Comprehensive assessment of urban water resources carrying capacity based on basin unit: a case study of Qingdao, China

Ling Yang and Lin Wang*
College of Environmental Science and Engineering, Ocean University of China, Qingdao, Shandong 266100, China
*Corresponding author. E-mail: lwangouc@126.com

ABSTRACT

With the quick development of social economy, the sharp contradiction between supply and demand of urban water resources is becoming much more obvious. Comprehensive assessment of urban water resources carrying capacity is of great significance to urban sustainable development planning. In this study, the urban water resources carrying capacity of Qingdao based on basin unit over 2010–2030 is predicted using analytic hierarchy process and system dynamics method. The results showed that the total water demand of all the nine basins have an upward annual trend from 2017 to 2030, among which the domestic water consumption increase obviously. The urban water resource carrying capacity indexes in all basins over 2017–2030 show a downward annual trend under the current social development model. So it is urgent to improve the water resource carrying capacity of each river basin by means of industrial structure optimization and upgrading and active development of new water sources.

Key words: analytic hierarchy process, river basin, system dynamics, water resources carrying capacity

HIGHLIGHTS

- System dynamics method and analytic hierarchy process were used to evaluate the urban water resources carrying capacity of Qingdao based on basin unit.
- The domestic water demand of all the nine basins in Qingdao increases obviously.
- The urban water resource carrying capacity index in all basins over 2017–2030 show a downward annual trend under the current social development model.

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (http://creativecommons.org/licenses/by/4.0/).
1. INTRODUCTION

Water resources are the indispensable basic resources to maintain the function of natural ecosystem and to sustain the sustainable development of local society (Walter et al. 2012). However, due to human activities, climate changes and other factors, the contradiction between supply and demand of regional water resources is sharpening, which seriously hinders the development of social economy (Cai et al. 2011a, 2011b; Safavi et al. 2016). According to statistics analysis, nearly two-thirds of China’s cities are facing the problem of water shortages and groundwater overextraction (Shang et al. 2016). Urban water resources carrying capacity (UWRCC), defined as the maximum supporting capacity of virtuous cycle of the ecosystem and social economic development of a city based on the available water resources, attracts extensive attention from the academia and relevant government departments (Song et al. 2011; Dou et al. 2015; Shi et al. 2015; Ait-Aoudia & Berezowska-Azzag 2016). Recently, there has been a lot of research on UWRCC, which mainly focused on the improvement of indicator system and model construction (Ait-Aoudia & Berezowska-Azzag 2016; Wang et al. 2017; Lu et al. 2017; Dai...
et al. 2019; Magri & Berezowska-Azzag 2019). However, little attention has been paid to the research units on UWRCC. Most studies on UWRCC take administrative unit as the research unit. Water resources is characterized by natural attributes, social attributes, overall circularity with the basin as the carrier, and externality of regional rights. Therefore the evaluation of UWRCC based on basin unit is consistent with the basic principles of sustainable development and scientific. It is urgent to evaluate UWRCC based on basin unit.

To date, there are a variety of methods to evaluate UWRCC, such as the fuzzy comprehensive evaluation method, ecological footprint method, analytic hierarchy process (Wang et al. 2013; Jia & Yu 2014; Wang et al. 2017; Chi et al. 2019). The above methods are static methods based on the optimal allocation of water resources. The impact of inputs and their changes on water supply and demand are not considered in these methods, and the dynamic feedback relationship between economic activities, population development and water resources system are also ignored (Fan 2008). The system dynamics method (SD) can simulate the behavior of complex systems dynamically using computer simulation technology. It can solve the problem that static research methods cannot reflect the change of UWRCC with time (Sun 2005; Wang et al. 2017), and the analytic hierarchy process (AHP) provides a feasible approach to accurately determine the weight of each index of UWRCC (Yang et al. 2019). Therefore, we used the AD–AHP method to integrate evaluation UWRCC of Qingdao, China.

