.2
Stomatal impedance correction coefficient	0.1–20	1
Channel roughness correction coefficient	0.01–100	1
Slope roughness correction factor	0.1–20	1
Soil saturated water conductivity correction coefficient	0.01–100	1
Aquifer side guide water coefficient correction coefficient	0.01–100	3
Correction coefficient of water conductivity of riverbed bottom material	0.01–100	1

Table 3. Simulation effect evaluation of cross-section discharge in Xiaoqing River Basin.

Hydrological Station	NSE	Re	R^2
Huangtaiqiao	0.85	0.12%	0.79
Chahe	0.79	0.12%	0.78
Shicun	0.82	0.25%	0.80
Beifeng	0.79	−0.23%	0.81
Mashang	0.75	0.42%	0.72
Zhenhou	0.82	0.33%	0.81

3.2. Simulation Results

We considered the period 1980–2020 for monthly runoff process simulation in Xiaoqing River. According to the hydrological frequency analysis, we selected 2004, 2009, and 2014 as representative years, and the simulation results are shown in Figure 5. It can be seen that the simulation results at the site were consistent with the observed data (Figure 6). The NSE of Huangtaiqiao Station was 0.85, Re was 0.12%, and R^2 was 0.79; while the NSE of Beifeng Station was 0.79, Re was −0.23%, and R^2 was 0.81.

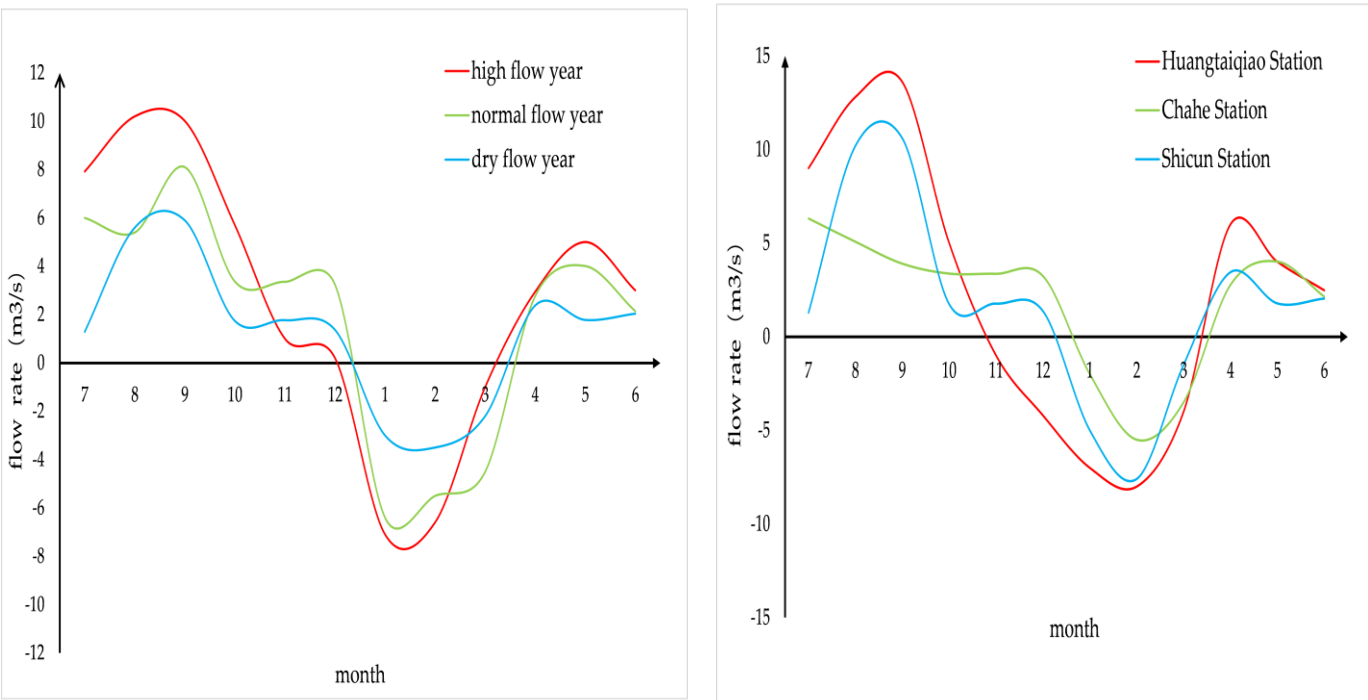


(**a**) (**b**)

Figure 6. Comparison of WEP-simulated and observed values for Huangtaiqiao Station and Beifeng Station. (**a**) Huangtaiqiao Station; (**b**) Beifeng Station.

