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Analysis of water yield service of Lianshui River Basin in China based on ecosystem services flow model

Yang Zou and DeHua Mao*
School of Geographical Sciences, Hunan Normal University, Changsha 410081, China
*Corresponding author. E-mail: maodehua@hunnu.edu.cn

YZ, 0000-0002-0599-5663

ABSTRACT

Water security assessment is very important to social development. However, most studies only focus on the status quo of water security in a static state and ignore the flow characteristics of water resources in water security assessment. This paper integrates multi-source data to construct a water supply and service supply–demand balance and spatial flow model in the Lianshui River Basin, simulates the spatial pattern of the service flow of the aquatic water ecosystem in the Lianshui River Basin from 1990 to 2018, and quantifies the service flow. Results show that: (1) From 1990 to 2018, the water supply in the Lianshui River Basin first decreased, then increased, and finally decreased. Water yield was the highest in 2010 and lowest in 2000. (2) Water demand increased year by year, and the amount of area with a poor water resource security index increased, indicating that water security was deteriorating. (3) The four main beneficiary areas in the basin are the urban area of Lianyuan City, the county seat of Shuangfeng County, the Louxing District of Loudi City, and the urban area of Xiangxiang City and nearby towns. The service flow showed the same changing trend as the water yield. In 2018, the water resource gap in the beneficiary area was as high as 4.49 billion m^3. Local governments should actively build a water-saving society, improve the efficiency of industrial and agricultural water-saving and residents' awareness of water-saving, and improve the water resources in the river basin. The research can provide a scientific basis for realizing the sustainable development of water resources in the Lianshui River Basin and improving the ecological compensation mechanism, and can also provide references for water resources management in other river basins.

Key words: ecosystem service flow, InVEST model, Lianshui River Basin, supply and demand balance, water yield

HIGHLIGHTS

- Water yield service was assessed using the InVEST model and the supply–demand balance model.
- The ecosystem service flow was introduced into the water security simulation study of the river basin.
- There are four main beneficiary areas and the area has doubled.
- Water safety status in the Lianshui River Basin is deteriorating, with a water shortage of up to 4.49 billion m^3.

1. INTRODUCTION

Ecosystem services are currently attracting considerable attention from the global scientific community (Lang & Song 2019), as they provide important natural environmental conditions and utilities that humans rely upon (Li *et al.* 2018). Among them, the water ecosystem has the highest service value (Lin *et al.* 2021). The assessment of water resources safety and the rational management and control of water supply services are very important to human life, sustainable social development, and ecological civilization (Shi *et al.* 2020; Zhang *et al.* 2021). Water yield evaluation is a key issue in the field of hydrology and river basin management, and it also plays an important role in research on seawater desalination (Panagopoulos & Haralambous 2020; Panagopoulos 2021). It must be considered when studying the watershed ecosystem (Wen *et al.* 2018).

The supply and demand of ecosystem services are mostly separated in time and space, which leads to the uneven distribution of ecosystem space (Deng *et al.* 2019; Wang *et al.* 2019). In the past, most water resources security assessments only focused on the status quo of water security in a static state, and did not incorporate the flow characteristics of water resources into regional water security assessment (Xu *et al.* 2019). If the flow of water resources is not included in the

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assessment of ecosystem services, the final conclusion is incomplete (Chen *et al.* 2020; Zhang *et al.* 2021). Therefore, how to establish the space–time connection between production and consumption and characterize the space–time flow of ecosystem services is a difficult point in the study of ecosystem services. Ecosystem service flow research connects natural ecosystems with human social systems. The main content of the research is to explore the spatial transfer process of ecosystem services from supply areas to demand areas (Shi *et al.* 2020; Thomas *et al.* 2020; Tong & Shi 2020). Studying the service flow of the water production ecosystem can quantitatively evaluate the supply and demand relationship of water yield services and water resources security, explore the spatial flow path of water production services, and better reflect the coupling of ecosystem service supply and human demand (Qin *et al.* 2019; Schirpke *et al.* 2019).

National and international research has made many useful explorations (Nie *et al.* 2020; Wang & Han 2020; Wang *et al.* 2020a), but the research has mostly stayed at the stage of conceptual framework analysis, and there are relatively few studies that draw specific service flow path diagrams (Báldi & Vári 2020; Gao *et al.* 2020; Tong & Shi 2020). The University of Vermont in the United States proposed the Service Path Attribution Networks (SPANs) model within the Artificial Intelligence for Ecosystem Services (ARIES) project (Bagstad *et al.* 2013). It can capture the spatial relationship of ecosystem service flows, and intuitively understand the dynamic changes of water output services. Qin *et al.* (2019) used the simplified SPANs model to analyze the water security situation under nine water supply scenarios in the future, and put forward water security management and control recommendations that meet the requirements of regional development. The spatial mapping of ecosystem service flows will be the future development trend (Thomas *et al.* 2020).

In this paper, the ecosystem service flow model was used to simulate the spatial distribution of the supply and demand of water yield ecosystem services in the Lianshui River Basin in 1990, 2000, 2010, and 2018, and to explore the direction and flow of water yield ecosystem service flows, and assess the safety of freshwater resources in the basin. This study would provide a scientific basis for regional water resources management and ecological compensation mechanisms.

2. MATERIALS AND METHODS

2.1. Study area and data sources

The Lianshui River Basin (27°17′–28°04′N, 111°31′–112°53′E) is located in the central part of Hunan Province in China and is a left-bank tributary of the Xiangjiang River. The catchment area of the basin above the Xiangxiang Hydrological Station is 5,919.03 km^2 (Figure 1). It is bordered by the Weishui River in the north, Zhengshui River, and Juanshui River in the south, with the watershed between the Xiangjiang River Basin and the Zishui River Basin to the west. The average elevation of the basin is about 202.9 m, and the terrain gradually lowers from west to east. It has a subtropical monsoon climate, and rainfall is mostly concentrated in April to September with an average annual rainfall of 1,350–1,450 mm. The imbalance between supply and demand of water resources in the river basin has intensified with rapid anthropogenic development within the area.

