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Regional water demand forecasting based on shared socio-economic pathways in the Zhanghe River Basin

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ABSTRACT

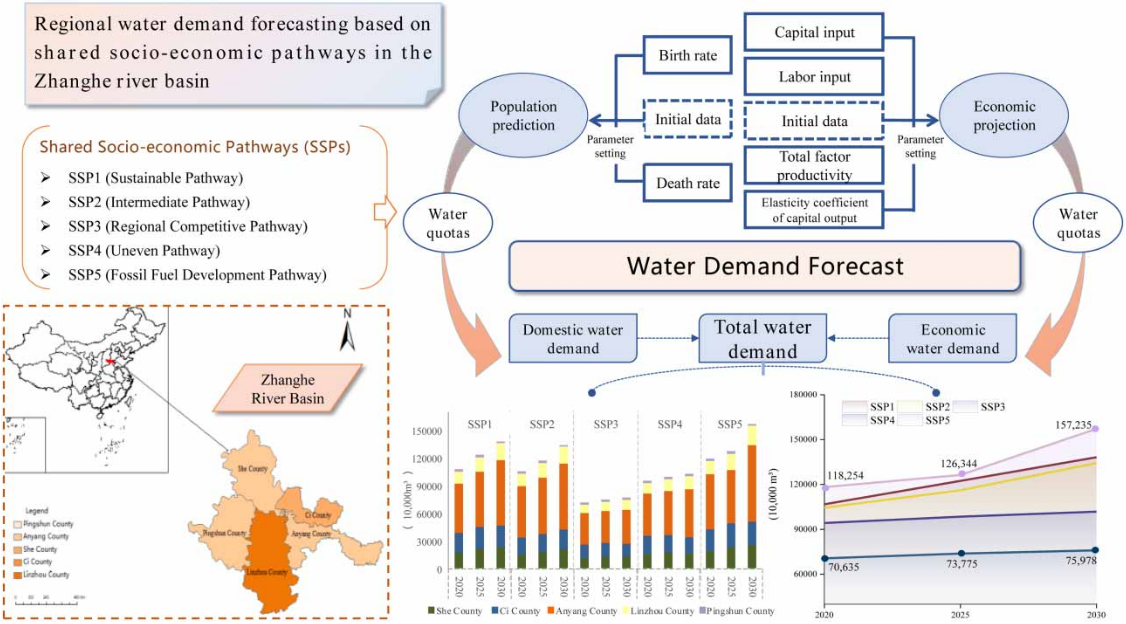
Based on the framework of shared socio-economic pathways, this study predicts future population and economic conditions of the Zhanghe River Basin and combines with the water quota to predict future water demand. First, the localization parameter system is constructed. Furthermore, the water demand is calculated. The results show that (1) under regional competitive pathway, the population is the largest, while under uneven pathway, the population is the smallest. The largest economic forecast is obtained under fossil fuel development pathway, while the smallest economic forecast is obtained under regional competitive pathway. (2) The results for domestic and economic water use in the basin show that the annual water demand shows an increasing trend. Fossil fuel development pathway is the scenario with the highest socio-economic water demand, while regional competitive pathway is the scenario with the least. (3) The Zhanghe River Basin faces a high risk of water resource shortage in the future. Even under the situation of minimum socio-economic water demand, the total water demand is difficult to meet fully. The forecasting framework established in this paper has high application value and can provide a reference for water demand forecasting and prospective water demand management in river basins.

Key words: Population and economy, River basin, The shared socio-economic pathways, Water demand projections

HIGHLIGHTS

- Building watershed water demand scenarios using shared socio-economic pathways.
- Forecasting watershed population and economy at the regional scale.
- Combining the water-use quota method with population and economic projection data to calculate future water demand.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Due to the limited amount of water resources and the disorder of water use, water demand regulation has gradually become the focus of water resources management. With population growth and economic development, the demand for water resources is constantly increasing (da Encarnação Paiva *et al*., 2020; Wang & He, 2022). At the same time, human activities aggravate climate change, which not only affects the water resources availability but also further aggravates the uncertainty of socio-economic development, thus forming a negative cycle. In order to maintain the sustainability of natural and social water systems, it is necessary to make scientific forecasts of water demand, so as to allocate water resources reasonably and maintain normal production and life under the background of limited water.

China is the largest developing country in the world with a large population and rapid development of industry and agriculture. According to the Ministry of Water Resources, although China ranks sixth in the world in total water resources, its per capita water resources are less than 28% of the world average. Water problems in transboundary basins are more severe and complex. Transboundary basins often involve multiple water management agencies and multiple water users with different interest objectives, and conflicts are likely to occur between upstream and downstream due to water resource competition. In the context of limited available water resources, the traditional water resources management mode from the perspective of supply has made it difficult to solve the problem of water conflicts in transboundary basins, and special attention should be paid to water demand management. Scientific assessment of water demand is the basis of water demand management. As a prospective work, the multi-scenario forecast of socio-economic water demand is of great significance to the rational allocation of water resources and the prevention of water conflicts under the uncertain socio-economic trends in the future.

The Zhanghe River belongs to the Haihe River Basin, which originates in Shanxi Province and flows through Hebei and Henan Province. According to the China Statistical Yearbook 2022, the population and Gross Domestic Product (GDP) of the three provinces account for 14 and 10% of the country, respectively, while their total water resources account for only 2% of the country. Thus, the water resources of Zhanghe River are indispensable to the regional economic and social development. In addition, the Zhang River basin is a typical transboundary small watershed, including Pingshun County, Shexian County, Ci County, Linzhou County and Anyang County, which belong to three different cities and provinces, respectively, as shown in Figure 1. Water disputes in the Zhanghe River Basin have existed for a long time. Due to the large population and small water resources in the basin, the upstream and downstream of the basin and the left and right banks have many conflicts for water, and even caused serious economic losses. The State Council attached great importance to this incident and formulated the document 'Zhanghe Water Allocation Plan' to deal with the problem of water resources allocation in this basin. However, with the continuous reduction of runoff in the basin under the influence of natural and social factors, and the continuous increase in water demand caused by population and economic changes, water conflicts in the basin become increasingly obvious. In this case, this study predicts the population and economy of the Zhanghe River Basin under Shared Socio-economic Pathways (SSPs) and combines the water quotas formulated by the governments of the basin under the constraint of saving water to obtain the socio-economic water demand under different pathways in the future, so as to provide certain references for adopting timely and effective water resource demand regulation strategies and alleviate water resource conflicts.