The results of WEP model showed that, from 1980 to 2020, the average annual rainfall in Xiaoqing River basin was 767.42 mm, the actual evapotranspiration was 335.43 mm, the total runoff was 235.96 mm, the surface runoff was 157.96 mm, the base discharge was 89.34 mm, the soil flow was 35.67 mm, and the dive recharge as 167.99 mm. Compared with the precipitation, the change in flow presented an obvious lag. According to the hydrological frequency analysis, 2004, 2009, and 2014 were selected to represent wet, normal, and dry years, respectively, for further study. It can be seen, from the simulation results, that the surface water and groundwater interaction was strong in the Jinan section of Xiaoqing River basin. With the increase in rainfall from June to September in the wet season, river runoff increases, the difference between surface water and groundwater level increases, and the water recharge from river water increases. In the dry season from December to March, river runoff is low, and groundwater is discharged to surface water. The exchange volume of surface water and groundwater generally increased first and then decreased. The cultivation area of farmland on both sides of Xiaoqing River is large, and agricultural irrigation is basically based on groundwater water intake. In the agricultural irrigation period with large water consumption, the trend of water leakage and groundwater recharge is especially intense.

In the Xiaoqing River drainage, by detailed analysis of the interaction between different regions of the middle and lower reaches of surface water groundwater, as shown in Figure 7, we can see that the surface water–groundwater transformation relationship presented obvious spatial variation. In particular, Huangtaiqiao Station, located in the upstream basin, presented larger interannual change, with the dominant effect of water exchange observed in September, but with weak regularity. Chahe Station, located in the middle reaches of the basin, did not present a significant variation trend in the annual scale. Meanwhile, Shicun Station, located in the lower reaches of the basin, having relatively gentle topography, mainly fluctuated at the annual scale. The significantly increased change from June to September increased in the annual variation trend, and the transformation relationship of surface water and groundwater in this section is due to river seepage replenishing the groundwater. In general, the exchange capacity of surface water and groundwater in the middle and upper reaches of rivers is greater than that in the lower reaches.



(a) (b)

Figure 7. Simulation results of monthly discharge at hydrological stations: (**a**) Change in exchange capacity in Jinan section during abundant and dry season; and (**b**) change in exchange capacity in the upper, middle, and lower reaches of Xiaoqing River basin. Huangtaiqiao Station, Chahe Station, and Shicun Station are in the upper, middle, and lower reaches of the basin, respectively.

The variation of exchange volume in the Jinan section of Xiaoqing River from 1980 to 2020 is shown in Figure 8. It can be seen that the exchange volume of surface water and groundwater fluctuated continuously over the long sequence, but tended to be stable as a whole. In most years, the Xiaoqing River replenishes the groundwater while, in some years, the groundwater is discharged to the Xiaoqing River.

3.3. Verification and Analysis

According to the relation curve of surface water and groundwater level in the time-series—see Figure 9a—there exists a close relationship between surface water level, groundwater level, and surface water–groundwater exchange capacity. It can be seen that surface water in the Jinan section of Xiaoqing River replenishes groundwater throughout most of the year, and the groundwater level fluctuates over the year, being closely related to the annual precipitation and the influence of human activities, but is generally stable. The surface water level change with respect to season is larger, with the upstream region presenting groundwater recharge and less artificial production of groundwater. The change in surface water level and groundwater level is basically synchronous, but some time points also presented differences; for example, when the relief upstream area is larger, considering the connection of surface water to groundwater, the groundwater recharge strength is higher. March is the key agricultural irrigation period, during which the amount of groundwater extraction increases and the groundwater level drops slightly. When the wet season comes (in July and August), the surface water replenishes the groundwater and the groundwater level continues to rise, reaching a peak in October, then reaching stability.