UWRCC is an important index to measure water resources security and an important basis to explore urban water use countermeasures. This study uses a case study of Qingdao City to establish system dynamics model of UWRCC in each basin by the SD–AHP method. The aims are: (1) to calculate the UWRCC of each basin, and quantitatively evaluate the status as well as the dynamic development trend of water resources; (2) to reveal the temporal and spatial characteristics of water resources in Qingdao City, and provide effective suggestions for the rational allocation and sustainable development of water resources.

2. MATERIALS AND METHODS

2.1. Study site

Qingdao (119°30′–121°00′E, 35°35′–37°09′N) is one of the cities with severe water shortage in north China and coastal areas. According to the meteorological data of Qingdao in the last hundred years, the average annual temperature is 12.3 °C, with 220 frostless days. Annual average precipitation is 688.2 mm, and the total amount of water resources is 22.1 × 10^8 m³, 12 and 15% of the national average respectively. The average water resource per capita occupancy amount is 312.8 m³, far lower than the internationally recognized average of 500 m³ per capita.

There are 224 rivers in Qingdao, all of which are rainfall-sources. In this study, remote sensing images covering the study area were used as data sources (http://www.gscloud.cn/). Combined with the available data (water resources quantity, socioeconomic data, etc.), water system extraction and basin division were carried out in Qingdao by using ArcGIS hydrologic analysis module. The study area was divided into nine basins, including Dagu river basin (DGRB), Baima river basin (BMRB), Baisha river basin (BSRB), Beijiaolai river basin (BJLRB), Feng river basin (FRB), Moshui river basin (MSRB), Nanjiaolai river basin (NJLRB), Yang river basin (YRB) and Zhoutuan river basin (ZTRB) (Figure 1).

2.2. Methods

2.2.1. System dynamics (SD)

System dynamics (SD) is a modeling method which can perform better simulation for a multivariable system, reflecting the internal mechanism of complex systems (Che et al. 2006; Xu & Sun 2008). The SD model in essence is a system of differential equations with time delay. It is expected in dealing with nonlinear, high-order, multi-variable, multi-feedback and complex time-varying phenomena, and can quantitatively analyze the internal relationship between the structure and function of various complex systems.

2.2.2. Analytic hierarchy process (AHP)

In this study, AHP is used to determine the weights of different indexes on UWRCC. The key steps of AHP are as follows (Fan et al. 2000; Wen et al. 2000; Ouma & Tateishi 2014):

1. Select relevant factors and determine their hierarchy. According to the dominant relationship, the factors are divided into object hierarchy, rule hierarchy, and index hierarchy.
2. Compare these factors and determine their comparative significance. The pairwise comparison judgment matrices are constructed according to the 1–9 scale for the degree of importance, and the corresponding grade is determined (Table 1).
**Figure 1** | Distribution of river basins in Qingdao.

**Table 1** | Scale of preference between two elements

| Numerical scale | Definition                                                   |
|-----------------|--------------------------------------------------------------|
| 1               | Equal significance between the two elements                 |
| 3               | Slight significance of one element compared to the other     |
| 5               | Strong significance of one element compared to the other     |
| 7               | Dominance of one element over the other                      |
| 9               | Absolute dominance of one element over the other             |
(3) Check the consistency of the matrices. The formulas are as follows:

\[ CR = CI / RI \]  
\[ CI = (\lambda_{\text{max}} - n) / (n - 1) \]  

\( \lambda_{\text{max}} \) is the maximum eigenvalue of different matrices; \( CI \) is the consistency indicators; \( RI \) is random consistency index, which can be acquired from Table 2; \( CR \) is the checkout ratio. When \( CR \) is <0.1, it indicates that the judgment matrix meets the consistency requirement (Chakraborty & Banik 2006).