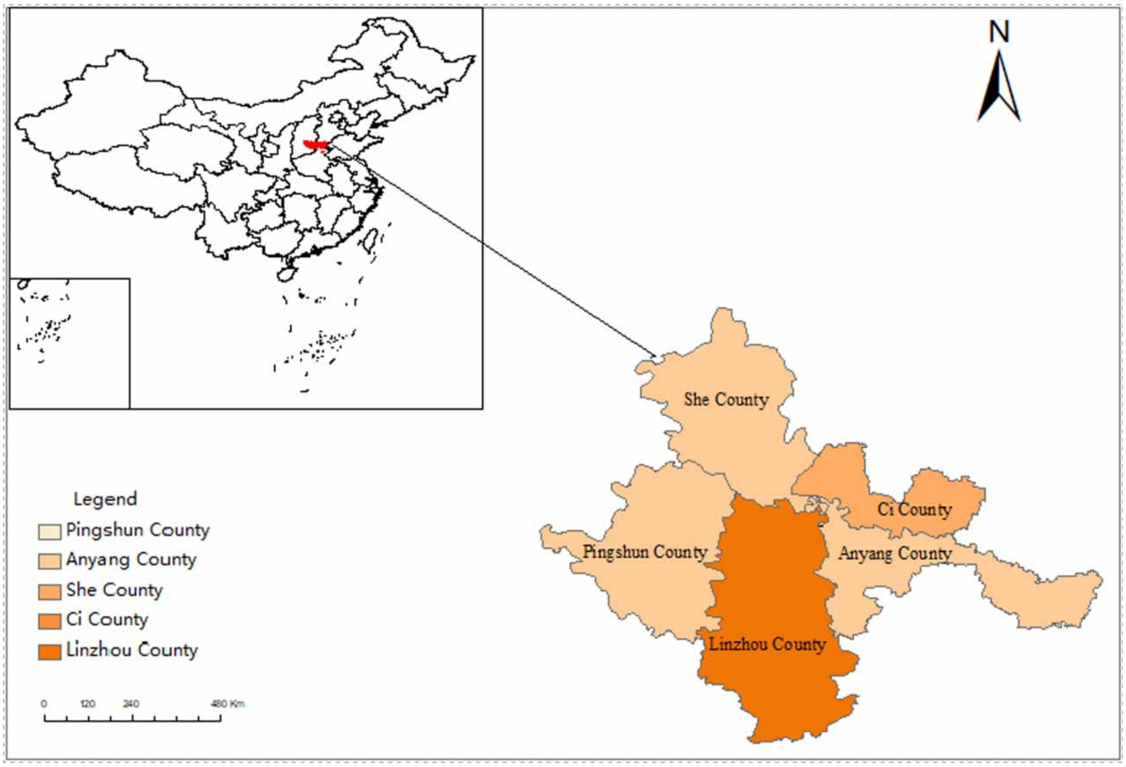


Fig. 1 | Zhanghe River Basin.

2. LITERATURE REVIEW

Under the background of water resources shortage, more and more studies have shifted the focus of water resources management from supply to demand. Nivesh *et al.* (2022) emphasized the importance of rational allocation of water resources among different water-use sectors. Shahangian *et al.* (2020) pointed out the necessity of water demand management in the context of increasing water supply cost. There are scholars exploring water demand management policies and best practices. For example, Mohseni *et al.* (2022) demonstrated the importance of price policies in water demand management. Wang & He (2022) believed that water demand management requires reasonable determination of water resource utilization thresholds, comprehensive regulation of social and economic systems and the development of efficient water-saving technologies, so as to reduce the interference of human water consumption on the water cycle process. In the context of climate change and intensified human activities, effective water demand management must consider different scenarios of socio-economic development, and grasp multiple possibilities of future water demand conditions through water demand forecasting (Distefano & Kelly, 2017). Zubaidi *et al.* (2018) emphasized the important role of reliable water demand prediction for the construction of urban water conservancy infrastructure. Cabral *et al.* (2019) used Portugal as an example to forecast water demand and emphasized that the key variables affecting water demand and uncertainties in future trends need to be taken into account when constructing water demand scenarios.

Population size and economic level are key elements of socio-economic scenario setting and have a significant impact on socio-economic water demand (Gondo *et al.*, 2020), which has been demonstrated in existing studies. For example, Nivesh *et al.* (2022) believe that future population growth, industrial development and increased acreage will lead to a sharp increase in water demand in the Dasan River basin in India. da Encarnação Paiva *et al.* (2020) took the Paraiba South Basin in Brazil as an example and found that urban expansion and population increase would significantly increase household water demand. Many studies have taken population and economy as important parameters in the scenario prediction of resource and environmental problems. Zhang *et al.* (2021) obtained China's future carbon emission data based on the combination of population and economic forecast data and regression model. Yan & Xu (2022) predicted the socio-economic water demand of Jiangsu Province under the scenario of industrial structure change and water consumption change of 10,000 yuan GDP, which provided a reference for the sustainable utilization of local water resources.

In order to more comprehensively reflect the multiple possibilities of socio-economic development in the context of climate change, the Intergovernmental Panel on Climate Change (IPCC) proposed the SSPs framework (O'Neill *et al.*, 2014). The framework considers five different paths for future socio-economic development, each of which represents a development mode (van Vuuren *et al.*, 2017). At present, the SSP method is widely used in the estimation of basic factors such as population, GDP and urbanization level. For example, Dellink *et al.* (2017) used the SSPs to obtain the economic situation of 184 countries. Chen *et al.* (2020) predicted the population and education level of Chinese provinces during 2010–2100. Bai *et al.* (2021) narrowed the study scale to counties and obtained population data for 101 banners and counties in Inner Mongolia. Zhu *et al.* (2020) conducted a basin-scale exploration and derived the population and economic changes in the Yangtze River basin during 2010–2100 based on the SSPs.

The SSPs method has also found some applications in water demand forecasting. Roson & Damania (2017) predicted potential water demand and water availability in 15 regions around the world under different SSPs and analyzed the economic impact of future water shortage. Flörke *et al.* (2018) used SSPs to project the water demand of the world's 482 largest cities by 2050 and analyzed water competition between cities and agriculture driven by climate change and urban growth. There are also some representative predictive studies related to water resources at the watershed scale. Alizadeh *et al.* (2022) combined SSPs with representative concentration pathways (RCPs) to predict future human water system vulnerability in the Rechna Doab watershed, Pakistan. Yin *et al.* (2017) used SSPs to predict water demand in the Yellow River basin in the 21st century.

As a relatively new forecasting tool, most of the current application scales of SSPs are global, national or provincial scales, with few applications at watershed or county level. From the perspective of water demand forecasting studies, most of them focus on administrative regions and seldom pay attention to the natural unit of river basin, let alone the special object of transboundary small river basin. In addition, water demand prediction is rarely combined with the evolution of population and economy to realize the coupling of natural and social dual water cycles. Based on the Sixth Census data and statistical data, this paper focuses on the Zhanghe River Basin and narrows the research scope to the county level. In this paper, SSPs are used to calculate the population and economy under five scenarios from 2011 to 2030, in which the results from 2011 to 2020 are used to compare with the historical data to test the prediction accuracy. Next, the water demand under different population and economy conditions is predicted by combining with water quotas.