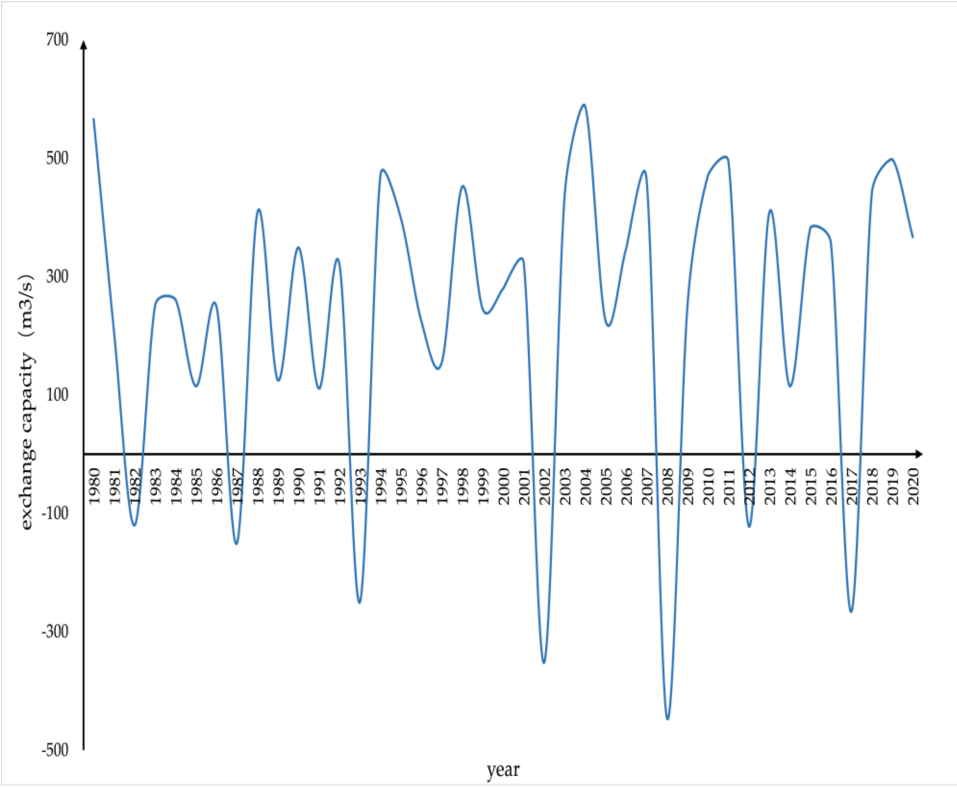


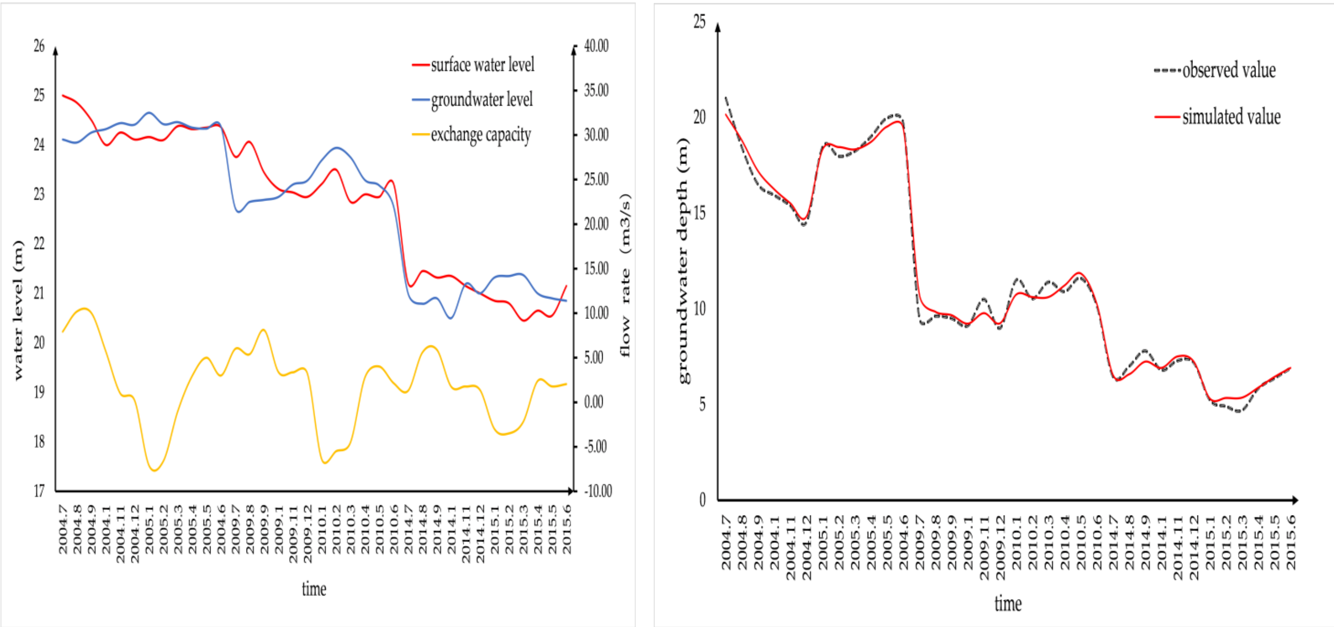
Figure 8. Change in exchange volume in Jinan section from 1980 to 2020.

By comparing the measured groundwater depth with the simulated value, it can be seen that the WEP model had a good simulation effect in the Xiaoqing River basin, and the simulated value was close to the measured value, as shown in Figure 9b, verifying the accuracy of the model and its applicability in the Xiaoqing River basin.

3.4. Hydrologic Effect Analysis

Regarding the process effect, the land use/cover change (LUCC) has a great impact on water resources in the basin. As can be seen from the land use type map, with the development of society, the urban land has constantly increased, and human activities are constantly changing the underlying surface conditions of the basin.

Regarding the annual runoff effect, with the development of the river basin economy and the increase in water consumption, the annual runoff distribution has been significantly affected by human activities, the annual distribution characteristics of natural runoff have been lost, and the Xiaoqing River basin presents varying degrees of flow interruption. The annual distribution of annual average runoff for each station in Xiaoqing River basin is provided in Table 4.



(**a**) (**b**)

Figure 9. Comparison of WEP-simulated and observed values: (**a**) Comparison of groundwater level and exchange capacity of surface water in Jinan section of Xiaoqing River; and (**b**) comparison of groundwater depth in Jinan section of Xiaoqing River.

