

Water Supply-Demand Situation Analysis Based on a Hierarchical Index System

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Abstract

In this study, a hierarchical index system is proposed for analysis of water supply-demand situation, which can overcome the shortcomings of complicated analysis and ambiguous decision, associated with the use of a single index like water shortage or water shortage ratio. Five indices responsible for water supply-demand imbalance are considered on both water resources supply and demand sides, and corresponding regulation strategies are proposed to restore water supply-demand balance by improving the water supply capacity of conventional and non-conventional water resources, improving water-use efficiency, and controlling the social and economic development scale. The proposed hierarchical index system has been successfully applied to the analysis of the water supply-demand situation in Qingdao. The results reveal that in order to improve the severe water supply-demand situation in Qingdao, it is necessary to divert water from other regions and improve agricultural water-use efficiency. This study may provide insights into the design and preparation of inter-basin or cross-regional water diversion projects and the formulation of annual water diversion plans.

1. Introduction

The gap between the uneven spatial and temporal distribution of water resources and the water demand from different sectors makes water supply a challenging task, and it is estimated that over one billion people in the world have no or limited access to safe drinking water (WHO, 2017). Worse still, climate change is exacerbating the severity of water supply-demand imbalance (Distefano and Kelly, 2017). A notable example is the so-called “Day Zero” experienced by the city of Cape Town in South Africa in June 2018, in which the city almost ran out of water due to a severe multi-year drought. In July 2019, Chennai, the capital city of Tamil Nadu in southern India, also faced an unprecedented water crisis due to monsoon failure (Ahmadi et al. 2020). Water resources allocation is expected to be a promising strategy to ensure water supply security, and the analysis of water supply-demand situation is the basic support of water resources macro-allocation. It should also be noted that the water supply-demand situation is likely to change with the advent of new policies and technologies (Schütze et al. 2019). In China, the actual water consumption described in China Water Resources Bulletin (Ministry of Water Resources of the People’s Republic of China, 2010-2020) is more than 10% lower than the forecasted water demand described in National Integrated Water Resources Plan (Ministry of Water Resources of the People’s Republic of China, 2010) in most basins and regions, and ecological water demand is also not taken into consideration in previous plans.

A common way for analysis of water supply-demand situation is to predict water demand and supply separately and then take the difference between them as the index of water shortage or water shortage ratio. Note that the prediction of water supply is often based on the available water supply for the basin or region of interest under the constraints of water diversion projects (Lv et al. 2016; McDonald et al. 2014); while that of water demand is mainly based on the quotas that are officially released such as social and economic development indices, standards and specifications. Because of this, there are several issues that need to be addressed: (1) the general neglect of ecological issues may lead to less or

even no availability of water to be supplied for ecological purposes in the prediction of water supply (Paul and Elango, 2018); (2) the prediction of water demand based on various social and economic indices is highly subjective in nature that is mostly determined by basin or regional planning rather than by actual situation (Saleem et al. 2021); (3) the use of water quotas from current standards or specifications does not take into account the improvement of water-use efficiency in the future (Ray and Shaw, 2016); (4) the prediction of water demand is often complicated considering the complex classification of water users, quality and quantity of data required, and choice of appropriate analysis method (Qin et al. 2018); (5) the use of a single index like water shortage or water shortage ratio makes it difficult to answer some questions that are more interesting to the authorities, such as the main causes of water shortage, satisfaction degree of rigid water demand, and exploration degree of water supply potential (Distefano and Kelly, 2017; Höllermann et al. 2010). In short, it remains difficult to match the scale, layout, structure and speed of social and economic development and water-use efficiency to the availability of water resources, and as a consequence the water demand that is closely associated with population, industrial layout, land and other resources in a given region is very likely to exceed or fall short of the supply capacity of water sources.

In this study, a hierarchical index system is proposed for analysis of water supply-demand situation considering the determinant factors on both supply (e.g., water sources and water supply potential) and demand (e.g., water users and water-use efficiency) sides from a macro perspective, based on which the causes of water shortage and corresponding regulation strategies could be determined. Thus, the results of this study may provide some insights into the design and preparation of inter-basin or cross-regional water diversion projects and the formulation of annual water diversion plans.

2. Methodology

In this study, the term water supply potential refers to the available water supply of conventional or non-conventional water sources on the premise that the basic ecological water demand is satisfied (You et al. 2020); and the term rigid water demand refers to the quantity of water required to ensure human survival, social stability and attainment of national strategic goals on the premise that the water-use efficiency can satisfy the water-saving requirement (Wang et al. 2020).