3. METHODS

3.1. The shared socio-economic pathways framework

The SSPs include five pathways that reflect the different levels of climate change adaptation and mitigation challenges faced in the future (O'Neill *et al.*, 2014). Climate change mitigation means avoiding and reducing greenhouse gas emissions to prevent more extreme warming of the planet. Climate change adaptation means changing our behavior and, in some cases, our lifestyles to protect our homes, economies and living environment from the effects of climate change. As Figure 2 shows, mitigation and adaptation challenges differ for different paths. These five pathways are described as follows (O'Neill *et al.*, 2017):

(1) SSP1 (sustainable pathway) is a green development pathway. The world is gradually shifting to a more sustainable path with an emphasis on inclusive development. Investment in education and health leads to lower birth and death rates, and economic growth is based on the goal of human well-being. Inequalities

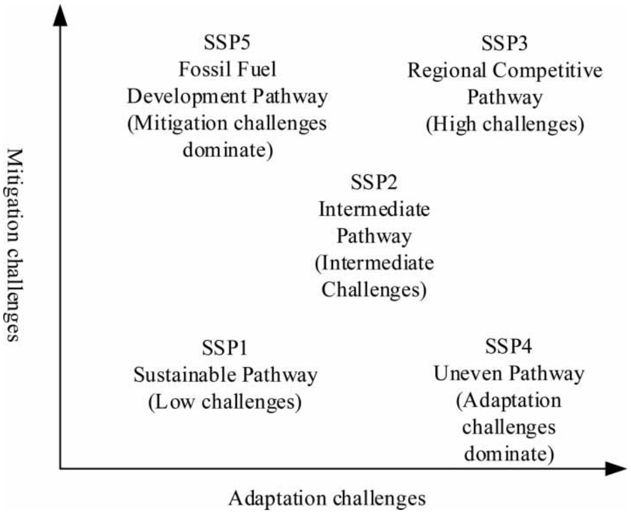


Fig. 2 | Climate change challenges under different socio-economic pathways.

are decreasing internationally and within countries, the level of science and technology has improved energy and resource efficiency, and there is a high priority on ecological health. Both climate change adaptation and mitigation challenges are low.

(2) SSP2 (intermediate pathway) is a path that maintains the current level and pace of development. Socio-economic and technological trends do not deviate significantly from historical patterns, with some countries achieving better development and some falling short of expectations. Living conditions, education and health are improving, but at a slow pace. Environmental systems have experienced degradation, and while there has been some improvement, they have not reached the desired level. Reliance on fossil fuels is low, and mitigation and adaptation challenges are moderate.

(3) SSP3 (regional competitive pathway) is a pathway of uncoordinated development. With strong local protectionism, countries are committed to their own energy and food security goals. Investment in education and technology is much reduced, and there are large differences between countries in birth rates, mortality rates and education levels. There is a low level of ecological concern and severe challenges of climate change adaptation and mitigation.

(4) SSP4 (uneven pathway) is a highly uneven path. Inequalities in human capital inputs and widening gaps in economic development lead to inequalities between and within countries. Disparities in income levels and educational attainment are increasing the gap between capital-intensive and labor-intensive regions. The energy sector is diversifying, investing in both intensive fuels such as coal and conventional oil and low-carbon energy sources. Low-income countries face greater challenges in adapting to climate change.

(5) SSP5 (fossil fuel development pathway) is a pathway that places a high priority on development. Under this path, countries focus on investing in education and health as a way to strengthen human and social capital. While driving economic and social development, fossil fuels are exploited worldwide, and resource- and energy-intensive lifestyles are adopted. The global economy has grown rapidly, and the population has tended to rise to a peak and then decline. There is a high mitigation challenge due to the overemphasis on economic development and neglect of environmental issues.

3.2. Population and economic forecasting methods

Demographic and economic changes are primary considerations in social development scenarios (Yin *et al.*, 2017). Based on the historical data of population and economic development in the Zhanghe River Basin, this paper constructs a localized parameter system and predicts the population and economic conditions of the five counties in the basin under different SSPs, which serves as the basis for the prediction of water demand for living and production. The population and economic parameters of each county are set according to the proportional relationship between the county and the whole city in the historical period.

3.2.1. Population projections

The population-development-environment (PDE) model is a commonly used method for population forecasting (Formula 1) (Meng *et al.*, 2014). P_t and P_{t+1} represent the population in year t and year $t+1$, respectively. $P_{B_{t+1}}$, $P_{D_{t+1}}$ and $P_{I_{t+1}}$ represent the number of births, deaths and immigrants in $t+1$ year, respectively. That is, the population in a given period is equal to the population in the previous period plus the natural and mechanical growth of the population in the current period. Considering the small research scale, and the population data used are the permanent population rather than the registered population, the inter-county population migration is not considered. In addition, most of the existing studies have carried out population prediction at the national or provincial scale, using fertility rate to calculate the number of births, but it is difficult to obtain fertility data at the county level, so this paper uses birth rate instead (Formula 2). B_{t+1} and D_{t+1} represent the annual birth rate and the annual death rate, respectively.

$$P_{t+1} = P_t + P_{B_{t+1}} - P_{D_{t+1}} + P_{I_{t+1}} \tag{1}$$

$$P_{t+1} = P_t + P_t \cdot (B_{t+1} - D_{t+1}) \tag{2}$$

when predicting the future population, the parameters under different paths should be set reasonably. Table 1 shows the hypothesis of population parameters corresponding to different SSPs. This parameter setting method has been adopted by many studies related to population prediction, with satisfactory prediction results (Jiang *et al.*, 2017; Wang *et al.*, 2020), so this method is also used in this paper to improve the scientificity of scenario setting. This study takes 2010 as the base year and the birth and death rates of each city published in the sixth National Census as the base period data. The parameters under the medium scheme are consistent with the current level (Kc & Lutz, 2014). The changes of parameters under different scenarios are set by referring to existing studies (Jiang *et al.*, 2017; Wang *et al.*, 2020), that is, the parameters of low or high schemes are 20% lower or higher than those of medium schemes by 2030.

3.2.2. Economic forecasting

Economic forecasting was obtained using the Cobb–Douglas model, widely used in studying economies (Zhang *et al.*, 2021; Li, 2023). As shown in Formula 3, this model illustrates the relationship between output and labor input, capital input, and total factor productivity. The year 2010 is used as the base period.

$$Y(t) = K(t)^{\alpha} L(t)^{1-\alpha} \mathrm{TFP}(0) e^{\lambda t} \tag{3}$$

In Formula 3, $Y(t)$ denotes GDP in the year t, L denotes labor input, K denotes capital input, α is the elasticity coefficient of capital output, TFP(0) denotes total factor productivity in the base period, and λ denotes the level of scientific and technological progress.