Table 4. Annual distribution of annual average runoff for each station in Xiaoqing River basin.

Hydrological Station	Distribution of the Four Seasons/%				Maximum Month	Minimum Month	Maximum Four Consecutive Months	
	3–5	6–8	9–11	12-2			Month	Percentage/%
Huangtaiqiao	3.30	42.40	17.90	16.40	8	5	7-10	77.30
Chahe	7.30	63.50	14.40	14.80	8	5	7-10	72.90
Shicun	0.55	73.40	25.10	0.95	8	2	7-10	67.99
Beifeng	33.00	10.10	37.10	19.80	8	2	8-11	69.45
Mashang	9.30	41.20	19.10	10.40	8	1	7-10	72.55
Zhenhou	7.30	53.50	24.40	14.80	8	1	7-10	74.30

Regarding the water quality effect, the excessive development of upstream water resources and the increased discharge of farmland wastewater with high salinity, industrial wastewater, and domestic sewage have resulted in the serious pollution of Xiaoqing River. In view of this problem, relevant departments have carried out corresponding treatment of Xiaoqing River, such as the Xiaoqing River mainstream treatment project launched in 1996. The monitoring results show that, with the increase in river flow, the salinity of river water is also increasing, indicating that the upstream salinity is low and the downstream salinity is high.

Regarding the environmental effect, with the rapid development of industry and agriculture, groundwater has been increasing, especially in the middle and lower reaches of the river. Due to groundwater interactions, sand and silt in downstream irrigation areas have increased, as well as increased the groundwater in downstream parts due to excessive exploitation of groundwater, the drawdown funnel, soil salinization, and other environmental problems.