The data included in this study was a Digital Elevation Model (DEM, 30 m resolution), land use/cover type, average annual precipitation, annual mean potential evapotranspiration, and water demand in 1990, 2000, 2010, and 2018. ArcGIS software was used to preprocess the DEM, define the outlet location of the watershed, and divide the watershed into 35 sub-basins. Spatial interpolation of the environmental data (specific data types and data sources are shown in Table 1) was conducted using the inverse distance weighting method. All data were resampled to a resolution of 1 km by the Nearest Neighbor Method (NEAREST) in ArcGIS10.5.

2.2. Methods

2.2.1. Calculating water yield in the InVEST model

The InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model was jointly developed by Stanford University, the World Wide Fund for Nature (WWF), and the Nature Conservancy (TNC) in 2007 (Yang *et al.* 2020). The model was quickly favored by researchers and widely used in water yield (Cong *et al.* 2020; Hu *et al.* 2020; Wang & Han 2020), water purification (Srichaichana *et al.* 2019), carbon storage (Maanan *et al.* 2019; Li *et al.* 2020; Nie *et al.* 2020), soil and water conservation (Qi *et al.* 2019; Hu *et al.* 2020), and the evaluation of other ecological functions.

The water yield module of the InVEST model, according to the water balance formula, ignores the interactive flow between the surface and groundwater and subtracts the annual actual evapotranspiration from the annual precipitation to obtain the regional annual water yield. At the same time, the model determines the contribution of each landscape to the water yield

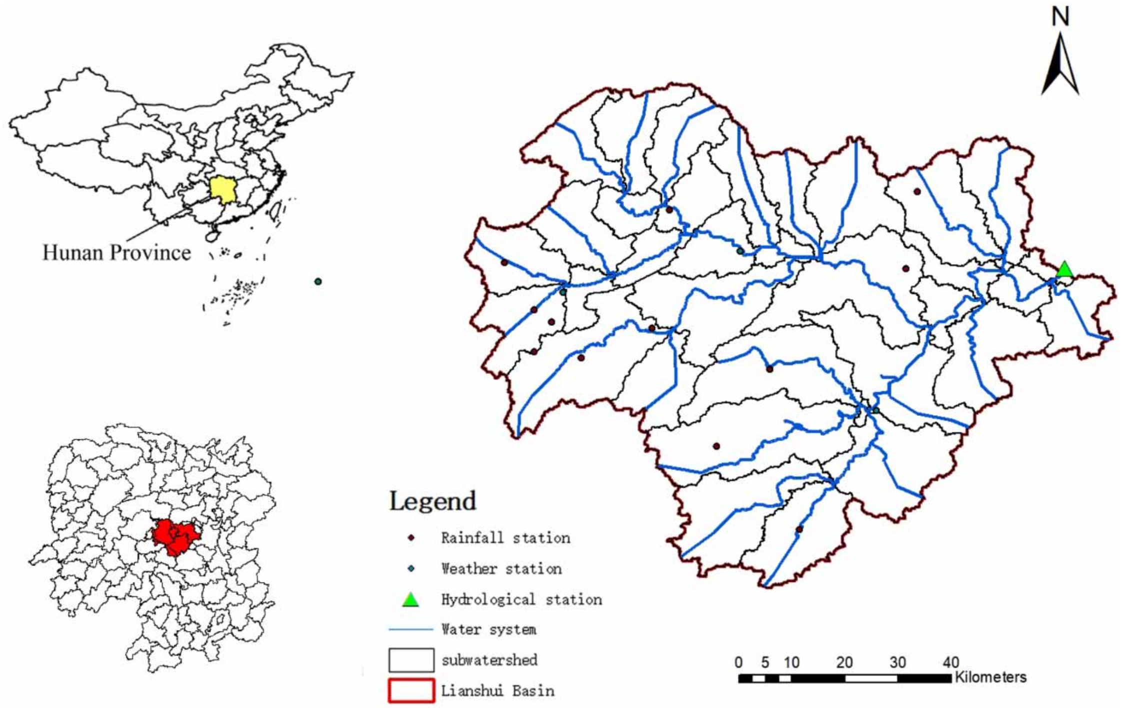


Figure 1 | Location of the Lianshui River Basin.

Table 1 | The data type and data sources

Type	**Data sources**
Terrain data (DEM, 30 m resolution)	Geospatial Data Cloud (https://www.gscloud.cn/)
Land use/cover data	Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/)
Meteorological data (precipitation, temperature, etc.)	
Hydrological data (runoff, etc.)	The Hydrological Bureau of Hunan Province
Water demand data	Water Resources Bulletin of Xiangtan City, Loudi City, Shaoyang City

(Shirmohammadi *et al.* 2020):

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \cdot P_x \tag{1}$$

where Y_{xj} is the annual water production of the j-th land-use type in the grid x, mm; AET_{xj} is the actual annual evapotranspiration of the j-th land-use type in the grid x, mm; P_x is the average annual precipitation in the grid x, mm; AET_{xj}/P_x is an approximation of the Budyko curve estimated by Zhang *et al.* (2001) as follows:

$$\frac{AET_{xj}}{P_x} = \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + \dfrac{1}{R_{xj}}} \tag{2}$$

$$\omega_x = Z \cdot \frac{AWC_x}{P_x} + 1.25 \tag{3}$$

where ω_x is an unrealistic parameter that describes the soil properties under natural climatic conditions; R_{xj} is the aridity index of the j-th type of land use type in the grid x, defined as the ratio of potential evaporation to precipitation; AWC_x is the available water content of the vegetation in grid x, mm, which is used to determine the amount of water provided by the soil for plant growth; Z is the Zhang coefficient, and the more rainfall in the study area, the greater the Zhang coefficient.