The capital stock (K) is calculated using the perpetual inventory method with Formula 4, where d denotes the depreciation rate and I_t denotes gross fixed capital formation (Leimbach *et al.*, 2017).

$$K_{t+1} = (1 - d)K_t + I_t \tag{4}$$

As shown in Formula 5, labor input (L) is related to the working-age population (W), the labor force participation rate (R), and the educational attainment (H). q refers to the group of working-age population, which is divided into 15–64 years old and over 65 years old. The calculation method of H is shown in Formula 6,

Table 1 | Population parameters under different SSP paths.

Population parameters	Birth rate	Death rate
SSP1	Low	Low
SSP2	Medium	Medium
SSP3	High	High
SSP4	Low	Medium
SSP5	Low	Low

where M refers to the average years of education. The calculations of L and H refer to the existing literature (Leimbach *et al.*, 2017).

$$L = \sum_{q} H \times R(q) \times W(q) \tag{5}$$

$$H = \exp\left(0.134 \min(M, 4) + 0.101 \min(\max(M - 4, 0), 4) + 0.068 \max(M - 8, 0)\right) \tag{6}$$

The initial value of TFP is calculated using the Solow growth model, as shown in Formula 7 (Pan *et al.*, 2019), where ΔG_Y, ΔG_K and ΔG_L are growth rates of GDP, capital input and labor input, respectively.

$$\Delta G_Y = \alpha \Delta G_K + (1 - \alpha)\Delta G_L + \mathrm{TFP} \tag{7}$$

In order to predict the future economy, it is necessary to make assumptions about labor participation rate, capital output elasticity coefficient and total factor productivity under different SSPs. Based on the characteristics of different scenarios and the scenario assumptions of existing studies, the above parameters are calibrated, as shown in Table 2 (Jiang *et al.*, 2018; Pan *et al.*, 2019; Bai *et al.*, 2021). In addition, historical data were obtained from the sixth National Population Census, China Population and Employment Statistical Yearbook and the statistical yearbook of each city.

3.3. Water demand prediction based on SSPs

In terms of domestic water use, in order to implement the strictest water resources management system and promote the construction of a water-saving society, the government departments of Shanxi, Hebei and Henan provinces involved in the Zhanghe River Basin have formulated official documents of water quota, limiting the per capita daily domestic water consumption. The documents are ‘Water Quota of Shanxi Province’, ‘Water Quota of Hebei Province’, ‘Local Standard of Henan Province – Agricultural and Rural domestic water Quota’ and ‘Local Standard of Henan Province – Industrial and urban domestic water Quota’. These documents provide water quota constraints for cities with different population sizes. According to the population prediction results, the corresponding water quota can be determined for each city, as shown in Table 3.

In terms of economic water demand, the governments in the basin have issued relevant plans for the construction of water-saving society, restricting the water consumption quota of 10,000 yuan of GDP. According to the ‘14th Five-Year Plan for Ecological and Environmental Protection in Hebei Province’, ‘14th Five-Year Plan for the Construction of Water-saving Society in Henan Province’, and the ‘14th Five-Year Plan for the Construction of Water-saving Society in Shanxi Province’, the water quota for 10,000 yuan GDP in She County and Ci County will be reduced by 15% in five years, by 16% in Anyang County and Linzhou County and by 12% in Pingshun County. This study obtains the water consumption quota in 2020 from the water resources bulletin of each

Table 2 | Economic forecast parameter setting.

	SSP1	SSP2	SSP3	SSP4	SSP5
Convergence value of labor participation rate (convergence time)	0.7	0.7	0.6	0.75	0.8
Convergence value of elasticity coefficient of capital output (convergence time)	0.35(75a)	0.35(150a)	0.25(150a)	0.3(75a)	0.45(250a)
Total factor productivity growth rate	0.7%	0.7%	0.35%	0.7%	1.05%

Table 3 | Domestic water quotas.

L/(p·d)	She County	Ci County	Anyang County	Linzhou County	Pingshun County
2020	100	100	90	90	97
2025	120	120	95	95	102
2030	130	130	100	100	107

city and then calculates the water consumption quota in 2025 and 2030 according to the requirements of the above government documents, as shown in Table 4.

By combining the population and economic prediction results with water quotas, the prediction results of water demand of the city can be calculated, as shown in Formula 8, where D_i, D_{id} and D_{ie}, respectively, represent the total water demand, domestic water demand and economic water demand of city i. Q_{id} and Q_{ie} represent the domestic water quota and production water quota of city i, respectively. P_i and Y_i are the predicted results of population and economy, respectively.

$$D_i = D_{id} + D_{ie} = Q_{id} \times P_i + Q_{ie} \times Y_i \tag{8}$$

4. RESULTS AND DISCUSSION

4.1. Population and economic forecasting results

In order to test the accuracy of population and economic forecasts, the forecast results under the SSP2, which most closely matches the current development trend, are compared with the actual statistics for 2011–2020. The prediction errors are shown in Table 5 and are generally acceptable. In addition, the population and GDP

Table 4 | Economic water demand quota.

m³/10,000 yuan	She County	Ci County	Anyang County	Linzhou County	Pingshun County
2020	55	60	120.7	18.3	45
2025	46.75	51	101.39	15.37	39.6
2030	39.74	43.35	86.18	13.07	34.85

Table 5 | The projection errors of population and GDP.

	Population		GDP	
	Minimum error (%)	Maximum error (%)	Minimum error (%)	Maximum error (%)
Ci county	7.01	7.04	0.71	5.9
She county	6.13	6.37	1.11	6.93
Anyang county	1.01	3.74	0.47	9.34
Linzhou County	1.07	8.8	0.22	7.92
Pingshun county	0.39	6.57	1.41	9.36

Note: In 2016, the administrative division reform of Ci County was carried out, and some towns were assigned to other districts, For consistency, its errors are verified only with historical data up to 2016.

trends predicted in this paper under the five SSPs in the Zhanghe River Basin are similar to those predicted by previous studies in China (Jiang *et al.*, 2018), which also indicates that the predicted results of this study are reasonable.

4.1.1. Population prediction results

From the population forecast results of each county (see Figure 3), the population on the whole presents a rising trend. In the early stage of the implementation of the 'two-child policy' in 2015, the population of some counties, such as Ci County and Anyang County, did not rise significantly. With the continuous promotion of relevant fertility promotion policies and the launch of the 'three-child policy', the population grows rapidly after 2023.

From the perspective of different scenarios, except Pingshun County, the scenarios with the largest and smallest population size in other counties are SSP3 and SSP4, respectively. The population of SSP1 is very close to that of SSP5. The population under the SSP3 is less educated and the birth rate is higher, resulting in the largest population size under this path. Under the path of SSP4, regional development is not balanced. As a region with low fertility rate, China still maintains a low fertility rate (Wang *et al.*, 2020), with a small number of births, but the death rate is at a medium level, resulting in a smaller population than other paths. The birth and death assumptions under the SSP1 and SSP5 paths were consistent. Due to the small study scale, population migration between counties was not considered, leading to similar population sizes under the two paths. The population of She County and Ci County under SSP1 and SSP5 is slightly higher than that under SSP2, while the population of Anyang County and Linzhou County under SSP1 and SSP5 is slightly lower than that under SSP2. In addition to the SSP4, the population size of the other four paths in Pingshun County is similar, which is also related to the small population base of the county.