3.5. Basin Hydrological Analysis under Climate Change Scenarios

The runoff and water resources under future scenarios were predicted using future climate models. Two scenarios are considered in this paper: (1) A 5% increase in rainfall; and (2) temperature increased by 0.2 °C (see Figure 10).

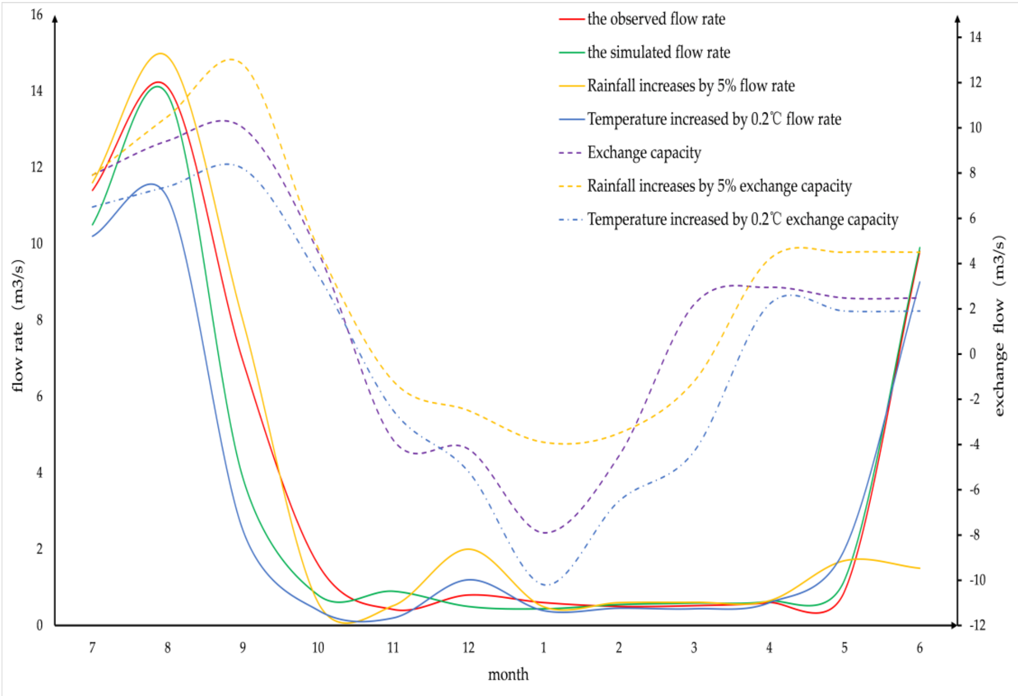


Figure 10. Flow changes under the climate change scenarios.

When rainfall increases by 5%, compared with the initial exchange capacity, the groundwater discharge to surface water decreases, the surface water level rises, the cross-section discharge increases, the difference between surface water and groundwater levels increases, and the surface water supply to groundwater increases in the wet season. Under a temperature increase of 0.2 °C, the evaporation of surface water is enhanced, thus affecting the infiltration of soil water simultaneously. The cross-section discharge decreases, and the interaction between surface water and groundwater has a weakened effect. The overall trend was that the interaction quantity and the total runoff both decreased.

The variation of basin runoff is affected by multiple factors. In recent years, human activities have changed the original water cycle mode of the basin and, so, it is necessary to explore the influence of human activities on the water cycle of the basin. In terms of runoff prediction and surface water–groundwater exchange under future change scenarios, the model needs to be improved.

The interaction between surface water and groundwater is a complex process. In order to deeply understand the situation of regional water resources, it is necessary to collect the hydrogeological data of the basin, synthesize various research methods, and conduct in-depth verification and analysis, in order to provide reference for determination of the water cycle process of the basin and regional water resource scheduling.

Finally, the calibration and optimization of the model require the support of a significant amount of measured data, which is also a great challenge for the majority of hydrologists. Therefore, how to collect and pre-process the data to help the model to play a better role is an urgent problem to solve.