Precipitation is first averaged over many years, and then the multi-year average precipitation grid data is obtained through inverse distance-weighted interpolation. Based on daily meteorological data, the FAO modified Penman–Monteith formula is used to calculate the potential evaporation, and the multi-year average potential evaporation raster data is obtained through the spatial interpolation method (Gong *et al.* 2017). The soil depth data comes from the World Soil Database constructed by the FAO. Based on the percentage content of the soil texture, the reference crop evapotranspiration is calculated in the SPAW software using the empirical formula of soil effective water content (Wang *et al.* 2020b). The root restricting layer depth can be replaced by approximate soil depth (Yang *et al.* 2021).

2.2.2. Water demand service model

The water demand service model in this study included agricultural water, industrial water, domestic water (rural and urban residents) and livestock water. For more details regarding the definition and classification of water resources consumption in the ARIES model, refer to Bagstad *et al.* (2013). The water demand service model in the study mainly included agricultural water, industrial water, domestic water (rural and urban residents), and livestock water. The calculation formula for water consumption in the Lianshui River Basin was as follows:

$$W_{\mathrm{u}} = W_{\mathrm{agr}} + W_{\mathrm{ind}} + W_{\mathrm{dom}} + W_{\mathrm{liv}} \tag{4}$$

where W_{agr}, W_{ind}, W_{dom}, W_{liv} are respectively agricultural irrigation water, industrial water, domestic water, and livestock water, respectively.

2.2.3. Quantification of water ecosystem service spatial flow

Following Zhang *et al.* (2021), we defined the water ecosystem flow as the water flowing downstream after the water resources meet the upstream demand by the SPANs. Given the difficulty of obtaining groundwater data, we only considered surface water in the model. The spatial relationship was identified as the path and direction of water flow were tracked in ArcGIS10.5 based on the DEM and river water system data. Figure 2 shows the schematic diagram of water yield ecosystem service flow.

2.2.4. Analysis method

ArcGIS technology and statistical methods were used to analyze the simulation results, the DEM was preprocessed, the outlet location of the watershed was defined, and finally, the watershed was divided into 35 sub-watersheds. The Freshwater Security Index (FSI) (Khan *et al.* 2020) was introduced into the analysis of the water supply and demand balance to clarify and compare the differences between supply and demand:

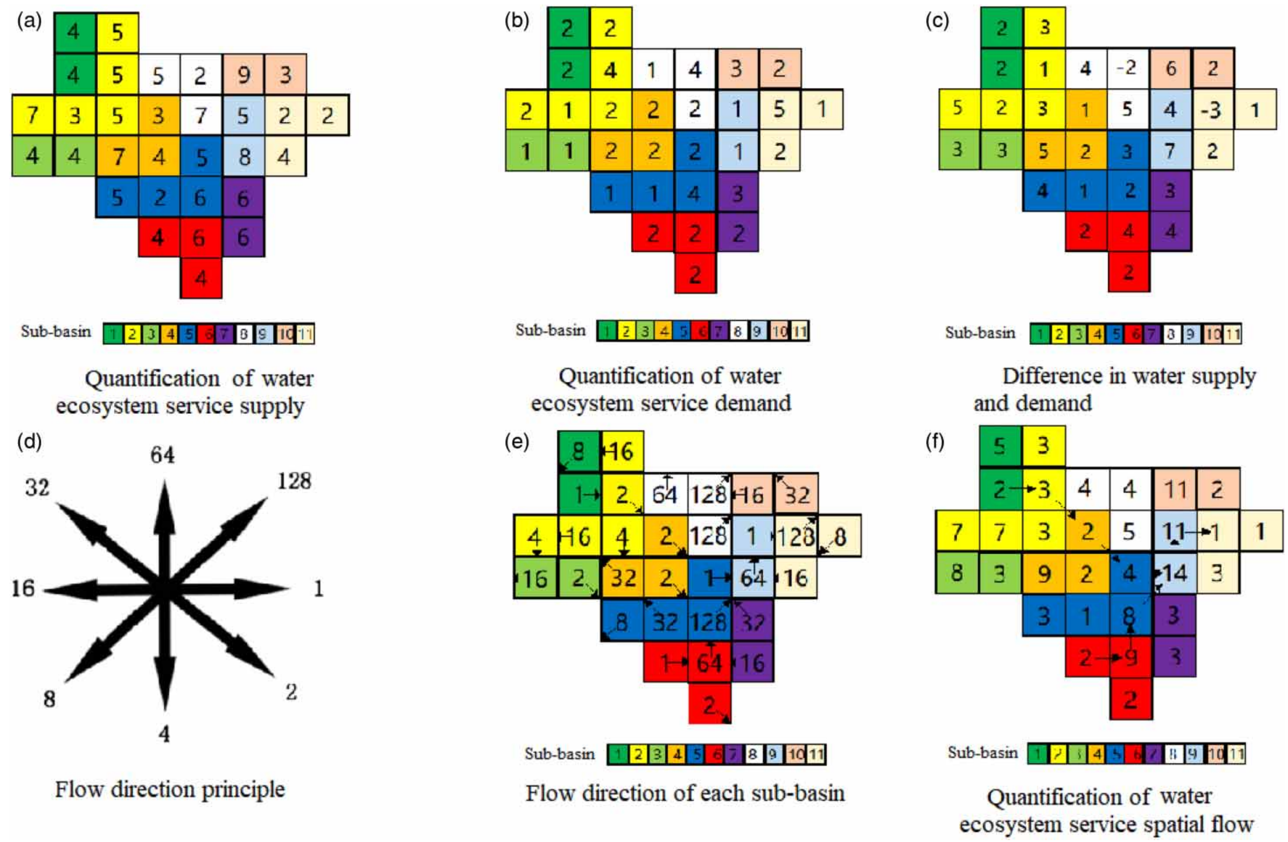
$$FSI_i = \lg\left(\frac{S_i}{D_i}\right) \tag{5}$$

where S_i is the water supply of the i-th sub-watershed, and D_i is the water demand of the i-th sub-watershed. When $\mathrm{FSI} > 0$, the supply exceeds demand and there is a surplus of water resources; when $\mathrm{FSI} < 0$, the demand exceeds the supply and the water resources are relatively short.