2.2.3. Calculation of UWRCC index

Making standardized treatment for the original data of various influencing factors by using the extreme standard method. Then all indexes are weighted and summed to calculate the UWRCC of each basin. Referring to existing literatures (Lu et al. 2017; Yang et al. 2019), the UWRCC index is divided into five categories (0.8–1.0, excellent; 0.6–0.8, positive; 0.4–0.6, normal; 0.2–0.4, poor; 0–0.2, weak.). The formulas are as follows (Lu et al. 2017):

\[ x_{ij}' = \frac{x_{ij} - \min \{x_{ij}\}}{\max \{x_{ij}\} - \min \{x_{ij}\}}; i = 1,2,\ldots,n, j = 1,2,\ldots,m \]  
\[ x_{ij}'' = \frac{\max \{x_{ij}\} - x_{ij}}{\max \{x_{ij}\} - \min \{x_{ij}\}}; i = 1,2,\ldots,n, j = 1,2,\ldots,m \]  
\[ R_j = \sum_{i=1}^{n} U_i x_{ij}' \]  

where \( x_{ij}, x_{ij}' \) represent the simulated value and the standard value of index \( j \) in the year \( i \) evaluation year, respectively; \( m \) and \( n \) are respectively the number of indicators and the number of evaluation years. In this study, the value of \( m \) and \( n \) is 13, 20. \( U_i \) is the weight value of each index, \( R_j \) is the UWRCC index, less than or close to 1.

2.2.4. Data sources

Combining the distribution map of river basins in Qingdao (Figure 1) with the Qingdao administrative map, the towns in each river basin were divided. If the town crosses two river basin, it was divided into the river basin where the town center is located. Then the relevant socio-economic data of each basin were obtained by integrating and analyzing the statistical data of each town in the Statistical Yearbook (2010–2018) of 10 districts. And there were also some data available from the official website of each district of Qingdao.

The hydrological data of each basin mainly were derived from Qingdao Water Resources Bulletin (2010–2018). Some important indexes and sources are listed in Table 3.

### 3. EVALUATION INDEX SYSTEM AND SD MODEL OF UWRCC

#### 3.1. Evaluation index system

The water resource system is a complex system, which is closely related to population, economy and society (Wang et al. 2005; Feng et al. 2006). By referring to the existing literatures and considering the actual water resources situation in each basin of Qingdao as well as the availability of data, the evaluation index system was divided into four subsystems, i.e. water resources subsystem (B1), social subsystem (B2), economic subsystem (B3) and ecological environment subsystem (B4) (Yang et al. 2010) (Table 4). The water resource subsystem (B1) included total available water resource (C1), the difference between supply and demand (C2), and sewage return rate (C3). Social subsystem (B2) included total population (C4),

### Table 2 | Random consistency index (RI)

| n  | 1  | 2  | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI | 0  | 0  | 0.58| 0.9 | 1.12| 1.24| 1.32| 1.41| 1.45| 1.49|
urbanization rate (C5), irrigated area (C6), urban domestic water quota (C7) and rural domestic water quota (C8). Economic subsystem (B3) included industrial production (C9) and water consumption per 10,000 RMB of industrial production (C10). Ecological environment subsystem (B4) included green area (C11), road land (C12) and treatment rate of sewage (C13).

### 3.2. SD model of UWRCC

The SD model was used to simulate the dynamic change of water resource system of each basin in Qingdao over 2011–2030. The SD model boundary of each basin was the boundary of each basin. The time boundary was from 2011 to 2030, and the simulation step length was one year with 2011 as the base year. Vensim-PLE software was used to establish the flow diagram of the UWRCC system of each basin (Figure 2).

The system flow diagram only showed the logical relationship between the system structure and variables, not the quantitative relationship between different variables. In order to show the quantitative relationship among variables, it was necessary to analyze the logical relationship among the variables of each subsystem. Function and constant were used to construct state variable equation, rate equation and auxiliary equation. The main function (in Vensim language) is summarized in Table A.1 in the appendix.