4.1.2. Economic forecast results

As can be seen from Figure 4, the future GDP of five counties in the Zhanghe River Basin presents a trend of fluctuation and rise. Among them, the economic growth of Ci County slowed down gradually, while the economic growth of other counties continued to improve. The paths with the highest and lowest GDP in five counties are SSP5 and SSP3, respectively. This is not difficult to understand, as SSP5 is a path that attaches great importance to economic development, while SSP3 is a path that shifts the target to regional security and economic development is slower. The SSP1 is the path with the second highest GDP, which is a path of sustainable development accompanied by more investment in education and science and technology, so it has a higher level of economic development. In addition, the GDP of Anyang County and Linzhou County under the SSP1 is close to that under the SSP2. The GDP of Shexian County and Cixian county under the SSP2 is close to that under the SSP4, which is mainly reflected before 2025. In general, the GDP under different paths can be ordered by SSP5 > SSP1 > SSP2 > SSP4 > SSP3.

4.2. Water demand forecast results

Population and economic differences among counties in the Zhanghe River Basin under different SSPs lead to multiple possibilities of water demand. The domestic water demand and economic water demand under different SSPs were calculated by combining the population and economic forecast results with water quotas, and the total water demand was obtained by adding the two together, which are shown in Figures 5–7, respectively.

As can be seen from Figure 5, domestic water demand is increasing between the three forecast years, but there is little difference between different scenarios, which is also related to the small population base at the county level. By 2030, domestic water demand can reach $13{,}765 \times 10^4\,m^3$ at most, which poses a great challenge to the local water supply system. In order to narrow the gap between domestic water supply and demand, all regions must promote household water-saving measures and improve the efficiency of water resources utilization. In

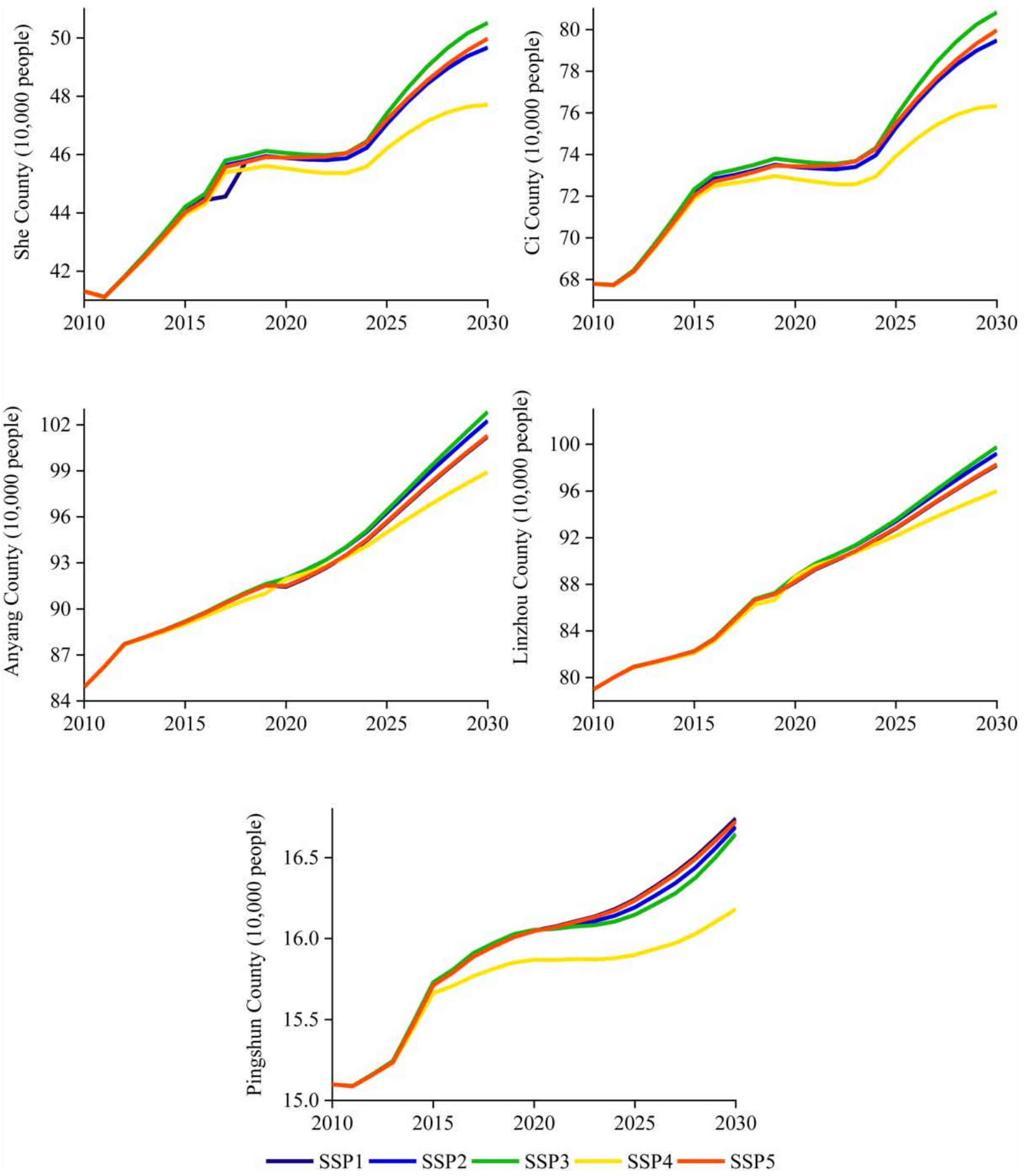


Fig. 3 | Population projection results under different paths.

terms of counties, Pingshun County always has the least water demand due to the smallest population scale, followed by She county. Domestic water use is similar in the other three counties.

