Optimal Water Allocation Scheme in Integrated Water-Ecosystem-Economy System

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Abstract

The water crisis is one of the three crises that is persecuting the world. China is among the countries that face severe water shortages. Water scarcity and water pollution have seriously affected China's sustainable development in terms of the economy and society. Water resources per capita of China are only one quarter of world's average, and as much as 70% of China's rivers, lakes, and reservoirs are affected by pollution. Due to limited water resources, a crucial issue for the sustainable development of river basins relates to how to optimally allocate water resources and achieve a coordinated development of the economy, society, and ecology. On the basis of defining water consumption for production, living, and ecology, this chapter proposes a framework for forecasting and optimally allocating water consumption for production, living, and ecology (WPLE) in integrated water-ecosystem-economy system. Using Zhangye, in the middle reaches of the Heihe River Basin as the case study area, we forecasted and optimally allocated WPLE under three development scenarios, i.e., the conventional development scenario (CDS), the economy-priority development scenario (EPDS), and the environment sustainable development scenario (ESDS). In 2010, the proportions of WPLE in Zhangye were 87.73%, 2.74%, and 9.53%, respectively. In 2020, the proportions of WPLE will be 74.80%, 4.50%, and 20.70% under the CDS; 76.16%, 5.27%, and 18.57% under the EPDS; and 74.99%, 4.51%, and 20.50% under the ESDS. In the future, the proportion of production water consumption of Zhangye will drastically decrease, while the proportion of ecology water consumption will significantly increase. The main contradiction of the coevolution of WPLE of Zhangye is the competitiveness of production and living water consumption with ecology water consumption.

Keywords

Water allocation scheme · Production water · Living water · Ecology water · Water-ecosystem-economy system · Scenario analysis · Genetic algorithm · Heihe River Basin · Zhangye

Introduction

Water is an essential and irreplaceable resource for human survival and development. However, water crisis currently plagues the world, and about 40% of the world population in more than 40 countries face water scarcity (Li et al. 2015; Shi et al. 2015a). Water resources are affected by natural conditions, socioeconomic development, global climate change, and other factors (Liu and Chen 2006; Piao et al. 2010). The water resource management of integrated water-ecosystem-economy system is facing many serious problems such as the contradiction between water supply and demand, water pollution, and water ecosystem degradation (Sahrawat et al. 2010; Hirt et al. 2012). Over the past 50 years, surface water and total water resources in China have decreased by 5% and 4%, respectively (Wang and Cheng 2000). Currently, China is one of the many countries facing a serious water scarcity. In addition, the inland river basin, which accounts for one-third of the whole area of China, has experienced a more severe water crisis than other regions. Due to the inherent shortage and irrational use of water resources, the contradiction between water supply and demand in the Chinese inland river basin has become increasingly worse (Deng and Zhao 2015; Deng et al. 2015a), and water crisis has become one of the key issues influencing socioeconomic development and environmental protection in the inland river basin (Ma et al. 2005; Feng et al. 2007). Water scarcity and water environment degradation have seriously affected economic and social development in China.

Water resources are an important component of the integrated water-ecosystem-economy system and are also one key factor maintaining the eco-economic balance. The allocation of water resources in water-ecosystem-economy system directly influences the coevolution of water consumption of production, living, and ecology (WPLE) (Li et al. 2006; Guan and Hubacek 2008). The components of WPLE are not only closely correlated but are also mutually exclusive; any increase in one component could lead to a decrease in the other two types. For example, an increase in production water consumption could aggravate the water use pressure of urban and rural residents' living and ecosystem production. The increase of living water consumption could affect industrial and agricultural development and ecosystem improvement. Many studies have reported that the over pursuit of economic development has resulted in a series of ecological and environmental problems, such as rivers drying out, the drawdown of lakes, the shrinking of wetlands, and a decrease in biological diversity (Srinivasan et al. 2012). At present, China has to not only maintain a reasonable pace in terms of economic development but also must ensure national food security. Meanwhile, China is developing the ecological civilization construction to curb ecosystem degradation. How to effectively coordinate the relationships among integrated water-ecosystem-economy system and reasonable allocation of WPLE have become key issues affecting China's sustainable development (Shen and Speed 2009; Deng et al. 2015b). The forecast and optimal allocation of WPLE have become a great concern in water research.

Since the 1950s, the development of computer technology has improved the application of linear planning, nonlinear planning, integrative planning, and dynamic planning in the optimal allocation of WPLE (Li and Huang 2008; Guo et al. 2009; Lu et al. 2010). In addition, other new methods, such as fuzzy optimization, neural networks, and genetic algorithms, were also adopted in the research of the allocation of WPLE (Merabtene et al. 2002; Bowden et al. 2002; Iliadis and Maris 2007). In terms of research contents, the reasonable allocation of reservoir water resources (Teegavarapu and Simonovic 2002) have gradually evolved into the optimal allocation scheme of river basin water resources (Jowett 1997; Orr et al. 2007), the development and utilization of regional water resources (Jaarsma et al. 1999), the risk assessment of natural drought and waterlog disasters (Zhang et al. 2012), and the management in river basin water environment (Xiang et al. 2014). The research issues of water resource allocation have correspondingly transformed from a certain single objective into the uncertain and stochastic multi-objectives.

Water scarcity and water pollution increasingly plagued the world since the 1990s. The aims of the allocation of WPLE in integrated water-ecosystem-economy system have shifted from demand-decide-supply to the integrative allocation of water yield and water quality (Afzal et al. 1992; Lind and Davalos-Lind 2002) and from pursuing maximum economic benefits to pursuing maximum integrative benefits of economy, society, and ecology (Liu et al. 2010, 2012; Han et al. 2011; Nouiri 2014). The research on WPLE increasingly concerns the harmonious and sustainable development of eco-environment and socioeconomy. In terms of model building, researchers usually build eco-economy watershed models to analyze the allocation of WPLE. Among them, the Patuxent Landscape Model (PLM) in Maryland Patuxent River Watershed and the Everglades Landscape Model (ELM) in the Everglades of Florida are representative (Fang et al. 2007). However, the existing eco-economy models were usually built on separate ecological and economic systems. The integrative models that can simultaneously consider the coevolution of WPLE are lacking (Costanza and Gottlieb 1998).

As a typical inland river basin in arid Northwest China, the Heihe River Basin (HRB) exists amidst diverse human activities such as animal husbandry, agriculture, industry and ecology protection, etc. Therefore, it has become the ideal test site for water allocation under the combined effects of integrated water-ecosystem-economy system in inland river basins (Shi et al. 2015b). Water resources are the focus of research in HRB, are the link of water-ecosystem-economy system, and are the key limitation to the sustainable development of economy, society, and environment. The main question regarding the HRB water resource issue is how to coordinate the human/nature relationship to solve the current and future water resource decision-making in integrated water-ecosystem-economy system, so that the limited water resources can meet the needs of the sustainable development of the basin economy, social population, and eco-environment (Biswas 2004; Oki and Kanae 2006; Lim et al. 2010). Therefore, to strengthen the unified management of rational allocation of water resources in HRB, it is of great significance to promote optimal allocation scheme and efficient utilization of WPLE so as to improve the carrying capacity of water resources and facilitate regional sustainable development.