### 3.3. Error test of the SD model

In this study, total population, industrial production, irrigated area, road land, and green area were selected for the error test of the model. The observed values of the above five indexes can be directly obtained, rather than calculated, and the weighted values of total population and industrial production on UWRCC were high (Table 4). The weighted values of irrigated area, road land, and green area on UWRCC were not high, but these three indexes are decisive factors in the model (Wu et al. 2013). The observed values and simulated values of these five indexes (a total of 650 samples) from 2011 to 2017 were used to test the model accuracy.
Statistical parameters of correlation coefficient ($R^2$), Nash-Sutcliffe efficiency (NSE), and Mean Absolute Relative Error (MARE) were used to evaluate the simulation ability of model. The ideal value of $R^2$ and MARE is 1 and 0, respectively. When NSE is $>0.75$, the simulation effect can be considered good; when $0.36 < \text{NSE} < 0.7$, the simulation effect is satisfactory; when NSE is $<0.36$, the simulation effect is not good.

$$R^2 = \left( \frac{\sum_{i=1}^{n} (Q_{Si} - \bar{Q}_s)(Q_{Oi} - \bar{Q}_o)}{\sqrt{\sum_{i=1}^{n} (Q_{Si} - \bar{Q}_s)^2 \sum (Q_{Oi} - \bar{Q}_o)^2}} \right)^2$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n} (Q_{oi} - Q_{si})^2}{\sum_{i=1}^{n} (Q_{Oi} - \bar{Q}_o)^2}$$

$$\text{MARE} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{Q_{Si} - Q_{Oi}}{Q_{Oi}} \right| \times 100\%$$

$Q_{Si}, Q_{Oi}$ are the simulated and observed value of the index $i$, respectively. $\bar{Q}_s, \bar{Q}_o$ are the mean of the simulated and observed value of the index $i$, respectively.

The results of error test of SD are shown in Table 5. The mean of $R^2$ was 0.8495. Except for $R^2$ of industrial production in BSRB (0.2902), irrigated area in DGRB (0.0451), and green area in DGRB (0.3682), the $R^2$ of other indexes were greater than 0.6. The mean of NSE was 0.70019. Except for NSE of industrial production in BSRB (0.0405), total population in DGRB...
(−0.02), irrigated area in DGRB (−0.5895), green area in DGRB (0.2642), and irrigated area in ZTRB (−0.3647), the NSE of other indexes were greater than 0.44. MARE of each index in the model were no more than 10%. Therefore the simulation results were in good agreement with the actual values, indicating that the model reflected the reality relationship between water resources and social-economic systems in each river basin.
4. RESULTS AND DISCUSSION

4.1. Water demand in each basin

Industrial water demand is mainly restricted by industrial output value, product structure, industrial water price, and water-saving rate (Lei & Li 2015). The industrial water demand of each basin over 2017–2030 is predicted in the order of DGRB > MSRB > NJLRB > YRB > FRB > BJLRB > BSRB > BMRB > ZTRB (Figure 3(a)). The industrial water demand of DGRB was the largest in 2017, at $0.25257 \times 10^8$ m$^3$. The industrial water demand of ZTRB is predicted to be $0.02017 \times 10^8$ m$^3$ by 2024, which is the smallest among all basins. The industrial water demand of MSRB, NJLRB, YRB, FRB, BJLRB and ZTRB both show an upward annual trend, while the industrial water demand of DGRB, BSRB and BMRB show a downward annual trend.