As shown in Figure 6, economic water demand has more significant differences between scenarios and between counties than domestic water demand. Due to the lag of economic development, the economic water demand of SSP3 is much lower than other paths, and the growth between different years is not very obvious. The increase in

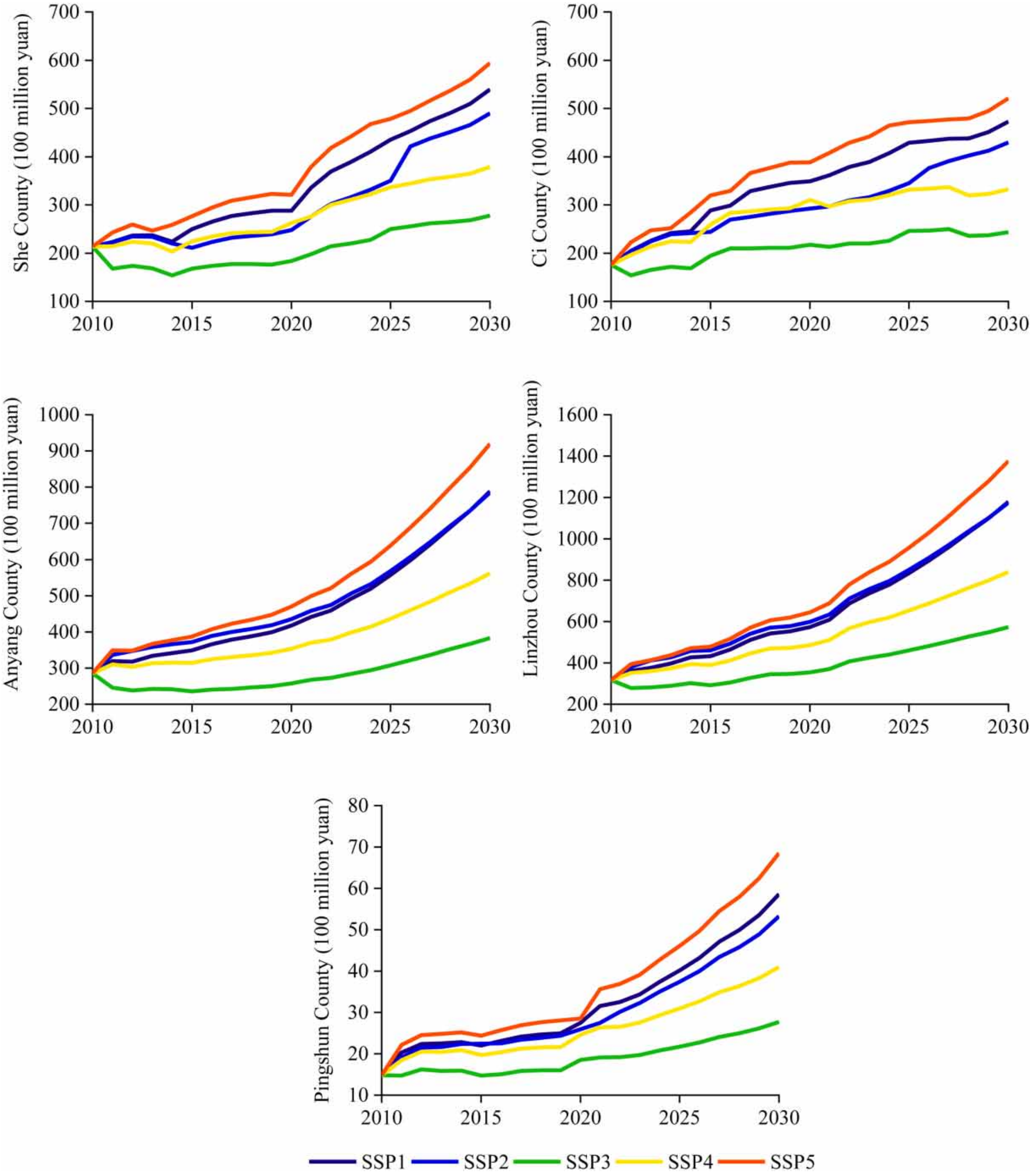


Fig. 4 | GDP forecast results under different paths.

the water demand under the SSP4 is also small, and its water demand is slightly larger than the SSP3. The water demand under the SSP1 and SSP2 paths is similar, with the former slightly higher than the latter, mainly related to the higher output level under the SSP1. The SSP2 path maintains the current development trend, and the economic water demand is also at the medium level. The SSP5 path attaches great importance to economic development, which cannot be separated from a large amount of water resources to support production.

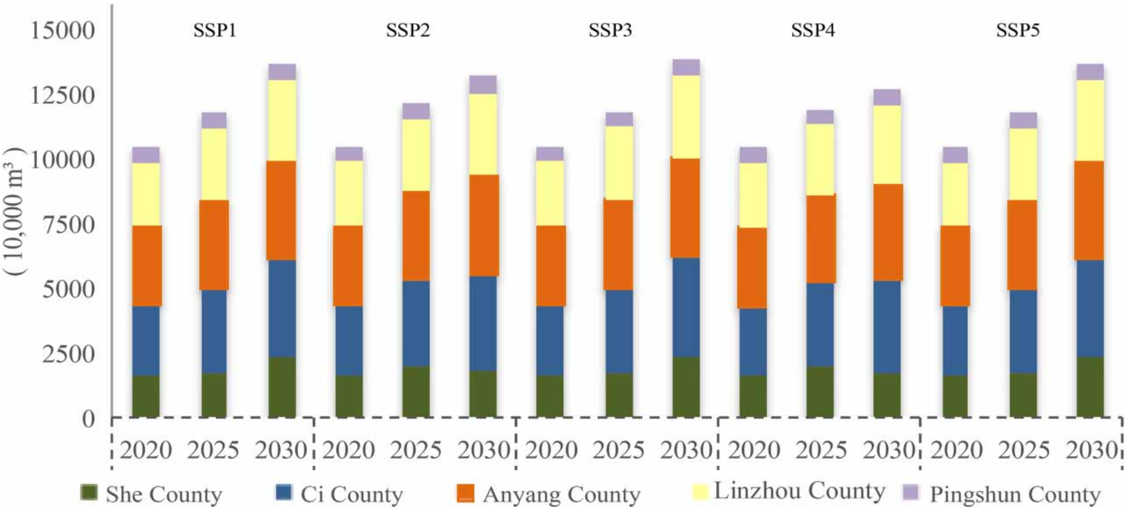


Fig. 5 | Domestic water demand for different counties in 2020, 2025 and 2030.