4. Discussion

The WEP-L model, a distributed hydrological model based on physical mechanisms, has been used to study the evolution of water resources in the Heihe River basin, the

Yellow River basin [26], and other regions. This approach was adopted as it helps to analyze the spatial and temporal variation of watershed runoff, and the interaction between surface water and groundwater under the climate change scenarios. The interaction between surface water and groundwater in Xiaoqing River is strong, and is greatly affected by human activities and climate change. The topography of the Xiaoqing River basin is very significant [27], and the influence of elevation on the basin is easily ignored by traditional hydrological models. The WEP model adopts the sub-watershed plus the contour zone as the basic calculation unit, which brings the simulation results closer to the actual situation. It can be seen, from the above simulation results, that the WEP-L model has good applicability in the Xiaoqing River basin, and can reflect the variation of runoff and the interaction between surface water and groundwater.

There are many research methods for assessing the interaction between surface water and groundwater, and how to select appropriate research methods and consider the impact of natural conditions and human activities, in order to quantify the surface water and groundwater in the study area, remains a great challenge. Previous studies on the interaction between surface water and groundwater, especially on their exchange capacity, have mainly focused on qualitative or semi-quantitative research. In this paper, the WEP distributed hydrological model was adopted to construct the natural–societal binary water cycle simulation, in order analyze the spatio-temporal changes in the exchange capacity between surface water and groundwater in the basin.

The uncertainty analysis of hydrological model simulation results is an important step to improve the reliability of a model, in which parameter uncertainty is one of the key factors. How to quantify and reduce the uncertainty of hydrological model parameters is of great significance to improve simulation accuracy. In addition, Xiaoqing River is greatly affected by human activities; the runoff process of the basin is not only affected by industrial, agricultural, and domestic water consumption, but also by sewage discharge, engineering scheduling, spring water recharge, etc. Therefore, how to measure and analyze the interaction between surface water and groundwater in Xiaoqing River basin under the influence of multiple factors remains an important issue to be solved urgently.

5. Conclusions

In order to explore the interaction between surface water and groundwater in the Xiaoqing River basin and its influence on the surrounding areas, based on the discharge and water level data of typical hydrological stations in the Xiaoqing River basin from 1980 to 2020, we used the WEP model for simulation, and drew the following conclusions:

Against the background of the multi-year average, the interaction between surface water and groundwater in the Jinan section of Xiaoqing River was strong and dominant. The exchange capacity between surface water and groundwater fluctuated continuously, but tended to be stable overall.

From the perspective of the interannual scale, the interaction between surface water and groundwater in the Jinan section of the Xiaoqing River was greatly affected by the season, where the exchange volume was higher in the wet season. The multi-year average exchange volume from 1980 to 2020 was 58.85 m^3/s, while the average exchange volume in the wet season was 28.69 m^3/s and that in the dry season was 13.46 m^3/s, accounting for 48.75% and 22.87% of the annual average exchange volume, respectively.

At the spatial scale, the interaction between surface water and groundwater in the upper reaches of the basin was the strongest, followed by the lower reaches and, finally, the middle reaches. The Jinan section of Xiaoqing River is located in the upper reaches of the river, and the water level difference between surface water and groundwater in this section was large. On average, it is mainly surface water that supplies groundwater throughout the year. The terrain in the middle and lower reaches is generally flat, and the interactions between surface water and groundwater are greatly affected by human activities.

Under the climate change scenarios, when the rainfall increased by 5%, surface runoff and surface water recharge to groundwater were increased, and the interaction between surface water and groundwater was more intense, but the overall trend was consistent. When the temperature increased by 0.2 °C, evaporation increased, surface runoff did not change significantly, and groundwater discharge increased.

With the development of society, the urban land is increasing, upstream water extraction is increasing, the annual runoff of Xiaoqing River is decreasing, and some reaches of the river have even presented cutoff phenomena. At the same time, the irrigation area is increasing, groundwater extraction is increasing, the surface water–groundwater interaction is strong, and the degree of mineralization is increasing. The excessive exploitation of groundwater has caused significant environmental problems, such as groundwater falling funnel and soil salinization.

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