2.1 Development of the hierarchical index system

The water supply-demand situation is the result of numerous factors on both supply (e.g., water sources and water supply potential) and demand (e.g., water users and water-use efficiency) sides. A hierarchical index system is proposed in order to identify the determinant factors affecting water supply-demand imbalance and subsequently to develop regulation strategies that can restore water supply-demand balance. In order to achieve this objective, all possible factors on both supply and demand sides should be taken into consideration. Finally, four possible regulation strategies are proposed: improving the water supply capacity of conventional water sources, improving the water supply capacity of non-conventional water sources, improving the water-use efficiency (Hurlimann and Wilson, 2018), and controlling the

social and economic development scale (Veerbeek, 2017). The hierarchical index system and representative indices are shown in Fig. 1.

2.1.1 Indices on the level of regulation direction

The indices on the level of regulation direction are used to determine from which side, the supply side or the demand side, the determinant factors responsible for water supply-demand imbalance might originate. Here, the water supply capacity of water sources (index A) is taken as the index on the supply side; while the proportion of rigid water demand (index B) is taken as the index on the demand side:

$$A = (AWS_c + AWS_{uc}) / (P_c + P_{uc}) \quad (1)$$

$$B = WD_r / WD_t \quad (2)$$

where AWS_c and AWS_{uc} are the available water supply of conventional and non-conventional water sources, $10^4 m^3$, respectively, both of which are dependent on the design capacity of the water diversion project. However, it should be noted that the water supply capacity may decline over time because of infrastructure aging or disrepair; P_c is the potential for conventional water development, $10^4 m^3$; P_{uc} is the potential for unconventional water development, $10^4 m^3$; WD_r is the rigid water demand, $10^4 m^3$; and WD_t is the total water demand for domestic, industrial and ecological uses, $10^4 m^3$.

2.1.2 Indices on the level of regulation strategy

The indices on the level of regulation strategy are used to determine the constraints of water shortage on the supply and demand sides in order to provide more appropriate regulation strategies to restore water supply-demand balance. The strategies on the supply side are intended to improve the water supply capacity of conventional (index A1) or non-conventional (index A2) water sources:

$$A1 = AWS_c / P_c \quad (3)$$

$$A2 = AWS_{uc} / P_{uc} \quad (4)$$

The strategies on the demand side are intended to improve the water-use efficiency in different sectors and control the social and economic development scale. Whether the industrial and agricultural water-use efficiency should be improved is determined by the decreasing rate of water consumption for industrial value added per ten thousand RMB (index B1) and that for irrigation per hectare (index B2), respectively:

$$B1 = (WC_{i-p} - WC_{i-f}) / WC_{i-p} \quad (5)$$

$$B2 = (WC_{a-p} - WC_{a-f}) / WC_{a-p} \quad (6)$$

where WC_{i-p} and WC_{i-f} are the water consumption for industrial value added per ten thousand RMB in the present and planning year, $m^3/10^4$ RMB, respectively; WC_{a-p} and WC_{a-f} are the water consumption for

irrigation per hectare in the present and planning year, m³/ha, respectively.

In addition, whether there is a need to control the social and economic development scale and whether the condition is mature can be determined depending on the circumstances.

2.2 Evaluation of the hierarchical index system

2.2.1 Evaluation of indices on the level of regulation direction

By comparing the values of indices A and B, the regulation direction of water supply-demand situation can be determined. The indices evaluation results are divided into four regions as shown in Fig. 2, and the regulation directions represented by the specific evaluation results are shown in Table 1.

Table 1 Regulation directions represented by the indices evaluation results

Regions	Value of indices	Evaluation results		Regulation directions			
		Water supply potential	Rigid water demand	Supply side		Demand side	
				Improve the water supply capacity	Develop the water transfer project	Improve the water-use efficiency	Control the social and economic development scale
I	$0 \leq A < 0.5$ $\leq B \leq 1$	high	high	√		√	
II	$0 \leq A, B < 0.5$	high	low	√			√
III	$0 \leq B < 0.5$ $\leq A \leq 1$	low	low				√
IV	$0.5 \leq A, B \leq 1$	low	high		√	√	

2.2.2 Evaluation of indices on the level of regulation strategy

According to the indices evaluation partition results, the regulation strategies on both supply and demand sides are calculated and evaluated in four scenarios.

Scenario 1

If the values of indices A and B fall in region I in Fig. 2, there is a need to improve the water supply capacity on the supply side and improve the water-use efficiency on the demand side according to the regulation direction described in Table 1. In this case, the indices A1 and A2 on the supply side are calculated and compared to determine the water supply potential of conventional and non-conventional

water sources. The indices evaluation results are divided into three regions as shown in Fig. 3, and the regulation strategies represented by the specific evaluation results are shown in Table 2. Also, the indices B1 and B2 on the demand side are calculated and compared to determine the industrial and agricultural water-use efficiency. The regulation strategies represented by the specific evaluation results side are shown in Table 3.