The water resources, ecology, and balance of water supply and demand are the main research foci in HRB (Fang et al. 2007; Song and Zhang 2015). However, less attention has been paid to the rational allocation of WPLE, particularly using an integrative model approach, especially in the Heihe River Basin of great significance. Therefore, this chapter aims to (1) define and forecast WPLE, (2) propose an optimal scheme to allocate WPLE, and (3) analyze the effects of the optimal water allocation scheme of WPLE in integrated water-ecosystem-economy system in Zhangye of HRB.

Forecast Framework of Water Consumption in Integrated Water-Ecosystem-Economy System

Definitions of Water Consumption in Production, Living, and Ecology

According to different uses, the water consumption in integrated water-ecosystem-economy system can be divided into production, living, and ecology water. Production water consumption refers to water used for agricultural irrigation and industrial production (Fig. 1). Living water includes water consumed by urban and rural human and livestock populations. According to the causes of ecological system formation, ecology water consumption is classified into natural and artificial ecology water consumption. Natural ecology water consumption refers to the water consumed by natural areas without artificial elements, including the water utilized for natural water bodies and vegetation. Artificial ecology water consumption refers to the water utilized by artificial methods, i.e., the water utilized to support the socioeconomic systems in artificial areas. Artificial ecology water consumption is directly or indirectly maintained by manpower. Artificial ecology water consumption also includes the water utilized for forests and grasslands and evaporation from

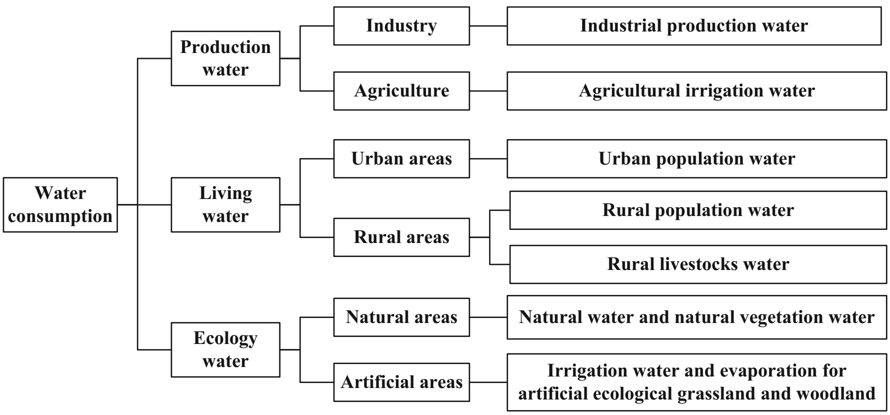

Fig. 1 The composition of water consumption in production, living, and ecology (Reprinted from Xu et al. 2016 with permission of Physics and Chemistry of the Earth)

reservoirs and ponds. Changes in ecology water consumption are influenced by technique progress factors and the areas of artificial ecological vegetation.

Study Area and Data Sources

Basic Information of Zhangye City

The Heihe River Basin is the second largest inland river basin in the arid and semiarid region of Northwest China, and it is in the core area of the ancient Silk Road and Eurasia land bridge. The Heihe River Basin is adjacent to the Qinghai-Tibet Plateau in the southwest, adjacent to the Shule River Basin in the west, adjacent to the Shiyang River Basin in the east, and adjacent to the Mongolian People's Republic in the north. The upper and middle reaches of the Heihe River Basin are separated by Yingluoxia, and the middle and lower reaches are separated by Zhengyixia. The upper reaches of the Heihe River Basin are the water conservation areas, which are the main areas of water resource production. The middle reaches are the main irrigated agricultural areas and are also the main areas of water consumption, consuming more than 85% of the total water consumption in the Heihe River Basin. The lower reaches are the main ecological protection area, which needs enough water resources to maintain the sustainable development of its fragile ecosystem. Therefore, the optimal water allocation scheme in integrated water-ecosystem-economy system rational allocation in the middle reaches of the Heihe River Basin is very important to protect and maintain the ecological environment in the lower reaches.

The agricultural production activities of the Heihe River Basin have a long history, and Zhangye City is the most developed agricultural area within this basin. Zhangye is located in the middle of the Hexi Corridor and the Heihe River Basin. The irrigated agriculture region of Zhangye is one of the top ten key bases for commercial food production in China. It is also the largest economic zone and the largest water consumption area in the Heihe River Basin (Fig. 2). Zhangye has a continental climate. In the winter, the weather is very dry and cold with little snow, while, in the spring, it is quite windy and sandy with little rainfall. The weather in the summer is hot with plenty of rainfall. The annual average temperature is 7.3 °C, with the lowest temperature being −28.7 °C and the extreme high temperature being 39.8 °C. The annual average precipitation in Zhangye is 130.4 mm (1971–2000 average), with a maximum and minimum value of 214.3 mm and 69.5 mm, respectively. The annual evaporation is 2002.5 mm (1971–2000 average), with a drought index of about 15. Zhangye is a typical arid area. The water consumption of Zhangye mainly includes the water consumption of agricultural and industrial production, urban and rural inhabitant, big and small livestock, and ecological irrigation.

Water Consumption of Zhangye in 2010

In 2010, the total water consumption in Zhangye was as high as 2.354 billion m^3 (Table 1). Among this number, the irrigation water was 2.022 billion m^3, and ecology water consumption was 224 million m^3, totally accounting for about

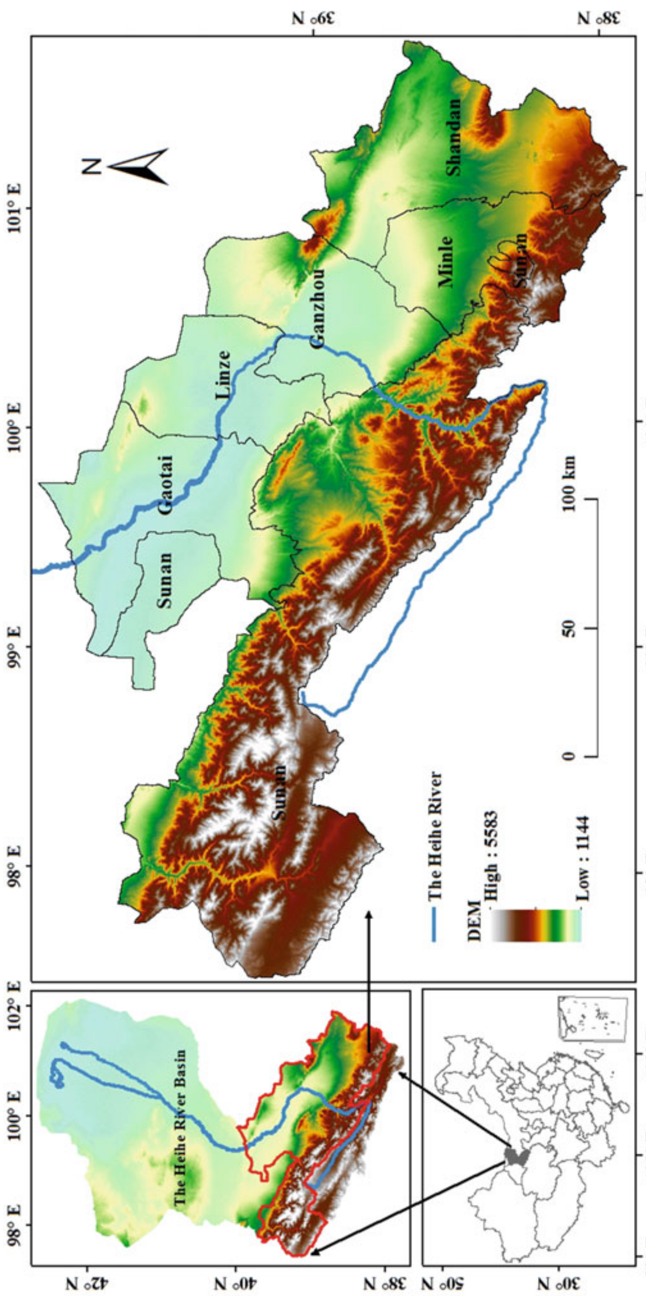

Fig. 2 The location of Zhangye (Reprinted from Xu et al. 2016 with permission of Physics and Chemistry of the Earth)