Agricultural water demand is mainly affected by irrigated area and irrigation quota (Wu et al. 2018). As shown in Figure 3(b), the agricultural water demand of each basin is predicted in the order of BJLRB > DGRB > NJLRB > YRB > MSRB > BMRB > ZTRB > FRB > BSRB. The agricultural water demand of BJLRB is predicted to rise to $0.905 \times 10^8$ m$^3$ by 2030, which is the largest one among all basins. This is mainly because BJLRB is widely surrounded by an agricultural zone area and the agricultural water demand is extremely large (Li et al. 2017). The agricultural water demand of ZTRB is predicted to be $0.3268 \times 10^8$ m$^3$ by 2030, which is the smallest among all basins. This is mainly related to the small agricultural planting area in ZTRB. The agricultural water demand of each basin over 2017–2030 has little change trend and basically presents a stable state. The reason is that the irrigated area of each basin increases year by year with the

Figure 3 | Simulated development trends for: (a) industrial water demand, (b) Agricultural water demand, (c) Domestic water demand and (d) Urban ecological water demand.
improvement of economy, but the irrigation quota is gradually reduced considering the influence of tillage technology, irrigation technology and variety improvement (Yang et al. 2016; Wu et al. 2018).

Total domestic water demand is the sum of the domestic water demand of urban residents and rural residents. Domestic water demand is mainly determined by the number of residents and domestic water quota. As the domestic water quota of urban and rural residents is different, the domestic water demand of each need to be calculated separately (Yang et al. 2019). As shown in Figure 3(c), the domestic water demand of each basin is predicted in the order of DGRB > MSRB > BJLRB > NJLRB > YRB > BMRB > FRB > BSRB > ZTRB. The total domestic water demand in MSRB and BJLRB over 2017–2030 will increase significantly. The county-level Jimo City, where MSRB is located, was adjusted to Jimo District in 2017. Therefore, the urban population of MSRB increased greatly, resulting in a significant increase in domestic water demand of this basin. The main reason for the substantial increase of domestic water demand in BJLRB is that the government has taken a series of measures such as a surface water retention project, water plant expansion and rural tap water construction (Sun et al. 2014). The total domestic water demand in other basins over 2017–2030 will increase slowly. The reason is that the domestic water demand will increase correspondingly with the development of urbanization and the continuous improvement of people’s living quality in the future. However, with the continuous enhancement of people’s awareness of water conservation and the effective reuse of water resources, the domestic water demand will not increase too much (Song et al. 2018).

With the development of social economy, urban ecological water demand becomes more and more important and cannot be ignored. In this study, urban ecological water demand is the sum of road sprinkler water demand and green area water demand, which is mainly affected by road area, green area and water quota (Altunkaynak et al. 2005; Wei et al. 2015). As shown in Figure 3(d), the urban ecological water demand of each basin is predicted in the order of DGRB > FRB > NJLRB > BSRB > MSRB > BJLRB > BMRB > YRB > ZTRB. The urban ecological water demand of each basin over 2017–2030 shows an upward annual trend. This is because of the increasing green area and road area and the ecological environmental water demand of each basin.

Total water demand is the sum of industrial water demand, domestic water demand, agricultural water demand and urban ecological water demand. The total water demand of all basin shows an upward annual trend. Industrial water demand shows a declining annual trend, but domestic water demand increases significantly, while agricultural water demand and urban ecological water demand slowly rise. The proportion of domestic water demand in total water consumption is increasing in the future.

4.2. Total water supply in each basin

In this study, the total water supply in each basin mainly includes the total available surface water resources, total available ground water resources and volume of water recycled. As shown in Figure 4, the total water supply of each river basin was small (3.8579 × 10^8 m^3) in 2015. The reason is that the precipitation in Qingdao was relatively low which resulted in extreme drought in 2015. The total water supply of each basin over 2017–2030 is predicted in the order of DGRB > FRB > NJLRB > BSRB > MSRB > BJLRB > BMRB > YRB > ZTRB. The overall trend of regional distribution of water supply in all basins shows a decrease from the southeast coast to the northwest inland region, which is basically consistent with the spatial distribution of precipitation in Qingdao over the years. The supply source of river runoff is mainly atmospheric precipitation in Qingdao and the amount of precipitation determines the change of water resources. The spatial and temporal distribution of precipitation and the difference in precipitation process can lead to the changes of water resources. Therefore, the overall trend of annual runoff regional distribution is basically consistent with precipitation.