Table 2 Regulation strategies represented by the indices evaluation results (supply side)

Regions	Value of indices	Evaluation results		Regulation strategies	
		Water supply potential of conventional water sources	Water supply potential of non-conventional water sources	Exploit water supply potential of conventional water sources	Exploit water supply potential of non-conventional water sources
a	$0 \leq A1 \setminus A2 \leq 0.5$	low	low	√	√
b	$0 \leq A2 < 0.5 \leq A1 \leq 1$	high	low		√
c	$0 \leq A1 < 0.5 \leq A2 \leq 1$	low	high	√	

Table 3 Regulation strategies represented by the indices evaluation results (demand side)

Value of indices	Evaluation results		Regulation strategies	
	Industrial water-use efficiency	Agricultural water-use efficiency	Improve the industrial water-use efficiency	Improve the agricultural water-use efficiency
$B1 < B2$	low	high	√	
$B2 < B1$	high	low		√

Scenario 2

If the values of indices A and B fall in region Ⅱ in Fig. 2, there is a need to improve the water supply capacity on the supply side and control the social and economic development scale on the demand side. In this case, the evaluation results and the regulation strategies on the supply side can refer to Fig. 3 and Table 2, respectively. On the demand side, some regulation strategies should be taken to reduce water consumption, such as reducing the population, optimizing the scale of economic development and adjusting the industrial structure.

Scenario 3

If the values of indices A and B fall in region Ⅲ in Fig. 2, there is a need to control the social and economic development scale on the demand side. In this case, the evaluation results and the regulation strategies can refer to Scenario 2.

Scenario 4

If the values of indices A and B fall in region \square in Fig. 2, there is a need to develop the water transfer project on the supply side and improve the water-use efficiency on the demand side. In this case, the evaluation results and the regulation strategies on the demand side can refer to Table 3. On the supply side, the potential sources of water transfer project should be actively sought to enhance water supply capacity.

3. Case Study

3.1 Study Area

Qingdao is located in the southeastern of Shandong Peninsula and borders the Yellow Sea (E 119°30'–121°00', N 35°35'–37°09'). The geographic location is shown in Fig. 4. Now Qingdao has a total population of over 10 million and a total area of 11282 km². Qingdao is an economically important city and it is well known as an important coastal open city in North China, one of the five cities that are specifically designated in the state plan, the leading city of the Blue Economic Zone of Shandong Peninsula. Thus, there is an increasing demand for water resources in order to maintain the rapid social and economic development of Qingdao.

However, the spatial and temporal distribution of precipitation in Qingdao is rather uneven with significant intra- and inter-annual variability, and it is also prone to drought and flooding. The rivers in Qingdao generally have short courses with no tributaries and flow rapidly and directly into the sea. The average annual precipitation is 679.43 mm, the average annual amount of water resources is 2.148 billion m³, and the amount per capita is 231 m³, accounting for only 11% of the national average and 73% of the provincial average of Shandong Province. As a city with limited water resources, Qingdao is facing increasing pressure on water supply security. It is necessary to develop new techniques for analysis of water supply-demand situation based on new ideas and situations, which can improve the utilization of water resources and the high-quality social and economic development of Qingdao. Hence, the water supply-demand situations of Qingdao in 2020 (current year), 2025 (short-term), and 2035 (long-term) are analyzed.

3.2 Data

The social and economic data in 2020 are obtained from the Statistical Yearbook of Qingdao 2021, the Statistical Bulletin of the Economic and Social Development of Qingdao 2020 and the data of water resources are obtained from the Statistical Bulletin of the Water Resources of Qingdao 2020.

Given the large inter-annual variation of water resources in Qingdao, the inflow and water demand in extremely dry years are analyzed in order to ensure high water supply security. The basic indices include AWS_C , AWS_{UC} , P_C , P_{UC} on the supply side, and WD_r , WD_t on the demand side. The calculation results are shown in Table 4.

Table 4

Basic indices calculation results of Qingdao (billion m³)

Year	Supply side				Demand side	
	AWS _c	AWS _{uc}	P _c	P _{uc}	WD _r	WD _t
2020	1.189	0.144	1.794	0.144	1.063	1.378
2025	1.240	0.315	1.260	0.315	1.102	1.460
2035	1.257	0.552	1.257	0.552	1.333	1.985

4. Results And Discussion

4.1 Determination of regulation direction

Figure 5 reveals that the values of indices A and B fall in region II . The values of index A in 2020, 2025 and 2035 are in the range of 0.5~1, indicating that the exploitation potential of water resources is low at present and in the future for Qingdao. On the supply side, it is almost impossible to further increase the supply potential of local water sources, and thus a more feasible option is to divert water from other regions. The values of index B are also in the range of 0.5~1, indicating high rigid water demand of Qingdao at present and in the future. On the demand side, it is impossible to decrease the water demand by controlling the social and economic development scale, and thus effort should be made to improve the water-use efficiency.