Table 1 The WPLE of different counties in Zhangye in 2010 (100 million m^3)

Water supply	Production water				Living water				Ecological water		
	Irrigation				Inhabitants		Livestock		Artificial areas		
	Paddy fields	Irrigated land	Vegetable farms	Industry	Urban	Rural	Large	Small	Woodlands	Grasslands	Natural areas
Ganzhou	0.015 0.06%	7.195 30.56%	1.145 4.86%	0.172 0.73%	0.194 0.82%	0.028 0.12%	0.015 0.06%	0.059 0.25%	0.062 0.26%	0.041 0.17%	0.129 0.55%
Gaotai	0.005 0.02%	2.463 10.46%	0.392 1.67%	0.040 0.17%	0.019 0.08%	0.030 0.13%	0.006 0.03%	0.025 0.11%	0.065 0.28%	0.043 0.18%	0.136 0.58%
Shandan	0.003 0.01%	1.571 6.67%	0.250 1.06%	0.059 0.25%	0.032 0.14%	0.035 0.15%	0.003 0.01%	0.013 0.06%	0.079 0.34%	0.052 0.22%	0.165 0.70%
Minle	0.006 0.03%	2.865 12.17%	0.456 1.94%	0.053 0.23%	0.019 0.08%	0.049 0.21%	0.005 0.02%	0.019 0.08%	0.054 0.23%	0.036 0.15%	0.112 0.48%
Linze	0.005 0.02%	2.553 10.84%	0.406 1.72%	0.051 0.22%	0.017 0.07%	0.029 0.12%	0.005 0.02%	0.021 0.09%	0.040 0.17%	0.027 0.11%	0.085 0.36%
Sunan	0.002 0.01%	0.766 3.25%	0.122 0.52%	0.058 0.25%	0.008 0.03%	0.006 0.03%	0.002 0.01%	0.006 0.03%	0.297 1.26%	0.197 0.84%	0.623 2.65%
Sum	0.036 0.15%	17.413 73.97%	2.771 11.77%	0.433 1.84%	0.289 1.23%	0.177 0.75%	0.036 0.15%	0.143 0.61%	0.597 2.54%	0.396 1.68%	1.250 5.31%

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95.42% of the water consumption. Industrial water consumption was 43 million m^3, accounting for 1.84%. The water consumption of urban living was about 29 million m^3, accounting for 1.23% of the total. The water consumption of rural living was about 18 million m^3, and the water consumption of livestock was 18 million m^3, accounting for 1.51% of the total.

Among different counties, Ganzhou had the highest water consumption, i.e., 905.5 million m^3, accounting for about 38.46% of the total. The water consumptions in Minle, Linze, and Gaotai were also high, with percentages of 15.61%, 13.70%, and 13.76%, respectively. In contrast, Shandan and Sunan consumed less water, with percentages of 9.61% and 8.87%, respectively. For agricultural irrigation water, the water consumed in Ganzhou reached 41.32% of the total because the irrigated land in Ganzhou accounted for 37.99% of Zhangye. The agricultural irrigation water consumed in Sunan and Shandan was as low as 4.4% and 9.02% of the total, respectively. The amount of industrial water consumption in Ganzhou reached 39.72% of the total due to the high GDP.

The urban population of Ganzhou accounted for 67% of Zhangye. Therefore, the living water consumption in Ganzhou accounted for 45.89% of the total in Zhangye, while the living water in Sunan only accounted for 3.41% of the total. The ecology water consumption in Sunan was as high as 49.8% of the total, while in Linze, it was as low as 6.78% of the total. The ecology water consumption in other counties was similar, i.e., about 10% of the total in each county. The high ecology water consumption in Sunan was mainly attributed to the high plantation area in artificial forests and grassland. In 2010, the artificial forests in Sunan accounted for 49.87% of the total in Zhangye.

Data Source

The population and GDP data were obtained from the Statistical Yearbook of Zhangye (The Statistical Bureau of Zhangye (2011)). The land use data, including the area of paddy fields, irrigated land, and vegetable farms, were sourced from the Bureau of Land Resources and Management of Zhangye. The water consumption of industry and agriculture in 2010 was sourced from the Annual Report of Farmland Irrigation in Zhangye obtained from the Water Supplies Bureau of Zhangye. The use coefficient of irrigation water was from the Report of Comprehensive Environmental Effect in Heihe River Basin (YREC 2012).

Forecasts of Water Consumption in Production, Living, and Ecology in 2020

The water consumption in production, living, and ecology (WPLE) can be forecasted by the water quota method. The water quota is the water consumption per calculating unit of each water consumption type. According to the definitions of WPLE, the water quota can be divided into the water consumption quota of agricultural irrigation, industry production, urban and rural inhabitants, big and small livestock, and ecological irrigation.

Forecast of Production Water Consumption

Production water consumption is divided into agricultural water consumption and industrial water consumption. The agricultural water consumption of Zhangye in 2010 can be directly obtained from statistical data. In 2020, it can be assessed according to the agricultural area and irrigation quota. The formula is as follows:

$$WCA_{t,i} = \frac{\sum_{i=1}^{n} \mathrm{Area}_{t,i} \times IN_{t,i}}{URIW_{t,i}} \tag{1}$$

where i is the category of agricultural crop, t is the year, $WCA_{t,i}$ is the water consumption of the i type of crop in year t, $Area_{t,i}$ is the agricultural area of the i type of crop in year t, $IN_{t,i}$ is the pure irrigation quota (irrigation water demand per unit area) of the i type of crop in year t (m^3/mu), and $URIW_{t,i}$ is the use coefficient of irrigation water (the ratio of irrigation water demand and actual irrigation water consumption) of i crop in year t, which ranges from 0 to 1.

With the development of techniques, the use coefficient of irrigation water continuously increases. In 2010, the use coefficient of irrigation water in Zhangye was as low as 0.48. Due to the popularization of water-saving technology and the implementation of comprehensive treatment projects in the Heihe River Basin, the use coefficient of irrigation water will continuously increase. According to the Report of Comprehensive Environmental Effects in the Heihe River Basin, the use coefficient of irrigation water in Heihe will reach 0.58 in 2020 (YREC 2012).