3. RESULTS

3.1. Spatio-temporal variation of water yield

In general, the water yield of the Lianshui River Basin from 1990 to 2018 showed a trend of decrease–increase–decrease over this period (Table 2). The water yield service capacity of the entire basin was strongest in 2010, with a unit water production volume of 914 m^3/ha and an annual water yield volume of 5.41 billion m^3. The weakest water yield service occurred in 2000 when the unit water yield was 701.13 m^3/ha, and the annual water yield was 4.15 billion m^3. Compared with 1990, the water supply in 2018 dropped by 0.93 billion m^3, and the decrease ratio was 18.09%; a 157.12 m^3/ha reduction in the average water yield. These results show that the water yield service function of the basin is weakening, which is unfavorable for the replenishment of water sources, such as rivers, lakes, and groundwater. The spatial distribution of water production per unit area in



Quantification of water ecosystem service supply

Quantification of water ecosystem service demand

Difference in water supply and demand

Flow direction principle

Flow direction of each sub-basin

Quantification of water ecosystem service spatial flow

Figure 2 | Schematic diagram of water yield ecosystem service flow model.

Table 2 | The annual and average water yield of the Lianshui River Basin from 1990 to 2018

Year	Water yield (billion m^3)	Water yields per unit area (m^3/ha)
1990	5.14	868.39
2000	4.15	701.13
2010	5.41	914.00
2018	4.21	711.27

the basin is heterogeneous, and the water yield varies greatly among sub-basins (Figure 3). The water yield capacity of the upper and downstream of Lianshui River is relatively strong, while the central areas are weak.

3.2. Spatio-temporal changes in water demand

In 1990, 2000, 2010, and 2018, the demand for water output services in the Lianshui River Basin was 5.19 billion m^3, 5.44 billion m^3, 6.37 billion m^3, and 7.36 billion m^3, respectively, showing a significant upward trend (Figure 4). Water demand is affected by factors such as farmland irrigation and population. From 1990 to 2018, the proportion of agricultural irrigation and industrial water demand was in the range 62.4%–64.66% and 21.9%–24.76%, respectively. Population, livestock products, and ecological water demand accounted for a relatively small proportion of the total water demand. Therefore, changes in the demand for water output services are mainly affected by changes in agricultural irrigation and industrial water demand. Analyses of the spatial patterns showed that owing to the large regional GDP and effective irrigation area of Xiangxiang City in the lower reaches of the Lianshui River, its industrial and agricultural water demand was much higher than that of other regions. The areas with low water consumption were mainly located in the southern area of the