The inter-annual variation trends of indices A and B are shown in Fig. 6. The increasing trend of index A implies that the water supply of conventional and non-conventional water sources is approaching the maximum capacity, and this will lead to an increase in the utilization rate but a decrease in the supply potential of local water sources. Once the utilization rate reaches the upper limit in the future, there would be no way to further increase the water supply if no new water diversion projects are built. However, the index B shows a decreasing trend, indicating a decrease in the percentage of rigid water demand. Although both rigid and total water demand have been increasing rapidly in recent years, there should be an upper limit for rigid water demand, and thus its percentage would decrease with the increase of water demand in the future.

In conclusion, this study emphasizes the importance of diverting water from other regions and improving the water-use efficiency in the future in Qingdao.

4.2 Determination of regulation strategy

4.2.1 Water demand-supply balance

The indices B1 and B2 are calculated, as shown in Fig. 7. It is seen that the values of B2 are larger than the values of B1 in 2020, 2025 and 2035, indicating that the agricultural water-use efficiency is always lower than the industrial water-use efficiency in Qingdao. This makes it necessary to implement more effective water-saving strategies in the future, such as optimizing plantation structure, implementing water-saving irrigation, and improving the effective utilization coefficients of irrigation water, in order to maximize the agricultural water-use efficiency and avoid unnecessary waste of agricultural water. On the supply side, it is necessary not only to take full advantage of local water sources, but also to divert more water from other regions.

Increase in water demand inevitably leads to conflicts among water users which usually have conflicting preferences and priorities, and priority should always be given to water supply for urban domestic use. In case of water shortage in the future, the guarantee rate of urban domestic water supply should also be the highest. The industrial water demand can be adequately met because of the unique advantage of Qingdao in seawater desalinization. As long as the irrigation area remains constant, the agricultural water demand can also be met in years with normal inflow or in which inflow is slightly reduced. However, there would be a low guarantee rate for non-rigid agricultural water demand. On the whole, the future water supply-demand situation is severe in Qingdao and the current water supply system could not maintain water demand-supply balance, resulting in low guarantee rate of water supply and consequently limitation of economic and social development. In order to ensure the steady and sustainable development of Qingdao and the ecological restoration of rivers and wetlands, it is necessary to divert more water from other regions and improve the agricultural water-use efficiency.

5. Conclusions

In this study, a hierarchical index system is proposed for analysis of water supply-demand situation in a given basin or region, which can overcome the problems associated with the use of a single index like water shortage or water shortage ratio, such as inability to distinguish regulation direction and strategies and complex computation. Five determinant factors responsible for water supply-demand imbalance are considered on both water supply and demand sides, and corresponding regulation strategies are proposed to restore water supply-demand balance by improving the water supply capacity of conventional and non-conventional water sources, improving the water-use efficiency, and controlling the social and economic development scale. The proposed index system has been successfully applied to the analysis of water supply-demand situation in Qingdao. The results reveal that the future water supply-demand situation is severe in Qingdao and it is necessary to divert more water from other regions and improve the agricultural water-use efficiency.

However, some limitations of this study should also be acknowledged. For instance, national development strategies and regional industrial layout should be taken into consideration in the analysis of rigid water demand. However, as it is difficult to obtain the data about regional industrial layout, it is necessary to simplify the analysis of rigid water demand. In addition, the effects of water price and water supply cost on the water supply-demand situation should also be considered in the future.

Declarations

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Authors Contributions All authors made a substantial contribution to this paper. Ting Wang designed the methods and analyzed the results of Qindao; Jinjun You wrote the first draft of the manuscript; Zhenzhen Ma performed the calculations of Qindao; Ping Xiao made the figures and tables. All authors commented on previous versions of the manuscript, and authors read and approved the final manuscript.

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Code Availability Not applicable.

Ethical Approval Not applicable.

Conflicts of interest/Competing interests The authors declare no conflict of interest.

Consent to Participate Not applicable.

Consent to Publish The authors confirm that the work described has not been published before, and not under consideration for publication elsewhere. Its publication has been approved by all co-authors, and we agree to publish this article in the journal of WARM by Springer.