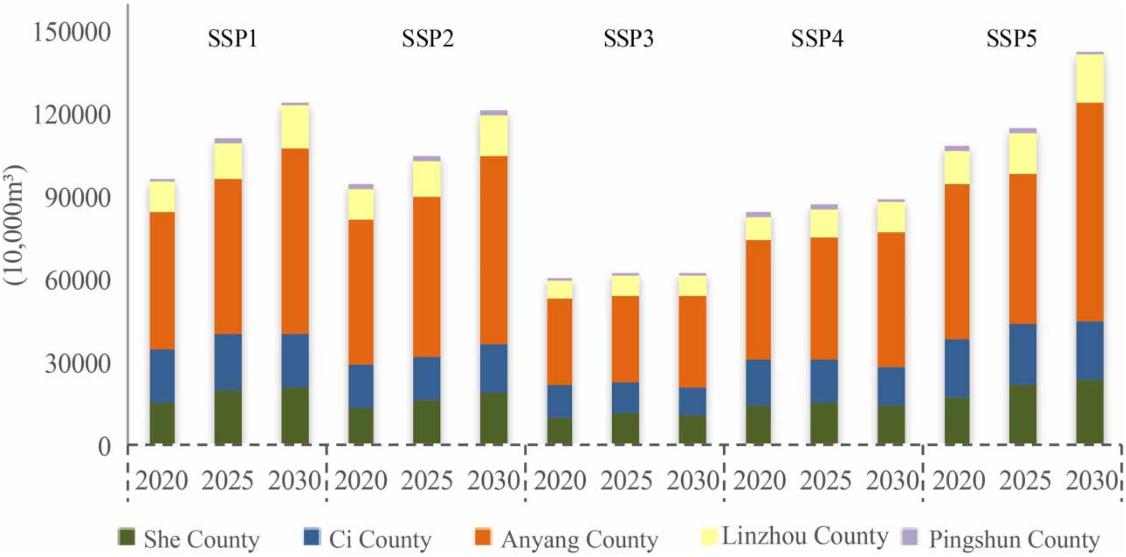


Fig. 6 | Economic water demand for different counties in 2020, 2025 and 2030.

Therefore, it becomes the path with the highest economic water demand, and its economic water demand will increase rapidly from 2020 to 2030. In terms of counties, Anyang County's economic water demand is much higher than that of other counties due to its high GDP and large water demand quota set by the government. On the contrary, Pingshun County has a low GDP and a low water demand quota, so its economic water demand accounts for a small proportion of the total economic water demand in the basin.

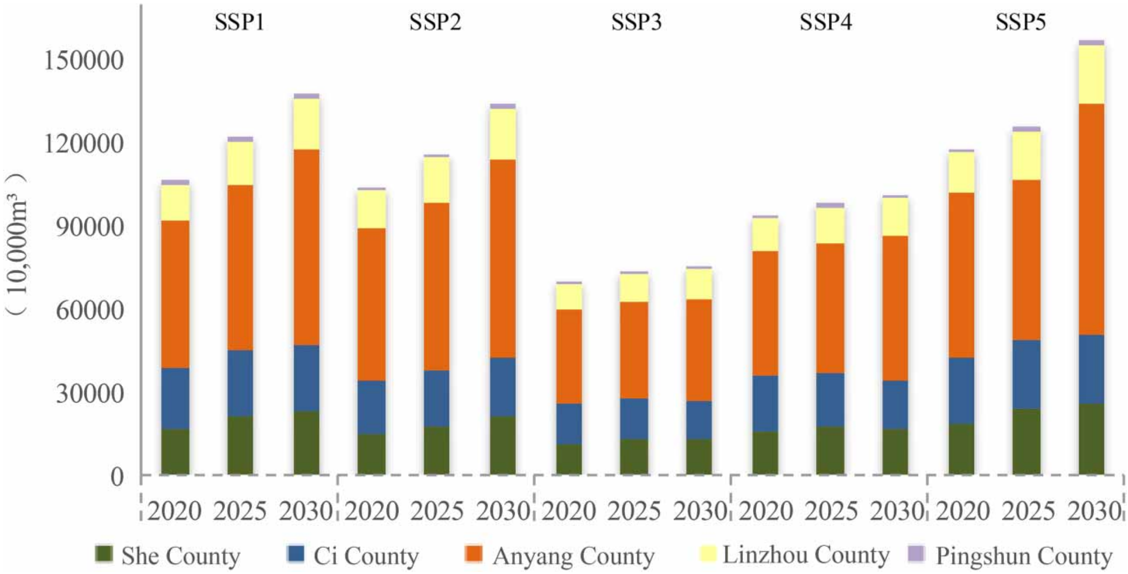


Fig. 7 | Total socio-economic water demand for different counties in 2020, 2025 and 2030.

On the basis of obtaining the domestic water demand and economic water demand of the Zhanghe River basin, the total socio-economic water demand can be obtained by adding the two together. By comparing Figures 6 and 7, it can be found that since economic water demand accounts for a large share in the total water demand, the change trend of total water demand, its scenario differences and county differences are consistent with economic water demand.

As can be seen in Figure 8, the socio-economic water demand scenarios from large to small are SSP5, SSP1, SSP2, SSP4 and SSP3 in order. By 2030, the maximum socio-economic water demand in the Zhanghe River Basin will be 157,235 × 10^4 m³ and the minimum will be 75,978 × 10^4 m³. However, at present, the available water supply in the Zhanghe River Basin in normal flow years is 60,537 × 10^4 m³, which indicates that the water resources shortage in the Zhanghe River Basin will be extremely serious in the future, and the water demand cannot be fully met even under the scenario of minimum water demand, to which needs to be attached great importance by relevant departments.

4.3. Discussion

For a long time, the large-scale diversion irrigation and the development of high-water consumption industries have made the water consumption in the Zhanghe River basin far exceed the amount of surface available water resources, and the overexploitation of groundwater has existed for many years. Moreover, with global warming and disorderly development and utilization of water resources, the river desertification and the reduction of reservoir water storage have occurred in the basin, implying a trend of further reduction of water supply (Gao & Hu, 2016). Although the water quota formulated by the governments of the Zhanghe River Basin is constantly decreasing under the water-saving constraint such as technological progress and the improvement of laws and regulations, the water demand of the Zhanghe River Basin will remain on the rise by 2030 due to the continuous population increase and economic development.

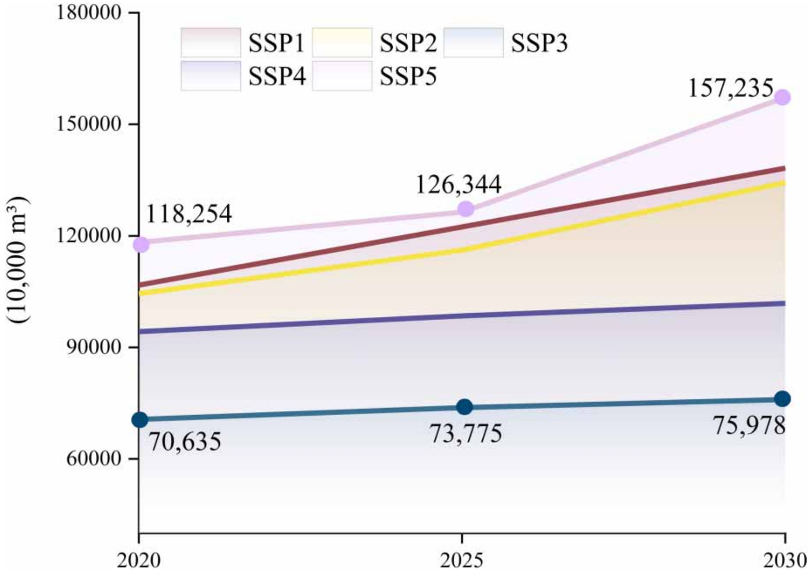


Fig. 8 | Total socio-economic water demand of Zhanghe River Basin in 2020, 2025 and 2030.