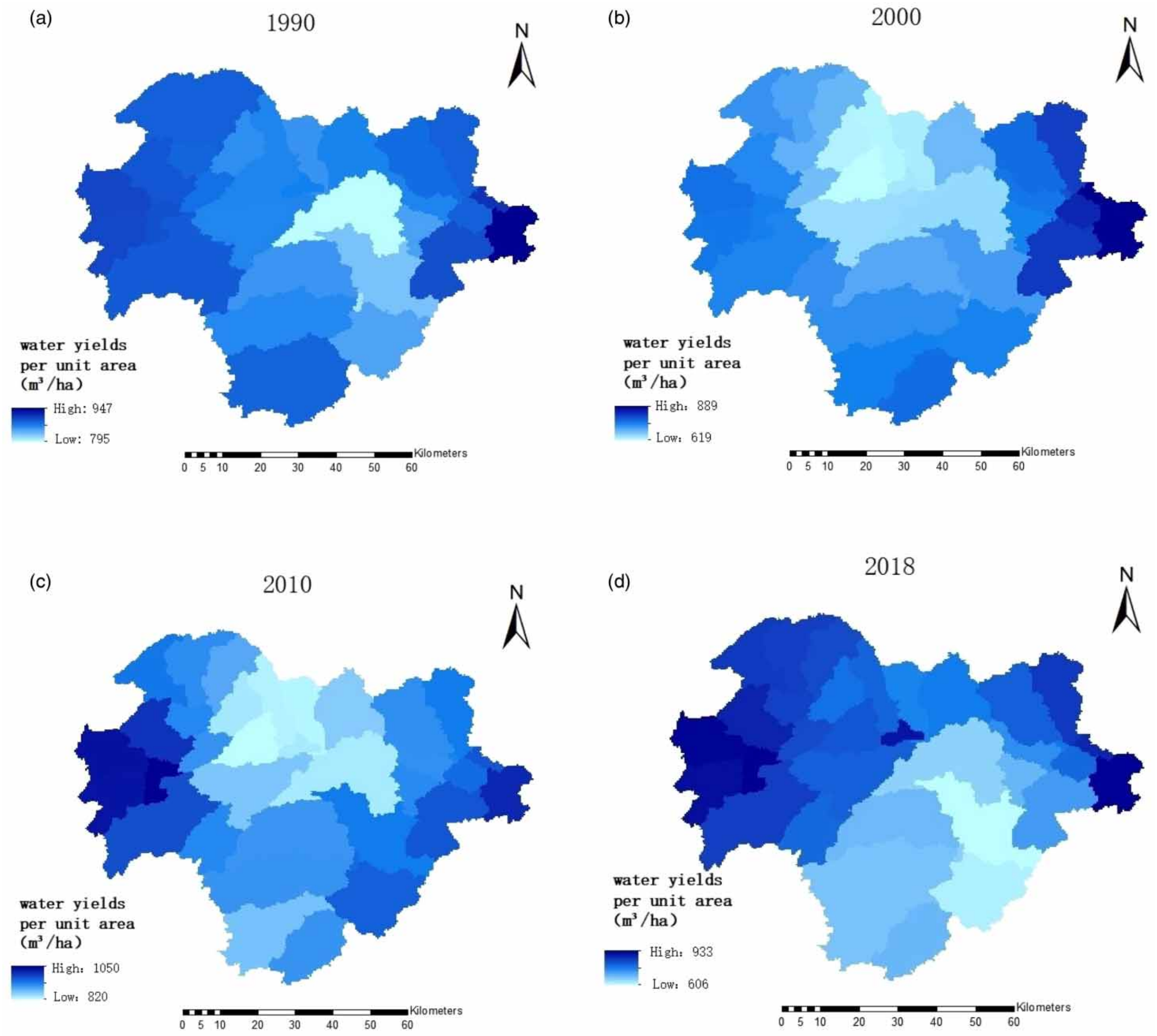


Figure 3 | Water yields per unit area of Lianshui River Basin in 1990, 2000, 2010 and 2018.

upper reaches of Lianshui River, Xinshao County, and Shaodong County, where the land cover is mainly woodland and cultivated land. Meanwhile, the regional population is relatively small, and the water consumption in daily life, industrial and agricultural production is also reduced accordingly.

3.3. Balance of supply and demand for water yield services

According to the FSI value, the water resources safety index was divided into three categories: low water safety index ($FSI < -1$), poor water safety index ($-1 < FSI < 0$), good water safety index ($FSI > 0$). As seen in Figure 5, most of the sub-basins in the Lianshui River Basin have FSI values greater than 0. The area of the sub-basins with FSI values less than 0, however, is gradually expanding and the gap between supply and demand is getting larger. This trend indicates that the shortage of water resources in the basin is becoming increasingly serious and could impact the production and life of residents within the area. From the perspective of the spatial pattern of the balance between supply and demand, the FSI values of the No. 12 and 28 sub-basins were less than -1, indicating a severe shortage of water resources in these areas. The size of these sub-basins was the main driver for this shortage. In 2018, a new sub-basin (No. 15) with serious water shortage was added to the basin, which is located in Xiangxiang City at the exit of the basin. The water scarcity situation was aggravated