According to the statistical data, the water consumption of industry production in Zhangye in 2010 can be calculated. The consumption in 2020 can be assessed based on the water consumption quota of the industry value per 10,000 CNY and the ratio of water reuse (technological progress factor). The two variables reflect the water-saving effects influenced by the industrial scale and structure and the improvement of the technological process of production. The formula is as follows:

$$WCI_{t,i} = \frac{IV_{t,i} \times RR_{t,i}}{ICIP_{t,i}} \tag{2}$$

where i is the county, t is the year, $IV_{t,i}$ is the industrial value of i county in t year, $WCI_{t,i}$ is the water consumption of i county in year t, $ICIP_{t,i}$ is the water consumption quota of industrial value per 10,000 CNY of i county in year t, and $RR_{t,i}$ is the ratio of industrial water reuse.

According to the Report of Comprehensive Environmental Effects in the Heihe River Basin (YREC 2012), the ratio of industrial water reuse in the Heihe River Basin will increase from 72% in 2010 to 90% in 2020. The water consumption quota of industrial value per 10,000 CNY in Zhangye was 120 m^3 in 2010. This value will continuously decrease in the future due to the improvement of the industry structure and the ratio of industrial water reuse. According to the relevant research studies, together with the local actual conditions, the water consumption quota of industrial value per 10,000 CNY is predicted to be 10^3 m^3 in 2020.

Forecast of Living Water Consumption

Living water consumption is divided into urban living water consumption, rural living water consumption, and livestock water consumption. Urban and rural living water consumption in 2010 can be obtained from actual statistics. The water consumption of urban and rural inhabitants and livestock in 2020 can be predicted via the water quota method. Urban living water consumption includes water consumed by residents and the public infrastructure. The total living water consumed by urban residents in Zhangye was 28.9 million m^3 in 2010. The average water quota of urban living was 190 L/person/day in 2010. According to historical records, the water consumption quota of urban living in Zhangye was 142 L/person/day in 2005. Based on the regression model, the water consumption quota of urban living in Zhangye will increase to 250 L/person/day in 2020. The total water consumption of urban living in 2020 can then be forecasted based on the predicted urban population. The formula is as follows:

$$WCR_{t,i} = NR_{t,i} \times WCNR_{t,i} \tag{3}$$

where i is the user category, t is the year, $WCR_{t,i}$ is the total water consumption of the i category of users in year t, $NR_{t,i}$ is the total number of i category of users in year t, and $WCNR_{t,i}$ is the living water quota of i category of users in year t.

Rural living water consumption refers to water used by rural inhabitants. The total water consumption of rural inhabitants in Zhangye in 2010 was about 18 million m^3, with an average water consumption quota of 65 L/person/day. However, the water consumption quota in Zhangye was much lower than that of cities in the Yellow River Basin such as Xianyang, Xian, Luoyang, Zhengzhou, and Jinan. With the development of socioeconomic and living standards, the water consumption quota in both rural and urban areas in the Heihe River Basin would increase. The water consumption quota of rural people living in Zhangye in 2020 is forecasted based on the trend of the historical changes and the water stress. The predicted value is 120 L/person/day in 2020.

Water for feeding livestock is also one kind of living water consumption. In 2010, the total livestock water consumption was about 23 million m^3. The water consumption quotas for feeding large and small livestock were 35 and 15 L/animal/day, respectively, in 2010. We assumed that the water consumption quota would not change much in the future, as it is expected to be 40 and 20 L/animal/day for the large and small livestock in 2020, respectively. In this way, the total amount of water consumed by livestock can be calculated.

Forecast of Ecology Water Consumption

Since the related research on natural ecology water consumption is immature, we did not adopt any of the existing methods to assess natural ecology water consumption in

Zhangye. In consideration of the undeveloped industry, the natural ecological areas in Zhangye will not change much in the near future. Therefore, we assumed that the natural ecological areas would be unchanged from 2010 to 2020. The changes in ecology water consumption resulted from the changes in artificial ecological areas. The assessment of water consumption of artificial ecological areas is similar to that of agricultural water consumption. The formula is as follows:

$$WCC_{t,i} = \frac{EA_{t,i} \times EWC_{t,i}}{UIE_{t,i}} \tag{4}$$

where i is the category of artificial ecology vegetation, classified as artificial grassland and forests, t is the year, $WCC_{t,i}$ is the ecology water consumption of the i category of vegetation in year t, $EA_{t,i}$ is the total area of i category of ecological vegetation in year t, $EWC_{t,i}$ is the irrigation quota of i category of ecological vegetation in year t, and $UIE_{t,i}$ is the use coefficient of irrigation water for i category of ecological vegetation in year t.

In 2010, most of the water in the Ejina district was consumed by ecology on both shores of the Heihe River. Therefore, the ecology water consumption was equal to 322 million m^3 in 2010, i.e., subtracting the living and producing water in Ejina from the water that flowed into Ejina.

Optimal Water Allocation Scheme of WPLE in Integrated Water-Ecosystem-Economy System in Zhangye of HRB

Three Scenarios of WPLE

Conventional Development Scenario

In this scenario, the economic development in Zhangye in the future will continue based on historical development in terms of population, agriculture, industry, and the artificial ecological areas. A conventional development scenario (CDS) is a basic scenario that can be compared to other scenarios to find the best one.

Economy-Priority Development Scenario

In economy-priority development scenario (EPDS), the development speed of industry and agriculture will increase. In order to guarantee rapid development, more resources will be allocated to industry and agriculture. On the basis of ensuring living water consumption, the water allocated to ecology will decrease. Thus, growth in the artificial ecological areas will decrease. Under this scenario, the speed of the GDP increase is 1.5 times of that under CDS. The speed of industry structure adjustment is 1.3 times of the past. For the occupation of ecological areas due to economic development, the artificial forests and grasslands will decrease by 0.4% annually, while the population growth rate will increase by 0.3% annually. In addition, the urbanization speed will reach 1.2 times of the past. Under this scenario, technique progress becomes the key factor influencing water consumption. Due to the application of new techniques, in this scenario, the water consumption of industry value will decrease, which is contrary to the other scenarios.

Environment Sustainable Development Scenario

This environment sustainable development scenario (ESDS) enhances ecological conservation. Compared to the CDS, this scenario will decrease the speed of agriculture and industry development. The ecology water consumption in this scenario will increase by 0.4% to guarantee the sustainable development of the environment. On the basis of guaranteeing living water consumption, the water consumption for economic development will be reduced. The GDP growth dropped to 0.95 of that in the past. The industrial structure adjustment rate decreased to 10/11 of the past. The population growth rate slightly increased compared to the past.

The three scenarios have different features regarding water consumption. For the economy-priority development scenario (EPDS), the technique progresses faster than in the other scenarios, which decrease the water consumption of industrial value per unit. For the environment sustainable development scenario (ESDS), the growth of water consumption for artificial forests and grasslands will decrease. For the different foci under the three development scenarios, the water consumption coefficients of WPLE are not the same. The water consumption coefficients of every index under the three scenarios are listed in Table 2.