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Figures

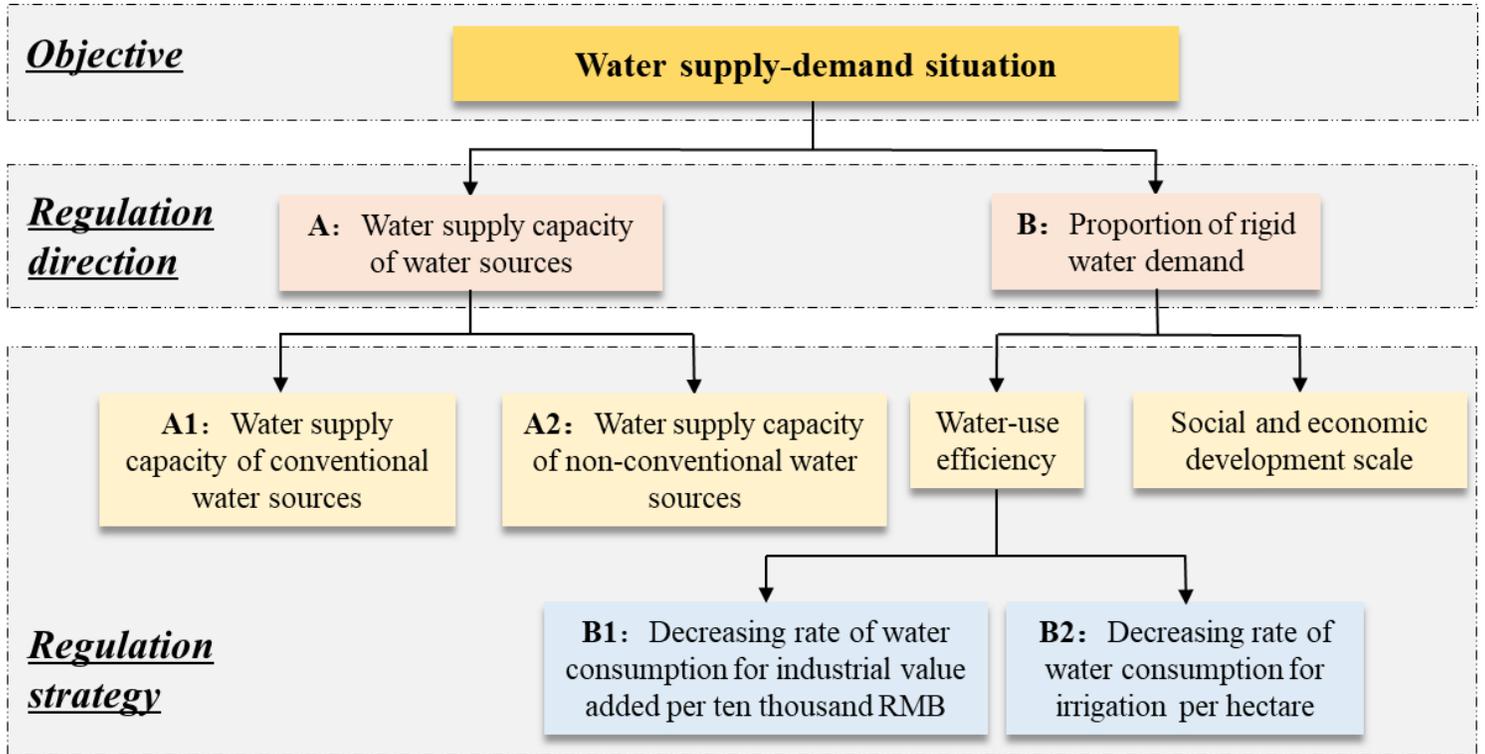


Figure 1

Hierarchical index system for analysis of water supply-demand situation

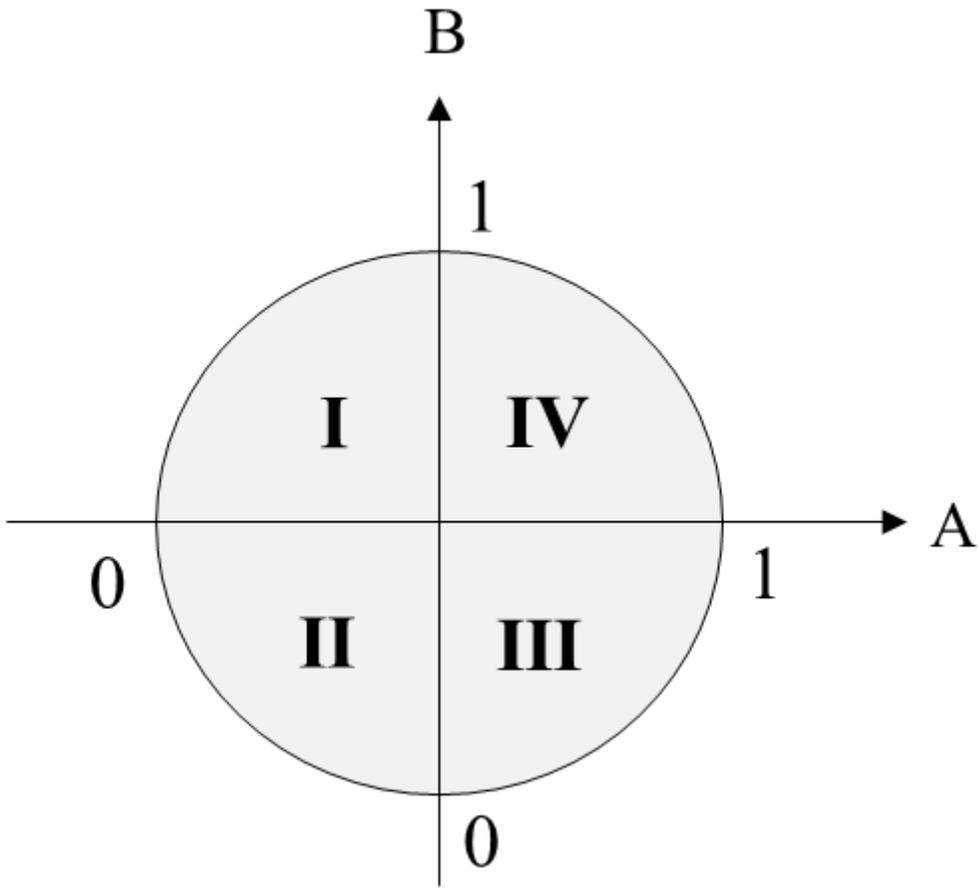


Figure 2