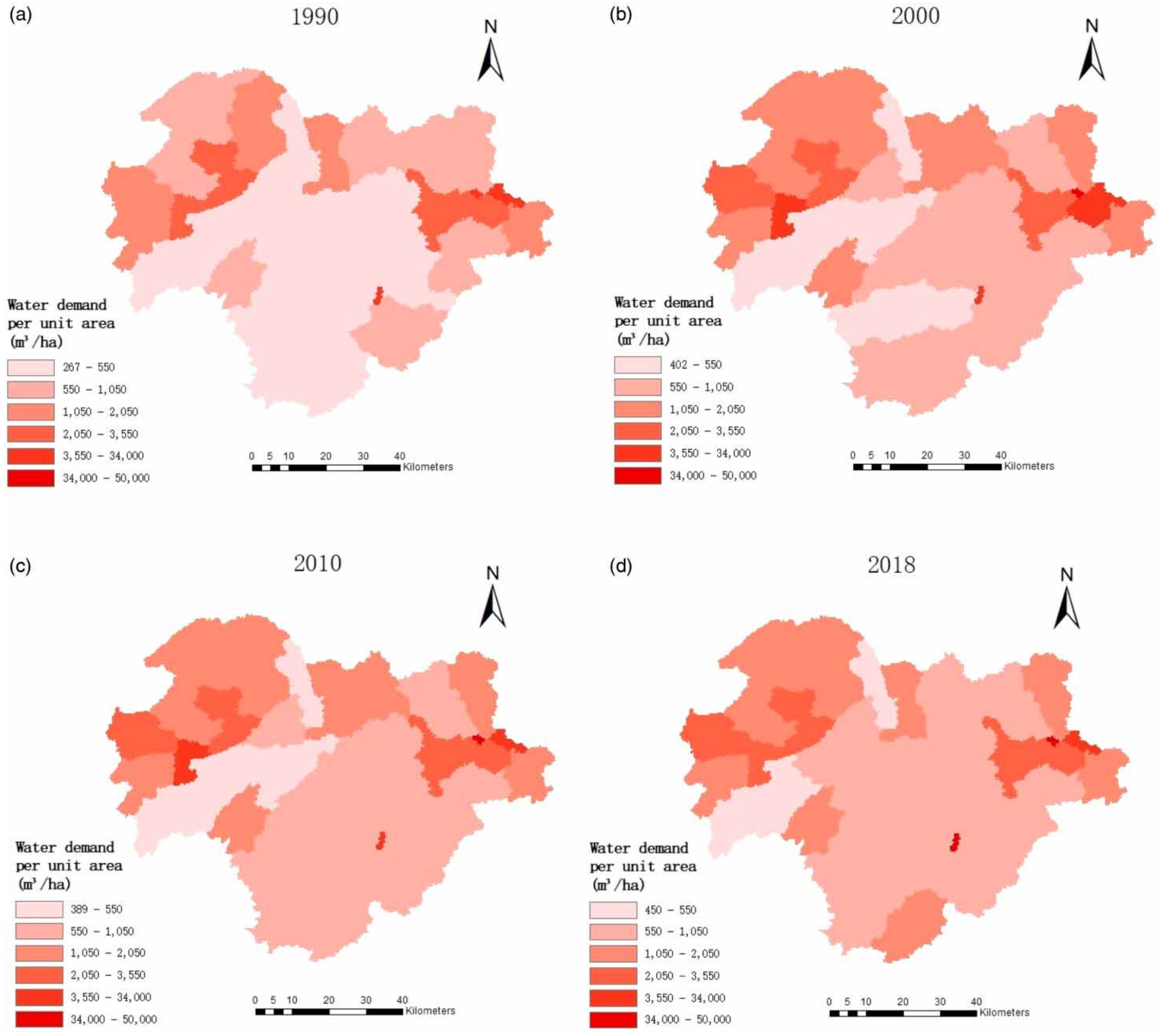


Figure 4 | Water demand per unit area of Lianshui River basin in 1990, 2000, 2010 and 2018.

because of the addition of new high-water-consuming industries, along with increases in urban construction and large-scale farmland irrigation projects in the region.

3.4. Water yield service flow

The spatial flow process between different sub-basins was mapped based on the characteristics of the balance between supply and demand of water supply services (Figure 6). In this study, a sub-catchment that cannot meet the actual water demand by its water supply and needs to be supplemented by an upstream sub-catchment is defined as a beneficiary area; conversely it is called a water supply area. Combining the spatial distribution of natural water systems and administrative divisions, the spatial flow pattern of water supply services in the Lianshui River Basin is divided into four main supply–demand flow relationships, which are the urban area of Lianyuan City and its surrounding areas (sub-basin No. 4, 5, 16, 20). The relationships between the spatial flow of Louxing District of Loudi City (sub-basin No. 11), Shuangfeng County (sub-basin No. 28), the urban and surrounding areas of Xiangxiang City (sub-basin No. 12, 15, 18, 19, 22), and their associated upstream supply areas were specifically examined. The surplus produced by each sub-basin was not the same, and there were certain spatial differences, but overall, the surplus had a downward trend in each sub-basin (Table 3). In 2018, the supply area's surplus

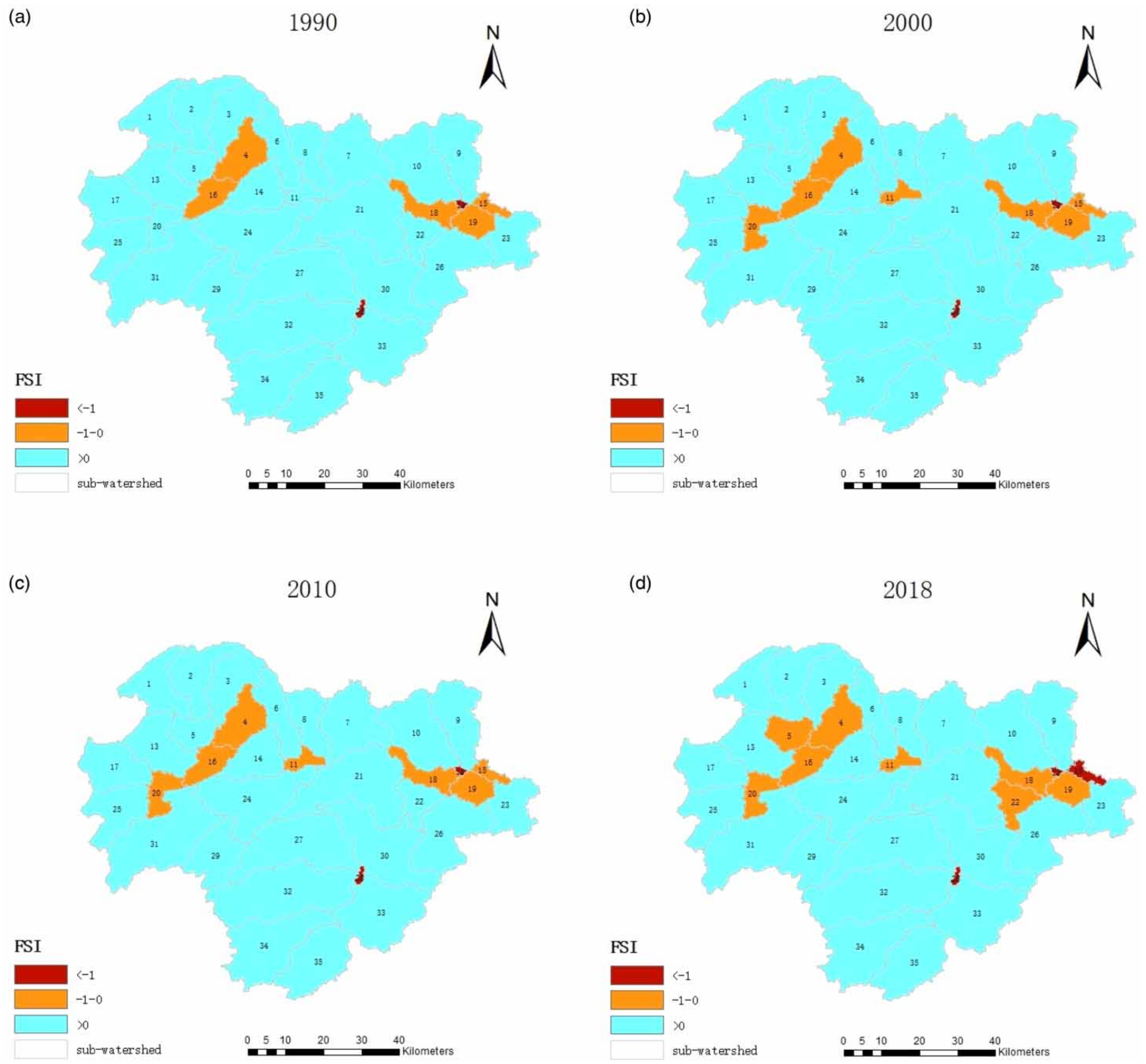


Figure 5 | Spatial distribution map of water yields and demand balance in Lianshui River Basin.

water volume totaled 2.76 billion m^3, and the beneficiary area still needed 4.49 billion m^3 water in addition to its water production. The available water resources in the supply area were far from meeting actual needs.