Optimal Allocation Model of WPLE

The optimal allocation of WPLE has many objectives, such as economic objective (output, profits, gross national product, and gross living product), social objective (social stability, quality of life, employment, and education), and environmental objective (minimizing water quality loss caused by water pollution, maximizing water environment benefits, maintaining the ecosystem balance, and improving the ecological system). Zhangye has shown water shortages, huge contradictions between the water supply and demand, fragile ecosystems, and a complicated water resource system. Therefore, this chapter, via the optimal allocation of WPLE, aimed to minimize the water shortage for the whole watershed and balance the water shortage in different districts.

Objective Function

In order to guarantee the positive cycle and continuous improvement of the ecological environment in the Heihe River Basin, the ecology water consumption in the lower reaches was set as a constraint condition. The water shortage of each sector in the middle reach should be reduced based on ensuring ecology water consumption in the lower reach. According to the concepts and goals of sustainable development, sustainable development should follow the criteria of maximizing benefits and being survivable, bearable, and sustainable. Therefore, we raised the objective function of water consumption allocation in Zhangye.

Table 2 The water use coefficients of WPLE in different water allocation scenarios

Water usage coefficient	Production water				Living water(L/person/day)				Ecological water(m^3/100,000 m^2)		
	Irrigation(m^3/acre)			Industry (m^3/10,000CNY)	Inhabitant		Livestock		Artificial areas		Natural areas
	Paddy fields	Irrigated land	Vegetable farms		Urban	Rural	Big	Small	Woodlands	Grasslands	
Scenario 1	18,405	10,845	10,395	110	240	120	50	35	4500	4500	1
Scenario 2	18,405	10,845	10,395	90	240	120	50	35	4500	4500	1
Scenario 3	18,405	10,845	10,395	110	240	120	50	35	4275	4275	1

Notes: Scenario 1 is the conventional development scenario; Scenario 2 is the economy-priority development scenario; and Scenario 3 is the environmental sustainable development scenario (Reprinted from Xu et al. 2016 with permission of Physics and Chemistry of the Earth)

1. Environmental objective: maximizing the demand of ecology water consumption

$$y_1 = \max\left\{\sum_{i=1}^{m} Q_i\right\} \tag{5}$$

2. Social objective: minimizing the differences in water shortages among different counties

$$y_2 = \min\left\{\max\left\{\frac{\sum_i\sum_j W_{i,j}^{\text{supply}}}{\sum_i\sum_j W_{i,j}^{\text{demand}}}\right\} - \min\left\{\frac{\sum_i\sum_j W_{i,j}^{\text{supply}}}{\sum_i\sum_j W_{i,j}^{\text{demand}}}\right\}\right\} \tag{6}$$

3. Economic objective: maximizing the economic benefits of the water supply

$$y_3 = \max\left\{\sum_{i=1}^{m} w_i^{ind} * W_i^{ind} + w_i^{agr} * W_i^{agr}\right\} \tag{7}$$

where y_1, y_2, y_3 are objective functions of environmental, social, and economic benefits, i is the number of counties, j is the index number of WPLE (i.e., production, or living, or ecology water) of each county, Q_i is the total water consumption in i county, $W_{i,j}^{\text{supply}}$ is the water supply amount of j index number in i county, $W_{i,j}^{\text{demand}}$ is the amount of water consumption of j index number in i county, w_i^{ind} is the coefficient of converting industrial water consumption to industry value in i county, w_i^{agr} is the coefficient of converting agriculture water consumption to agriculture value in i county, W_i^{ind} is the amount of industrial water consumption in i county, and W_i^{agr} is the amount of agricultural water consumption in i county.

Constraint Conditions

1. Minimum water supply reliability constraint

$$\beta_{y,m,u,k} \geq \min\left(\beta_{m,u,k}\right) \tag{8}$$

$$\beta_{y,m,u,k} = Sp_{y,m,u,k}/D_{y,m,u,k} \tag{9}$$

where $\beta_{y,m,u,k}$ is the water supply assurance rate of u computation unit in y year during m period of k type of users (%), $\min(\beta_{m,u,k})$ is the minimal water supply assurance rate for u computation unit in y year and k type of users, $Sp_{y,m,u,k}$ is the amount of water supply for u computation unit in y year during m period of k type of users(10,000 m^3), and $D_{y,m,u,k}$ is the amount of water consumption for u computation unit in y year during m period of k type of users(10,000 m^3).

2. Constraint in WPLE

$$\min\left(Wy_{m,j}\right) \leq Wg_{m,j} \leq \max\left(Wy_{m,j}\right) \tag{10}$$

$$\min\left(Wy_{m,j}\right) = \partial_j \max\left(Wy_{m,j}\right) \tag{11}$$

where j is the type of water consumption, i.e., living water consumption, production water consumption, and ecology water consumption (10 k m^3), and max ($Wy_{m,j}$) is the upper limit value of WPLE during m period. It is a predicted value for the amount of water stored (10 k m^3); min($Wy_{m,j}$) is the lower limit value of WPLE during m period (10 k m^3); and ∂ is the basic water consumption coefficient.

3. Nonnegative constraint

$$\sum_i \sum_j W_{i,j}^{\text{supply}} > 0 \tag{12}$$

where i is the number of counties, j is the number of WPLE, and $W_{i,j}^{\text{supply}}$ is the lower limit of water supply for j indicator in i county. Every value of indicators should be larger than 0.

Genetic Algorithm

The genetic algorithm is adopted to build the optimal allocation model in WPLE. First, a random initial population was selected and encoded according to certain rules such as binary encoding. Then, the objective function was used to calculate the fitness value of each individual. The groups that suited the objective function were selected, and the groups with smaller individual fitness were removed (Fig. 3). Then, genetic cross operation and mutation operations were performed among the rest of the individuals to create new groups. The loops were circulated, i.e., select-crossover-mutation, until a termination condition was met (Fig. 3). In this chapter, Matlab was used to model the multi-objective planning of the genetic algorithm. The parameters were set as follows: population size was 100, mutation probability was 0.7, and crossover probability was 0.8. The default iteration number was 100 times the number of modeling variables, i.e., 6600 times.

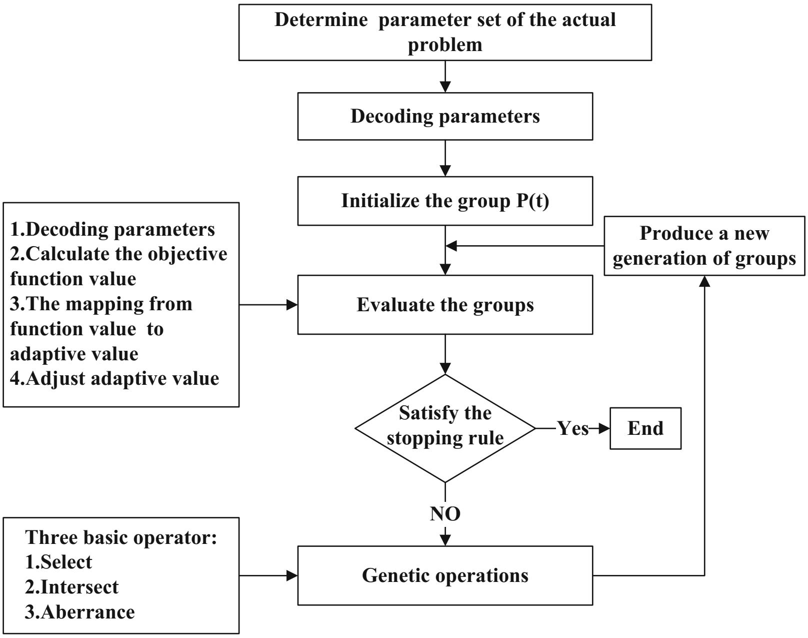

Fig. 3 Technical route of the genetic algorithm (Reprinted from Xu et al. 2016 with permission of Physics and Chemistry of the Earth)