4.3. Comparative analysis of UWRCC index in each basin

The UWRCC index of each basin was low in 2015 (Figure 5). It can be seen from the above analysis that there was little precipitation in Qingdao in 2015, the water supply in each basin was significantly less than the demand, and the contradiction between water supply and demand was obvious. The UWRCC indexes in all basins show a downward annual trend over 2017–2030. It means that the contradiction between water supply and demand will continue to worsen with the current social development trend. So the current development model can no longer meet the needs of sustainable socio-economic and water resources development of each basin in Qingdao.

As shown in Figure 5, the UWRCC indexes over 2017–2030 of FRB and BSRB remain in a normal state; the UWRCC indexes of MSRB and ZTRB are positive to normal to poor; the UWRCC indexes of BMRB, DGRB, YRB and NJLRB are normal to poor; and the UWRCC index of BJLRB is always poor. Overall, the UWRCC indexes of the southeast coast are higher than that of the northwest inland region. Precipitation and the level of economic development are also important
Figure 4 | Total water supply of each basin.

Figure 5 | UWRCC index of each basin.
factors influencing the development potential of UWRCC. Precipitation affects the water supply in each basin. The level of water resources utilization, sewage treatment capacity and recycling rate of reclaimed water are closely related to economic development (Cai et al. 2016).

In order to improve the UWRCC in Qingdao, the following suggestions are proposed: (1) Industrial structure optimization and upgrading. At present, agricultural water consumption and domestic water consumption account for a high proportion of water resource utilization in all river basins. Popularizing new water-saving irrigation technology and advocating the use of water-saving appliances are feasible ways to reduce urban water consumption; (2) Actively develop new water sources. As a coastal city, Qingdao can give full play to its advantages of being close to the ocean and expand the use of seawater.

5. CONCLUSION

In this study, Qingdao was divided into nine river basins according to the situation of water system. The UWRCC indexes of all basin were calculated and analyzed using the SD-AHP method. The results indicated that the total water demand of all basins show an upward annual trend over 2017–2030. Especially, the domestic water consumption show an obvious increasing trend. The total water supply in all basins, except BSRB, are on the rise. The regional distribution trend of water supply in all basins show a decrease from the southeast coast to the northwest inland region, which is basically consistent with the spatial distribution of precipitation in Qingdao over the years, and the UWRCC indexes in all basins will decline over 2017–2030. The contradiction between water supply and demand will continue worsening, which indicates that the current social development model can no longer meet the requirements of sustainable development of water resources in Qingdao. The UWRCC indexes of all basins can be improved through industrial structure optimization and upgrading and active development of new water sources in Qingdao.

ACKNOWLEDGEMENT

This work was supported by the National Key Research and Development Program of China (NO.2018YFC0408000, 2018YFC0408004).