Schematic diagram of the indices evaluation partition results on the level of regulation direction

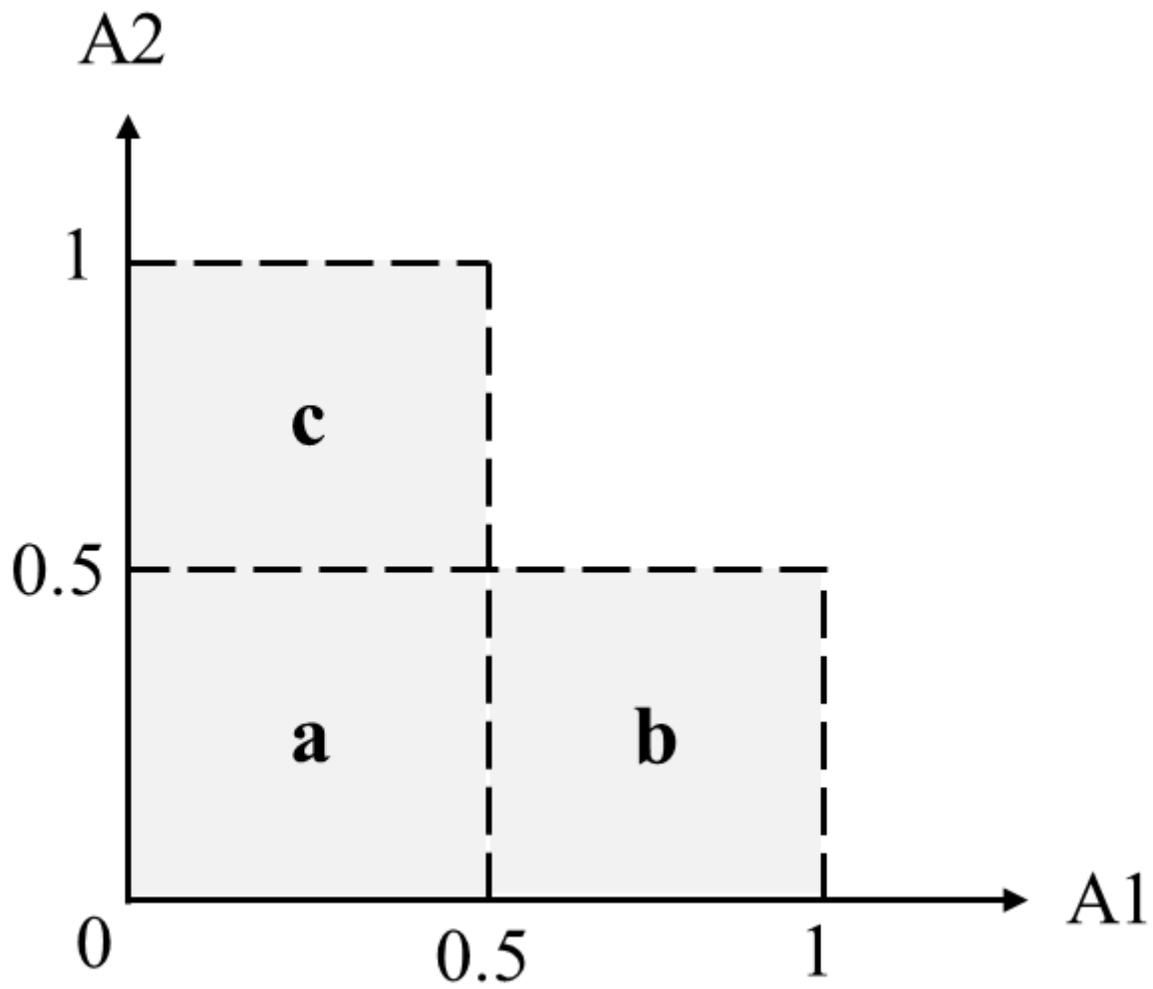


Figure 3

Schematic diagram of the indices evaluation partition results on the level of regulation strategy (supply side)