Scenario-Based Water Allocation Scheme of WPLE in Zhangye in 2020

Optimal Allocation of WPLE in Zhangye in 2020 Under the Conventional Development Scenario

Based on the historical socioeconomic data from 2003 to 2010 and the parameters set under the three scenarios, after optimal allocation, the WPLE in 2020 was calculated based on the three scenarios. Under CDS, the WPLE are 176.1 million m^3, 10.6 million m^3, and 48.7 million m^3, and the proportions of WPLE are 74.80%, 4.50%, and 20.70%, respectively (Table 3). Compared with the WPLE in 2010, the proportions of production water consumption decreased, while the proportion of ecology water consumption significantly increased. In addition, the living water also slightly increased.

Compared with the water consumption in 2010, the production water consumption in 2020 under CDS decreased by 14.72%. The decrease in the production water consumption was mainly due to the reduction in irrigated land. The water consumption of industrial production increased by 419.4%. Due to the impacts of population growth, the living water consumption will significantly increase under the CDS. The ecology water consumption for artificial forests, artificial grasslands, and natural areas will increase by 160.3%, 144.70%, and 88.08%, respectively.

Table 3 Water optimal deployment in Zhangye under the conventional trend development scenario (100 million m^3)

	Production water				Living water				Ecological water		
	Irrigation				Inhabitants		Livestock		Artificial areas		
Water supply	Paddy fields	Irrigated land	Vegetable farms	Industry	Urban	Rural	Large	Small	Woodlands	Grasslands	Natural areas
Ganzhou	0.026 0.11%	5.591 23.75%	0.963 4.09%	0.824 3.50%	0.386 1.64%	0.040 0.17%	0.062 0.26%	0.022 0.09%	0.134 0.57%	0.104 0.44%	0.220 0.93%
Gaotai	0.005 0.02%	1.973 8.38%	0.452 1.92%	0.295 1.25%	0.040 0.17%	0.048 0.20%	0.027 0.11%	0.010 0.04%	0.146 0.62%	0.131 0.56%	0.239 1.02%
Shandan	0.005 0.02%	1.100 4.67%	0.140 0.59%	0.316 1.34%	0.064 0.27%	0.056 0.24%	0.012 0.05%	0.005 0.02%	0.239 1.02%	0.114 0.48%	0.333 1.41%
Minle	0.004 0.02%	1.495 6.35%	0.270 1.15%	0.241 1.02%	0.040 0.17%	0.073 0.31%	0.019 0.08%	0.008 0.03%	0.163 0.69%	0.108 0.46%	0.214 0.91%
Linze	0.006 0.03%	2.096 8.90%	0.322 1.37%	0.296 1.26%	0.035 0.15%	0.046 0.20%	0.022 0.09%	0.009 0.04%	0.094 0.40%	0.082 0.35%	0.143 0.61%
Sunan	0.010 0.04%	0.768 3.26%	0.137 0.58%	0.277 1.18%	0.016 0.07%	0.008 0.03%	0.007 0.03%	0.003 0.01%	0.778 3.30%	0.430 1.83%	1.202 5.11%
Sum	0.056 0.24%	13.023 55.31%	2.284 9.70%	2.249 9.55%	0.581 2.47%	0.271 1.15%	0.149 0.63%	0.057 0.24%	1.554 6.60%	0.969 4.12%	2.351 9.99%

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In different districts, the proportion of water consumption in Ganzhou and Minle will decrease by 2.91% and 4.42%, respectively, while, in Sunan, it will increase by 6.58% due to the substantial increase in ecology water consumption.

Optimal Allocation of WPLE in Zhangye in 2020 Under the Economy-Priority Development Scenario

Under the EPDS, accelerated economic growth will increase the industrial and agricultural value and the population growth. However, ecological areas will be constricted due to rapid economic growth. Consequently, ecological grassland and forest areas will decrease. The WPLE under this scenario would be 179.3 million m^3, 12.4 million m^3, and 43.7 million m^3, accounting for 76.16%, 5.27%, and 18.57%, respectively (Table 4). Compared to the CDS, the proportion of production water consumption is slightly greater due to the increase in industry water consumption. Nevertheless, the proportion of ecology water consumption increased under the EODS, which means that the increase of production water consumption will mainly reduce the living water consumption but will not significantly influence the ecology water consumption. Compared to the WPLE in 2010, the production water consumption in 2020 significantly increased.

Compared to the CDS, the water consumption in the paddy fields would slightly increase by 21.43%, while the water consumption for irrigated land and vegetable farms would decrease by 1.04% and 6.13%, respectively.

The water consumption of industrial production under the EPDS would significantly increase by 25.74% more than that under the CDS. Due to the influence of urbanization and population growth, the water consumption of urban living would increase by 10.84%, while the water consumption of rural living would decrease by 1.85% more than under the CDS. The water consumption of large and small livestock significantly increased by 61.07% and 59.65%, respectively. Compared to the CDS, the ecology water consumption of artificial forests, grasslands, and natural areas would decrease by 8.3%, 12.38%, and 10.76%, respectively. The water consumption distribution in various counties under the EPDS is similar to the CDS.

Optimal Allocation of WPLE in Zhangye in 2020 Under the Environment Sustainable Development Scenario

Under the ESDS, economic development will slow due to the deceleration in industrial production growth and urbanization. Due to the conservation of the ecosystem, the area of ecological forests and grasslands will increase. The population will slightly grow due to the improvement of the ecological environment, but the rate of growth will be quite similar to that under the CDS.

Under this scenario, the WPLE in Zhangye were 176.5 million m^3, 10.6 million m^3, and 48.3 million m^3, and the proportions of WPLE were 74.99%, 4.51%, and 20.50%, respectively (Table 5). Compared to the other two scenarios, the proportion of production water consumption was larger than in the CDS but smaller than in the EPDS. The living water consumption was the same as production water consumption, i.e., higher than in the CDS and lower in the EPDS. The proportion of ecology

Table 4 Water optimal allocation in Zhangye under the economic priority development scenario (100 million m^3)