DATA AVAILABILITY STATEMENT

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

REFERENCES

Ait-Aoudia, M. N. & Berezowska-Azzag, E. 2016 Water resources carrying capacity assessment: the case of Algeria’s capital city. Habitat Int. 58, 51–58.
Altunkaynak, A., Özger, M. & Çakmakci, M. 2005 Water consumption prediction of Istanbul city by using fuzzy logic approach. Water Resour. Manag. 19, 641–654.
Cai, Y. P., Huang, G. H., Tan, Q. & Liu, L. 2011a An integrated approach for climate-change impact analysis and adaptation planning under multi-level uncertainties. Part II. Case study. Renew. Sustain. Energy Rev. 15, 3051–3073.
Cai, Y. P., Huang, G. H., Wang, X., Li, G. C. & Tan, Q. 2011b An inexact programming approach for supporting ecologically sustainable water supply with the consideration of uncertain water demand by ecosystems. Stoch. Environ. Res. Risk Assess. 25, 721–735.
Cai, J., Varis, O. & Yin, H. 2016 China’s water resources vulnerability: a spatio-temporal analysis during 2003–2013. J. Clean. Prod. 142 (4), 2901–2910.
Chakraborty, S. & Banik, D. 2006 Design of a material handling equipment selection model using analytic hierarchy process. Int. J. Adv. Manuf. Technol. 28, 1237–1245.
Che, Y., Zhang, M. C. & Yang, K. 2006 Evaluation and predication of water resources carrying capacity based on SD model: a case study of Chongming Island. J. East China Norm. Univ. (Nat. Sci.) 6, 73–80 (in Chinese).
Chi, M., Zhang, D. S., Fan, G. W., Zhang, W. & Liu, H. L. 2019 Prediction of water resource carrying capacity by the analytic hierarchy process-fuzzy discrimination method in a mining area. Ecol. Indic. 96, 647–655.
Dai, D., Sun, M. D., Xu, X. Q. & Lei, K. 2019 Assessment of the water resource carrying capacity based on the ecological footprint: a case study in Zhangjiakou City, North China. Environ. Sci. Pollut. Res. 26, 11000–11011.
Dou, M., Ma, J. X., Li, G. Q. & Zuo, Q. T. 2015 Measurement and assessment of water resources carrying capacity in Henan Province, China. Water Sci. Eng. 8 (2), 102–113.
Fan, J. 2008 Study on Regional Comprehensive Planning of Beijing-Tianjin-Hebei Metropolitan Area. Science Press, China (in Chinese).
Fan, Y., Luo, Y. & Chen, Q. 2000 Investigation on quantity method in vulnerability evaluation indexes of bearing disaster objects. J. Disaster Sci. 15, 78–81.
Feng, H. Y., Zhang, X., Li, G. Y., Mu, N. J. & Chen, J. 2006 A system dynamic model and simulation for water resources carrying capacity in Beijing. *J. China Agric. Univ.* 11 (6), 106–110 (in Chinese).

Jia, H. H. & Yu, G. M. 2014 Assessing the carrying capacity of water resources in Wuhan City, China. *Adv. Mater. Res.* 905, 357–361.

Lei, Y. T. & Li, R. F. 2015 Study on the dynamic long-term interaction-mechanism of Chinese industry water consumption and influencing factors. *China Popul. Resour. Environ.* 25 (2), 1–8 (in Chinese).

Li, Y. C., Li, H. P., Wang, Y. X., Sun, Y. P., Wang, K. R. & Yang, Q. X. 2017 Pollution status and control countermeasures of polyethylene mulch film residue in farmland soils of Qingdao City, China. *J. Agric. Res. Environ.* 34 (3), 226–233 (in Chinese).

Lu, Y., Xu, H. W., Wang, Y. X. & Yang, Y. 2017 Evaluation of water environmental carrying capacity of city in Huaihe River Basin based on the AHP method: a case in Huai’an City. *Water Res. Ind.* 18, 71–77.

Magri, A. & Berezowska-Azzag, E. 2019 New tool for assessing urban water carrying capacity (WCC) in the planning of development programs in the region of Oran, Algeria. *Sust. Cities Soc.* 48, 101316.

Ouma, Y. O. & Tateishi, R. 2014 Urban flood vulnerability and risk mapping using integrated multi-parametric AHP and GIS: methodological overview and case study assessment. *Water* 6, 1515–1545.

Safavi, H. R., Mehrparvar, M. & Szidarovszky, F. 2016 Conjunctive management of surface and ground water resources using conflict resolution approach. *J. Irrig. Drain. Eng.* 142, 05016001.

Shang, Y., You, B. & Shang, L. 2016 China's environmental strategy towards reducing deep groundwater exploitation. *Environ. Earth Sci.* 75 (22), 1439.

Shi, M., Zhang, Z. & Zhou, D. 2015 *Studies on Carrying Capacity of Water Resources in Beijing and Tianjin: Based on the Water Footprint.* Report on Development of Beijing, Tianjin, Hebei Province. Springer, Berlin Heidelberg.