The water quotas adopted is a kind of water-saving constraint that is expected to be achievable in the future, formulated by the governments of Zhanghe River Basin under the existing development path, which is close to SSP2. The water quotas under other paths may deviate from them but are difficult to quantify, which needs attention when analyzing the water demand of different SSPs for greater rigor. Specifically, SSP3 requires the least water, but its technical level and water-saving consciousness are lower than SSP2, so it is likely to exceed the given water quotas, and then exceed the predicted water demand. Moreover, SSP3 is at the lowest economic level. It is not the ideal path for long-term development. SSP4 has slightly less water demand than SSP2, but it lags behind SSP2 in economic terms. The predicted water demand of SSP1 is slightly higher than that of SSP2, but it has higher resource utilization efficiency and attention to the ecological environment, so that the water quota constraint can be better met, and even the water demand can be lower than the predicted value. SSP5 has the largest water demand and lacks attention to the environment. Its economy is highly dependent on fossil fuels, which require a lot of water in the exploitation process. Overall, SSP1 is a relatively ideal development path for coordinating economic development and controlling water demand.

5. CONCLUSION AND IMPLICATIONS

As a relatively new scenario analysis tool, SSPs have made rich achievements in population and economic forecasting, but few studies have carried out water demand forecasting on this basis. In addition, SSPs are rarely used at the basin scale, especially in transboundary watersheds, which involve multiple water management administrations and are often subject to water conflicts in the event of water scarcity. In this paper, the population and economy of the Zhanghe River Basin are projected up to 2030 under the SSPs framework, and five different socio-economic development scenarios are constructed. Furthermore, this paper combined the prediction results under the SSPs framework with the potential constraints of water quotas to forecast the water demand of the basin. It is a new attempt to apply the SSPs framework to forecasting water demand in transboundary watersheds, which has important reference value for watershed water resource managers to identify potential water resource shortage risks and take prospective water demand management measures to resolve water-use conflicts.

As the results show, since the evolution of the population pattern is a long historical process, there is little difference in population under different development paths by 2030, and this difference is mainly reflected after 2025. The population size under SSP3 is slightly larger than other paths, and that under SSP4 is the smallest. As a result, the difference in domestic water demand under different paths is also less obvious. Pingshun County has the least domestic water demand due to the least population. The economy of Zhanghe River Basin shows a trend of fluctuating growth in the future. The paths with the largest and smallest economic scale are SSP5 and SSP3, respectively, which are also the paths with the largest and least economic water demand, respectively. Pingshun County has the smallest economic aggregate, so its economic water demand is much lower than other counties, while Anyang County has the largest economic water demand. Since economic water demand accounts for a large proportion of the total water demand in the basin, the scenario heterogeneity and regional heterogeneity of total water demand are similar to that of economic water demand. By 2030, the total water demand will be between $75{,}978 \times 10^4$ and $157{,}235 \times 10^4$ m^3. Under SSP2, a path most likely to be maintained in the short term, the socio-economic water demand of the basin in 2030 will reach $134{,}314 \times 10^4$ m^3, which will bring great challenges to the water supply system of the basin.

From the perspective of balancing economic development and water utilization, SSP1 is the most ideal path for long-term development. In order to realize the transformation to SSP1, effective measures should be taken in the Zhanghe River Basin to realize the sustainability of the water resources system and socio-economic development. Specifically, it can be considered from the following aspects:

(1) A critical action is to improve the unified water resources management mechanism at the basin level. Previously, due to the lack of macro-control at the basin level, water competition in the transboundary area led to repeated construction of water conservancy projects, exceeding the local water resources carrying capacity, and weakening project benefits. Subsequently, the Zhanghe Upstream Administration Bureau was established to coordinate the water resource allocation in the basin and resolve water disputes, which has played a positive role in maintaining the water use order in the basin. In the future, it is also necessary to improve water-use efficiency and control water demand under the unified command of the agency, as well as scientifically dispatch water intake. At the same time, it is required to improve the water resources laws and regulations, cultivate and guide the water rights trading market, so as to avoid the damage to the water resources system caused by the disorderly development and utilization.

(2) It is urgent to strengthen water-saving publicity and education and establish a scientific reward and punishment system to maintain water fairness. On the one hand, the governments in the basin should form a sense of community of water resources interests and actively respond to the call for water conservation. At the basin level, a scientific reward and punishment system should be established to effectively deal with water disputes between administrative regions. Water-use supervision should be strengthened, especially for counties with a large population and economic scale. On the other hand, the existence of large-scale irrigation areas and the dependence on high-water consumption industries such as metallurgy and chemical industry have solidified the development mode and increased the difficulty of water conservation. Therefore, it is necessary to adjust the industrial structure to achieve the goal of water saving and sustainable development.

(3) From a micro perspective, the development of all industries in the basin cannot be separated from the availability of water resources in the Zhanghe River Basin. Enterprises should enhance the awareness of social responsibility, strictly implement the wastewater discharge standard and speed up the research and development of water-saving equipment, so as to help the whole society improve the utilization efficiency of water

resources. In addition, residents should enhance the awareness of water saving in daily life, use more household water-saving appliances and promote water recycling.

Finally, the demand for water resources comes from the requirements of human life and economic development, so the total socio-economic water demand of the basin is closely related to the size of population and economy. Therefore, it is necessary to pay attention to the tradeoff between socio-economic development and water resource utilization, neither to limit population and economic growth in order to save water resources, nor to blindly pursue economic development while ignoring the rigid constraint of water resources. It is important to save water rationally by improving the utilization efficiency of water resources and improving the allocation of resources while maintaining healthy social and economic development.

This study is a novel exploration of water demand prediction by combining SSPs and water quotas, which is of great significance for water management departments to make long-term water demand management plans and alleviate water conflict in basins. But there is still a limitation. Due to the difficulty in quantifying future water quotas under different paths, the expected water quotas under the current trend is used to forecast water demand, but then specific analysis is made for each path to enhance rigor. In the future, other methods can be considered to obtain more accurate parameters and more exploration can be carried out in the prediction of water demand.

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AUTHORS CONTRIBUTION

The authors confirm their contribution to the paper as follows. D. S. conceptualized the whole article, developed the methodology, validated the article, rendered support in formal analysis, investigated the data, brought resources, wrote the article, supervised the process and administered the project. M. Y. rendered support in formal analysis, investigated the article, wrote the original draft, wrote the review and edited the article, arranged the software, and visualised the article. X. W. rendered support in formal analysis, investigated the data, wrote the original draft, wrote the review and edited the article, developed the methodology, validated the article, and visualised the article. G. L. conceptualized the whole article, investigated the data, supervised the process and administered the project.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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