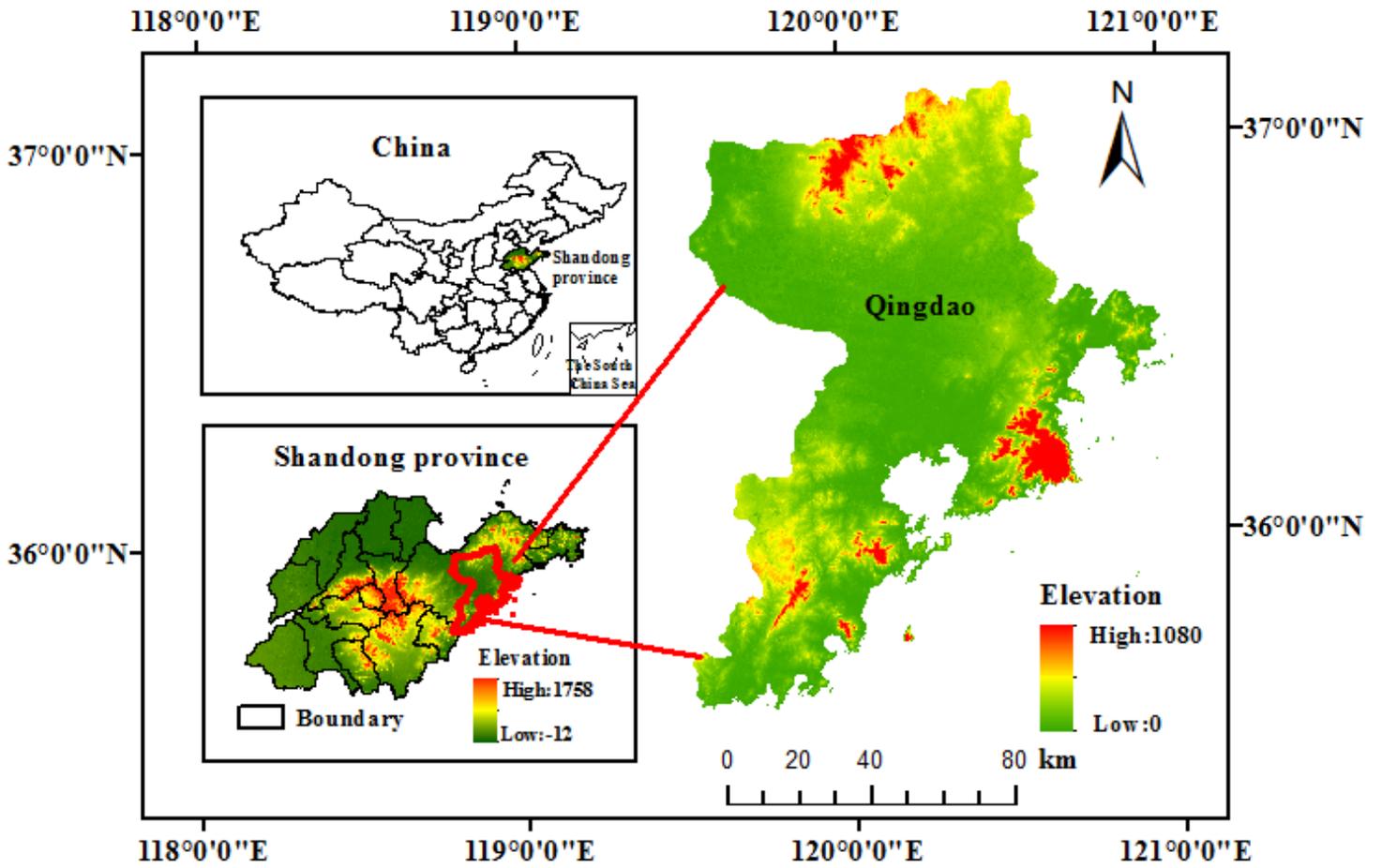


Figure 4

The geographic location of Qingdao

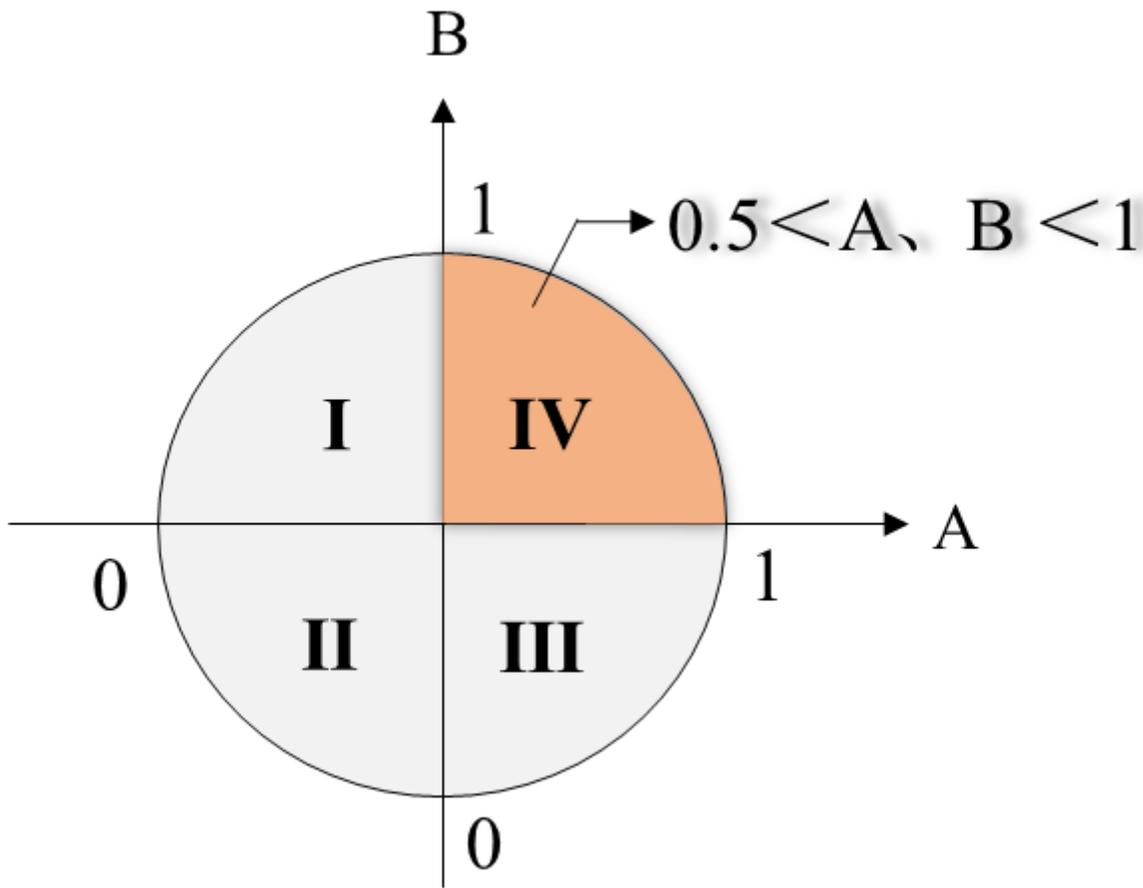


Figure 5