Song, X. M., Kong, F. Z. & Zhan, C. S. 2011 Assessment of water resources carrying capacity in Tianjin City of China. *Water Resour. Manag.* 25 (3), 857–873.

Song, M. L., Wang, R. & Zeng, X. Q. 2018 Water resources utilization efficiency and influence factors under environmental restrictions. *J. Clean. Prod.* 184, 611–621.

Sun, Z. F. 2005 Application of system dynamics to water resources management. *Water Resour. Hydropower Eng.* 6, 14–16 (in Chinese).

Sun, H. H., Ma, S., Sun, Q. S. & Liang, C. H. 2014 Investigation and consideration on rural drinking water safety in Pingdu City. *City Town Water Supply* 03, 91–92.

Walter, A., Cadenhead, N., Lee, V. S. W., Dove, C., Milley, E. & Elgar, M. A. 2012 Water as an essential resource: orb web spiders cannot balance their water budget by prey alone. *Ethology* 118, 534–542.

Wang, W., Lei, X. D., Yu, X. X. & Chen, L. H. 2005 Study on the region carrying capacity of water resources based on system dynamics (SD) model. *J. Water Res. Water Eng.* 16 (3), 11–15 (in Chinese).

Wang, S., Yang, F. L., Xu, L. & Du, J. 2013 Multi-scale analysis of the water resources carrying capacity of the Liaohe Basin based on ecological footprints. *J. Clean. Prod.* 33, 158–166.

Wang, C. H., Hou, Y. & Xue, Y. 2017 Water resources carrying capacity of wetlands in Beijing: analysis of policy optimization for urban wetland water resources management. *J. Clean. Prod.* 161, 1180–1191, S0959652617306716.

Wei, S., Yang, H., Song, J., Abbaspour, K. C. & Xu, Z. 2015 System dynamics simulation model for assessing socio-economic impacts of different levels of environmental flow allocation in the Weihe River Basin, China. *Eur. J. Oper. Res.* 221, 248–262.

Wen, S., Ma, Z. Q., Zhou, Z. H. & Ma, Y. J. 2000 The application of analytic hierarchy process method on assessment of sustainable development of regional lake water resources. *Resour. Environ. Yangtze Basin* 9, 196–201.

Wu, G. Y., Li, L. H., Ahmad, S., Chen, X. & Pan, X. L. 2013 A dynamic model for vulnerability assessment of regional water resources in arid areas: a case study of Bayingolin, China. *Water Resour. Manage.* 27, 3083–3101.

Wu, L., Su, X. L., Ma, X. Y., Kang, Y. & Jiang, Y. N. 2018 Integrated modeling framework for evaluating and predicting the water resources carrying capacity in a continental river basin of Northwest China. *J. Clean. Prod.* 204, 366–379.

Xu, Y. & Sun, C. Z. 2008 Simulation of water resources carrying capacity based on a system dynamic model in Dalian. *J. Saf. Environ.* 6, 73–76 (in Chinese).

Yang, Q. N., Sun, X. H., Zhang, J. & Wang, Y. P. 2010 Simulation of carrying capacity of water resources in Jinan City based on system dynamics model. *J. Econ. Water Res.* 28 (2), 16–20 (in Chinese).

Yang, X. X., Guo, P. & Li, M. 2016 A fuzzy multi-objective optimal allocation model of water resource oriented ecology in the middle reaches of Heihe River. *Water Sav. Irrigat.* 5, 65–70.

Yang, Z. Y., Song, J. X., Chen, D. D., Xia, J., Li, Q. & Ahamad, M. I. 2019 Comprehensive evaluation and scenario simulation for the water resources carrying capacity in Xi’an city, China. *J. Environ. Manage.* 230, 221–235.

First received 26 January 2021; accepted in revised form 28 September 2021. Available online 11 October 2021