Water supply	Production water				Living water				Ecological water		
	Irrigation				Inhabitants		Livestock		Artificial areas		
	Paddy fields	Irrigated land	Vegetable farms	Industry	Urban	Rural	Large	Small	Woodlands	Grasslands	Natural areas
Ganzhou	0.026 0.11%	5.394 22.91%	0.798 3.39%	1.105 4.69%	0.428 1.82%	0.042 0.18%	0.102 0.43%	0.037 0.16%	0.178 0.76%	0.085 0.36%	0.207 0.88%
Gaotai	0.008 0.03%	1.969 8.36%	0.449 1.91%	0.320 1.36%	0.043 0.18%	0.044 0.19%	0.044 0.19%	0.016 0.07%	0.139 0.59%	0.095 0.40%	0.221 0.94%
Shandan	0.007 0.03%	1.161 4.93%	0.130 0.55%	0.412 1.75%	0.074 0.31%	0.053 0.23%	0.022 0.09%	0.008 0.03%	0.168 0.71%	0.111 0.47%	0.261 1.11%
Minle	0.004 0.02%	1.525 6.48%	0.264 1.12%	0.277 1.18%	0.043 0.18%	0.075 0.32%	0.029 0.12%	0.012 0.05%	0.161 0.68%	0.076 0.32%	0.215 0.91%
Linze	0.009 0.04%	1.950 8.28%	0.310 1.32%	0.343 1.46%	0.038 0.16%	0.043 0.18%	0.033 0.14%	0.014 0.06%	0.122 0.52%	0.059 0.25%	0.189 0.80%
Sunan	0.014 0.06%	0.888 3.77%	0.193 0.82%	0.371 1.58%	0.018 0.08%	0.009 0.04%	0.010 0.04%	0.004 0.02%	0.657 2.79%	0.423 1.80%	1.005 4.27%
Sum	0.068 0.29%	12.887 54.75%	2.144 9.11%	2.828 12.01%	0.644 2.74%	0.266 1.13%	0.240 1.02%	0.091 0.39%	1.425 6.05%	0.849 3.61%	2.098 8.91%

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Table 5 Water optimal allocation in Zhangye under the environment sustainable development scenario (100 million m^3)

Water supply	Production water				Living water				Ecological water		
	Irrigation				Inhabitants		Livestock		Artificial areas		
	Paddy fields	Irrigated land	Vegetable farms	Industry	Urban	Rural	Large	Small	Woodlands	Grasslands	Natural areas
Ganzhou	0.020 0.08%	5.467 23.22%	0.775 3.29%	0.973 4.13%	0.392 1.67%	0.046 0.20%	0.058 0.25%	0.021 0.09%	0.186 0.79%	0.089 0.38%	0.291 1.24%
Gaotai	0.006 0.03%	2.120 9.01%	0.339 1.44%	0.286 1.21%	0.039 0.17%	0.050 0.21%	0.023 0.10%	0.010 0.04%	0.152 0.65%	0.133 0.56%	0.242 1.03%
Shandan	0.007 0.03%	1.141 4.85%	0.132 0.56%	0.339 1.44%	0.064 0.27%	0.054 0.23%	0.012 0.05%	0.005 0.02%	0.200 0.85%	0.117 0.50%	0.295 1.25%
Minle	0.003 0.01%	1.534 6.52%	0.383 1.63%	0.204 0.87%	0.040 0.17%	0.078 0.33%	0.017 0.07%	0.007 0.03%	0.124 0.53%	0.083 0.35%	0.205 0.87%
Linze	0.007 0.03%	2.069 8.79%	0.333 1.41%	0.240 1.02%	0.035 0.15%	0.048 0.20%	0.020 0.08%	0.008 0.03%	0.126 0.54%	0.084 0.36%	0.194 0.82%
Sunan	0.014 0.06%	0.790 3.36%	0.143 0.61%	0.327 1.39%	0.016 0.07%	0.010 0.04%	0.006 0.03%	0.002 0.01%	0.770 3.27%	0.461 1.96%	1.075 4.57%
Sum	0.057 0.24%	13.121 55.74%	2.105 8.94%	2.369 10.06%	0.586 2.49%	0.286 1.21%	0.136 0.58%	0.053 0.23%	1.558 6.62%	0.967 4.11%	2.302 9.78%

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water consumption under this scenario was similar to that of the CDS. The water consumption of different districts and counties was similar to that of the other two scenarios.

The WPLE under ESDS is similar to that under CDS while significantly different from that under EPDS. The water consumption in paddy fields, irrigated land, and vegetable farms will be 16.18% less, 1.82% more, and 1.82% less than the ones under EPDS, respectively. The industrial water consumption will reduce significantly by 16.23%. The water consumed by large and small livestock will reduce by 43.33% and 41.76%, respectively. The water consumption of urban living will decrease by 9%, while the water consumption for rural living will increase by 7.52%. The water consumed by artificial forests, grasslands, and natural areas will increase by 9.33%, 13.90%, and 9.72%, respectively.

Effects and Policy Implications of the Optimal Water Allocation Scheme of WPLE in Zhangye

Effects of the Optimal Water Allocation Scheme of WPLE

On the basis of maximizing ecology water consumption and the benefits of water consumption, after the optimal allocation of WPLE, the proportion of production water consumption in 2020 will significantly decrease compared with that in 2010 under all the scenarios, ranging from 11% to 14%, while the water consumption for industrial production will increase. The reduction of production water consumption in Zhangye in the future results mainly from the decrease in water consumption for agricultural production. Therefore, in order to adapt to the new situation that the agricultural production water consumption reduce in the future, it is imperative to restrict the expansion speed of the agricultural oasis, carry out the adjustment of agricultural planting structure, and develop water-saving crops in Zhangye.

Under the three scenarios, living and ecology water consumption increase. The continued increase of living water consumption is used to sustain the growing population and economy, and the increase of ecology water consumption will promote the sustainable development of ecological environment in Zhangye in the future. As the future production water consumption will decrease while other two consumption of WPLE will increase, the conflicts in WPLE in Zhangye are mainly attributed to the contradictions of production water consumption with living and ecology water consumption, in particular with ecology water consumption. The contradiction of industry and agriculture development with ecological protection will be an entrenched problem in Zhangye. After the optimal water allocation scheme of WPLE under the three scenarios in integrated water-ecosystem-economy system, the ecological benefits have received the same attention like the economic benefits, and the future economy will develop on the basis of the protection of the ecological environment.

The competition for water resource consumption in Zhangye exists not only among the WPLE but also inside the WPLE. Under the EPDS, both the urban population and industry will experience rapid development. Living water consumption will increase due to the fast-growing urban population. Industrial development will inevitably consume a great deal of water, which will influence the water consumption for agricultural production. Although, under the EPDS, the production water consumption in Zhangye only increased by 1.79% compared to that under the CDS, the water consumption for industrial production increased by 25.74%. In addition, the water consumption for agricultural production decreased by 1.72%.

Policy Implications for the Optimal Water Allocation Scheme of WPLE

The optimal allocation of WPLE is a key issue influencing regional sustainable development. Environmental, social, and economic objectives were set in our study to achieve the optimal allocation of WPLE in 2020. However, the contradictions among the WPLE in integrated water-ecosystem-economy system are inevitable. Any increase in one component of production, living, and ecology water consumption could lead to a decrease in the other two types. In addition, the total amount of water resources in a region is generally maintained in a range with slight changes. Thus, some policies are needed to be implemented for the followed objectives: maximizing the demand of ecology water consumption, minimizing the differences in water shortages among different counties, and maximizing the economic benefits of the water supply.

Zhangye is located in an arid and semiarid area with a fragile ecosystem. The stability of the ecosystem is crucial to guarantee the sustainable development of industrial and agricultural production. Therefore, the policies of ecological civilization construction, e.g., grain-for-green and artificial forest construction, need to be strengthened to protect the regional ecosystem development, especially in the water shortage region with the fragile ecological environment. The water consumption in integrated water-ecosystem-economy system should give priority to ensuring the development of ecological environment, namely, ecology water consumption needs to increase, while living water consumption and production water consumption should be reduced.