4. DISCUSSION

4.1. Adaptability and improvement of the model

This paper couples the InVEST model and SPANs models to build a water production ecosystem service spatial flow model, which simulates the spatio-temporal evolution of the service flow of water supply and demand in the Lianshui River Basin under natural conditions, and analyzes the regional water security status. It can conduct long-term sustainable research on the water supply service of the river basin and provide some references for the optimal allocation of water resources. However, there are many influencing factors for water supply services, and the simulation results also have certain limitations. In the simulation process, groundwater resources and the loss of water resources during the transmission process were ignored, which may lead to underestimation of regional water resources (Hu *et al.* 2020; Wang & Han 2020). Due to difficulties in data

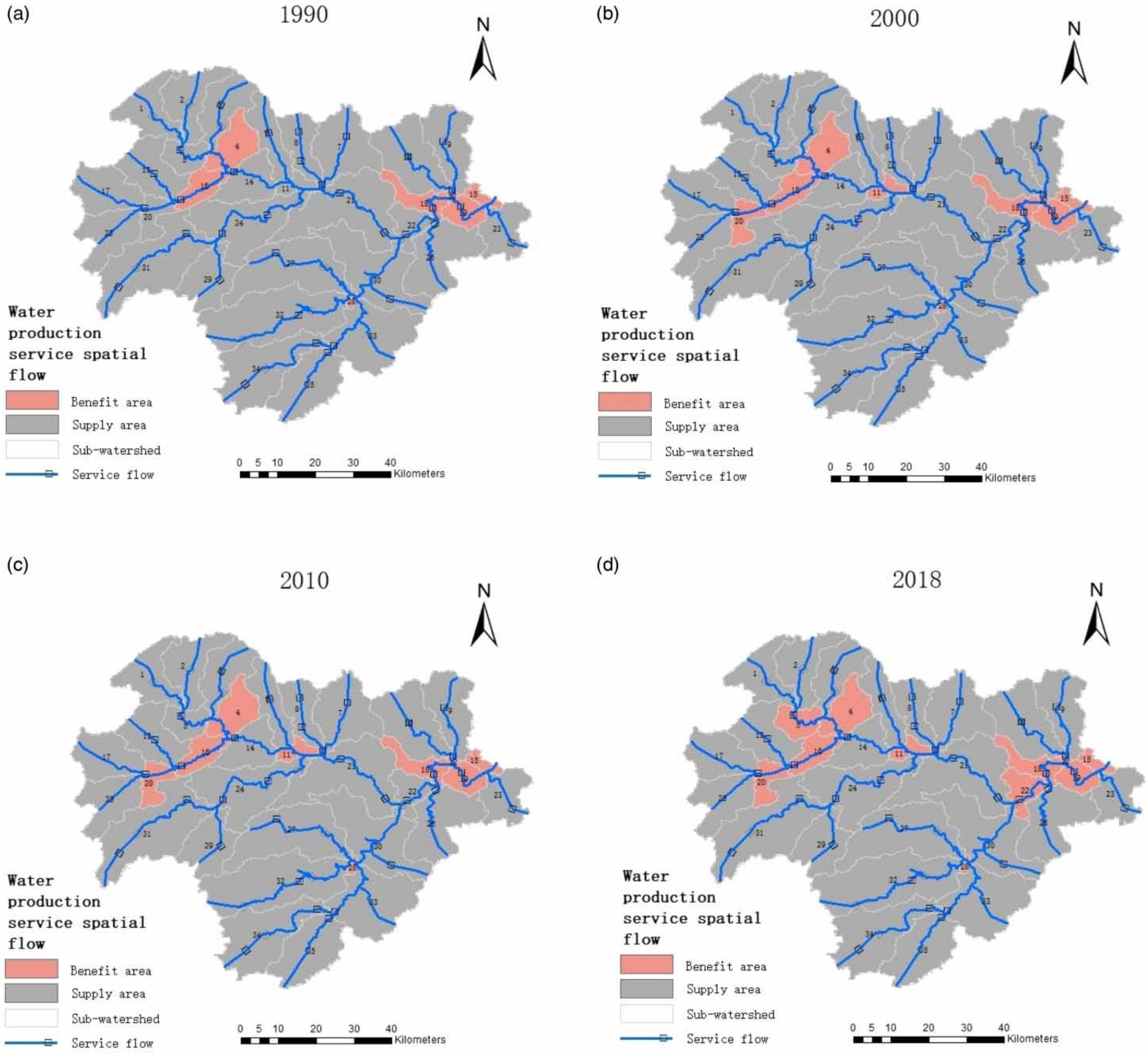


Figure 6 | Spatial flow diagram of water yield service in Lianshui Basin in 1990, 2000, 2010, 2018.

acquisition and quantification, the simulation did not consider the impact of human-built infrastructure such as reservoirs, dams, and diversion projects on regional water resources regulation. Water supply service demand refers to the various types of water resources consumed by humans in life and production activities. Quantifying this service demand exposes the amount of water used for specific land uses (Lang & Song 2019; Yang *et al.* 2019; Zhang *et al*. 2021). Due to the limited available statistical data, this study only considers agricultural, industrial, residential, and livestock water consumption. It does not cover all social production, domestic water consumption, and water consumption needed to maintain natural ecological processes in the basin, and the data in some areas is not complete, which may cause the water consumption in some areas to be underestimated.