With the growth of economy and population in integrated water-ecosystem-economy system, the water resource consumption of Zhangye in the future will face greater challenges than ever. However, the living water consumption of Zhangye in the future will inevitably increase along with the continuous growth of population and urbanization, and what we can do is reduce the quota of living water to make its unit water consumption lower. In order to guarantee the ecology water consumption in the future, the population growth should be slowed down, and water-saving technology of living water needs to be extensively applied.

The main contradiction of WPLE is the competition between ecology water consumption and production water consumption. Therefore, production water consumption must be reduced in order to ensure that ecology water consumption is sufficient to maintain the sustainable development of ecosystem. However, the agricultural producing water accounts for more than 85% of the total production water consumption of Zhangye. Thus, production water consumption, especially agricultural producing water consumption, should be decreased. In order to reduce agricultural producing water consumption, it is necessary to curb the expansion of the agricultural oasis, adjust the agricultural planting structure, and develop water-saving crops (Liu et al. 2016). Furthermore, the improvement of the efficiency of both agricultural and industrial water use is necessary to first ensure the demand of ecology water consumption and to optimally allocate water consumption.

Summary

In recent years, with global change and the rapid development of social economy, water resources in many countries are facing the serious problems such as water scarcity and water pollution, especially in China, where water resources per capita are only one quarter of world's average. The contradiction between supply and demand, water environment pollution, and water ecosystem degradation has seriously affected the sustainable development of China's economy and society. The Heihe River is the second largest inland river in the arid and semiarid region of Northwest China, which is the cornerstone of the sustainable development of the ecosystem, economy, and society in the Heihe River Basin. Water resources, and its scarcity especially, is one of the key factors that restrict the development of the Heihe River Basin. Zhangye City is the most important irrigated agriculture region in the middle of the Heihe River Basin, for which water consumption accounts for more than 85% of the total basin water consumption. It is crucial to study the optimal allocation of water resources in integrated water-ecosystem-economy system of Zhangye and to achieve the harmonious and sustainable development of ecosystem, economy, and society.

According to the different uses of the water resources, the water consumption in integrated water-ecosystem-economy system of Zhangye can be classified into production, living, and ecology categories. We proposed the definitions of water consumption in production, living, and ecology (WPLE). According to the irrigation quota method, we provided a forecast framework of WPLE and designed three different development scenarios, i.e., conventional development scenario (CDS), environment sustainable development scenario (EPDS), and environment sustainable development scenario (ESDS). Based on the development objectives of socioeconomic-ecological benefit maximization (survivable, bearing capacity, and sustainable), the water optimal allocation model of Zhangye is built and utilized to assess the changes in WPLE under three scenarios. After defining and forecasting WPLE, we performed the optimal allocation of WPLE under three scenarios based on the method of genetic algorithms. However, there were a few insufficiencies in our study. First, the natural ecological areas in Zhangye from 2010 to 2020 were assumed to be unchanged due to the lack of a defendable method of forecasting changes in natural ecological areas. Therefore, the changes in ecology water consumption are only based on the changes in artificial ecological areas. In addition, due to the lack of related data of WPLE in Zhangye, except for 2010, the validity of the

method was not verified. Moreover, the predictions of future land use changes are not presented in space. It would be better to predict both spatial and quantitative land use changes via land use change models or methods.

In 2010, the total water consumption in Zhangye was as high as 2.354 billion m^3. Among this number, the water consumptions in production, living, and ecology were 206.5 million m^3, 6.5 million m^3, and 22.4 million m^3, respectively, and the proportions of WPLE were 87.73%, 2.74%, and 87.73%, respectively. Production water occupies the largest proportion of water consumption. Production water is mainly used for agricultural irrigation, which accounts for 97.90% of the total consumption of production water. In the future, under the constraint of constant total water consumption, the WPLE under the CDS are 176.1 million m^3, 10.6 million m^3, and 48.7 million m^3, accounting for 74.80%, 4.50%, and 20.70% of the total consumption, respectively. The WPLE under the EPDS are 179.3 million m^3, 12.4 million m^3, and 43.7 million m^3, accounting for 76.16%, 5.27%, and 18.57% of the total consumption, respectively. The WPLE under the ESDS are 176.5 million m^3, 10.6 million m^3, and 48.3 million m^3, accounting for 74.99%, 4.51%, and 20.50% of the total consumption, respectively. Production water consumption will significantly decrease, while living and ecology water consumption will increase during 2010–2020.

The WPLE under those three scenarios were optimally allocated based on the sustainable development of society, economy, and ecology, while the water consumption in 2010 was not based on these multiple objectives. To achieve the maximization of social, economic, and ecological benefits in the integrated water-ecosystem-economy system of Zhangye, necessary measures, i.e., adjusting agricultural and industrial structure, controlling the rapid development of population and economy, and protecting the ecological environment, need to be implemented. Under the CDS, population, agriculture, industry, and the artificial ecological areas will continue based on historical development. Water resources will be optimally allocated to production, living, and ecology for the maximal benefits of society, economy, and ecology. Thus, production water consumption needs to reduce, and living and ecology water consumption needs to increase from 2010 to 2020. Compared with the CDS, more water resources will be allocated to industry and agriculture in order to guarantee rapid development under the EPDS. To ensure enough living water consumption for growing population, ecology water consumption of the EPDS will decrease. Under the ESDS, the ecology water consumption will increase to guarantee the sustainable development of the environment, and the water consumption for economic development will be reduced compared with the CDS. In different districts of Zhangye, Ganzhou's economy is the most developed, and its water consumption is the biggest. The rapid economic development of Zhangye will aggravate the unequal distribution of water resources among counties, which is not conducive to regional sustainable development. The ESDS pays more attention to the principle of fairness in the development of the counties and adapts to the sustainable development of Zhangye. Moreover, the WPLE of ESDS takes ecological conservation as its primary objective and maintains reasonable economic development, which is more convenient to achieve the joint and harmonious development of society, economy, and ecology in integrated water-ecosystem-economy system. Thus, the water allocation of WPLE under the ESDS is the best scheme for the economic, social, and environmental multi-objective.

Due to the economic development of Zhangye City which is relatively backward in China, the overall level of social and economic could increase in short time by accelerating the economic development, but the ecological environment in Zhangye region was very fragile. Sustainable development of ecosystem is the foundation of sustainable socio-economic development. Thus, economic development should be based on the premise of healthy ecology if we are to achieve the sustainability in Zhangye. The optimal allocation of WPLE in the future year, 2020, will be achieved under conditions of maximizing ecology water consumption and the benefits of water consumption. The establishment of the optimal allocation model in WPLE is valuable to suggest certain policies that will help to promote the optimal allocation of regional water resources and improve the bearing capacity of water resources. To achieve the optimal allocation of WPLE in integrated water-ecosystem-economy system, it is necessary to protect the ecological environment, adjust agricultural and industrial structure, improve the use efficiency of both agricultural and industrial water consumption, curb agricultural oasis expansion, and develop water-saving crops in Zhangye. Through the rational allocation of WPLE, economic development can be maintained at a reasonable pace, and a more stable ecosystem will be crucial to guarantee sustainable development of both industrial and agricultural production.

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