At the same time, the model simulation needs to input a large amount of high-precision topography, geomorphology, weather, soil, and other natural environment data and accurate localization parameters. There are large subjective factors in the selection of initial parameter values (Li *et al.* 2017; Yang *et al*. 2019, 2020), which will affect the simulation accuracy. Water resources are generally abundant in southern China (Yang *et al*. 2019), but seasonal water shortages and water qualitative water shortages are serious (Wang & Zhou 2019). In the future, it is necessary to carry out multi-temporal- and spatial-scale ecosystem service flow research.

Table 3 | The main benefiting areas and service flow produced from the corresponding provisioning areas from 1990 to 2018

	Supply area			Benefit area	
Year	**Water system**	**Sub-basin number**	**Supply amount (billion m^3)**	**Administrative unit**	**Sub-basin number**
1990	Meeshui	1, 2, 3, 5	0.2664	Lianyuan City	4
	Sunshui	13, 17, 20, 25	0.2964		16
	Ceshui	27, 32, 33, 34, 35	1.5169	Shuangfeng County	28
	Lianshui	9, 10	0.3360	Xiangxiang City	12
		23	0.0521		15, 19
		21, 22, 26, 30	0.8571		18
	Total		3.3249		
2000	Meeshui	1, 2, 3, 5	0.1497	Lianyuan City	4
	Sunshui	13	0.1011		16
		17, 25	0.2124		20
	Lianshui	6, 14, 24	0.2345	Louxing District	11
	Ceshui	27, 32, 33, 34, 35	1.1973	Shuangfeng County	28
	Lianshui	9, 10	0.2936	Xiangxiang City	12
		23	0.0774		15, 19
		21, 22, 26, 30	0.7147		18
	Total		2.9806		
2010	Meeshui	1, 2, 3, 5	0.2203	Lianyuan City	4
	Sunshui	13	0.1013		16
		17, 25	0.2915		20
	Lianshui	6, 14, 24	0.3080	Louxing District	11
	Ceshui	27, 32, 33, 34, 35	1.5293	Shuangfeng County	28
	Lianshui	9, 10	0.3641	Xiangxiang City	12
		23	0.0899		15, 19
		21, 22, 26, 30	0.9250		18
	Total		3.8293		
2018	Meeshui	3	0.0642	Lianyuan City	4
		1, 2	0.1438		5
	Sunshui	13	0.0850		16
		17, 25	0.2296		20
	Lianshui	6, 14, 24	0.2322	Louxing District	11
	Ceshui	27, 32, 33, 34, 35	1.0734	Shuangfeng County	28
	Lianshui	9, 10	0.2650	Xiangxiang City	12
		23	0.0464		15, 19
		26	0.1605		18
		21, 30	0.4654		22
	Total		2.7655		

4.2. Implications for water resources policy and management

The Chinese government proposed the construction of ecological civilization in 2012 (Gao *et al.* 2020). Ecological compensation in the river basin is one of the representative policies, and various ecological compensation policies have been introduced one after another (Li *et al.* 2021; Sun & Li 2021). But now most domestic research on the service flow of water ecosystems is based on the national or administrative district scale, and few studies are conducted on the basin or even sub-basin scale. Our analysis provides detailed information on the service flow of the water-producing ecosystem in the watershed, which can promote the integrated management and decision-making of the watershed, and it can also promote local ecological compensation for water resources management decision-makers. The principle of ecological compensation policy is that the beneficiary subsidizes the supplier, and the ecosystem service flow can well realize the connection between the service supply area and the beneficiary area, and it has objective applicability in the ecological compensation policy.

Our results show that the urban area of Lianyuan City, the county seat of Shuangfeng County, Louxing District of Loudi City, the urban area of Xiangxiang City and surrounding towns where the sub-watershed is located are the four major beneficiaries of the water production ecosystem service flow of the watershed. Therefore, these areas need to provide ecological compensation to the upstream corresponding supply areas. The county seat of Shuangfeng County gets the most water supply, which may raise its ecological compensation standard. Given the long-standing water shortages in these four beneficiary areas, the freshwater security situation is not optimistic, and some water diversion projects can be considered for water replenishment.

5. CONCLUSION

In this paper, the InVEST model and the SPANs model were used to explore the spatial and temporal correlation characteristics of the supply and demand of water supply services in the Lianshui River Basin at the sub-basin scale and simulated the water output of the basin in 1990, 2000, 2010, and 2018. The spatial flow process of service from production to use clarifies the spatial scope and service flow of the supply area and benefits area of the river basin. The research shows that the water resources in Lianshui River Basin are not evenly distributed in time and space, the water output decreases while the demand increases, and the contradiction between supply and demand becomes more and more prominent. The upstream and downstream areas of the Lianshui River Basin are areas with high water supply, and the water supply in the middle reaches is insufficient. The water resources of most of the sub-basins can meet their development, but the area of benefit areas is gradually increasing. Typical urban areas such as the urban area of Lianyuan City, Louxing District of Loudi City, the county seat of Shuangfeng County, the urban area of Xiangxiang City, and surrounding areas have low water resource security levels, which are not conducive to the sustainable development of the basin. The research results provide a scientific basis for the sustainable development of water resources in the Lianshui River Basin and a new idea for ecological compensation. If the concept of ecosystem service flow is incorporated into the ecological compensation mechanism, the principle of ‘beneficiary pays’ can be truly realized. For the future, water resources management in the Lianshui River Basin needs to vigorously carry out ecological compensation for the optimal allocation of water resources, raise the awareness of water-saving of the whole population, and realize sustainable development in the region.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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