The evaluation partition results of indices A and B in Qingdao

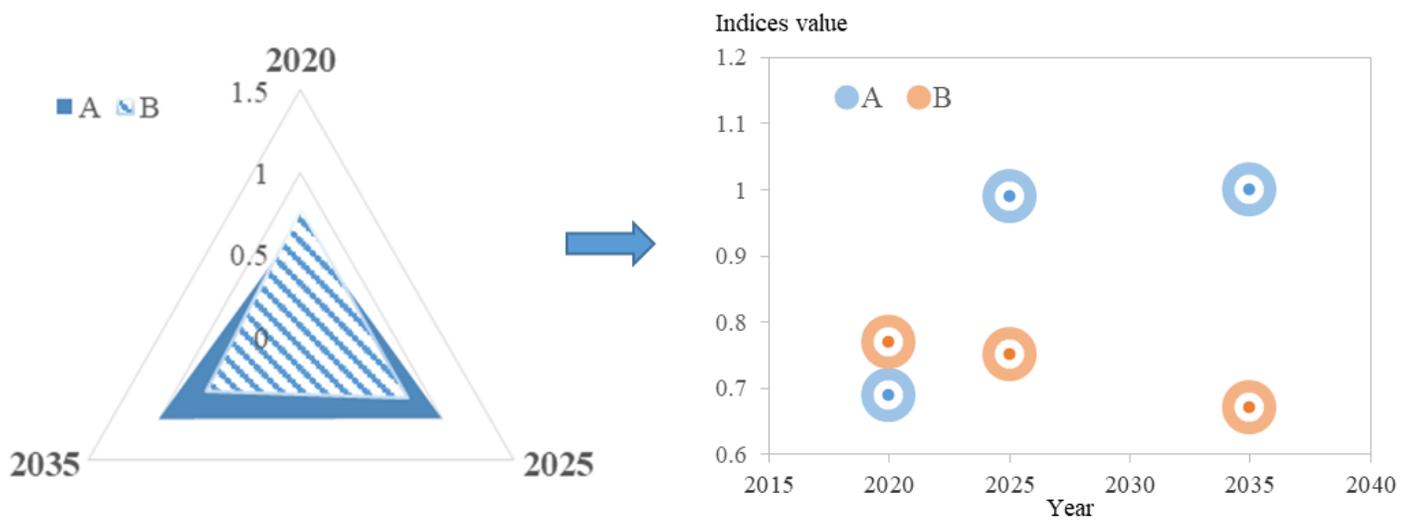


Figure 6

The inter-annual variation trend of indices A and B in Qingdao

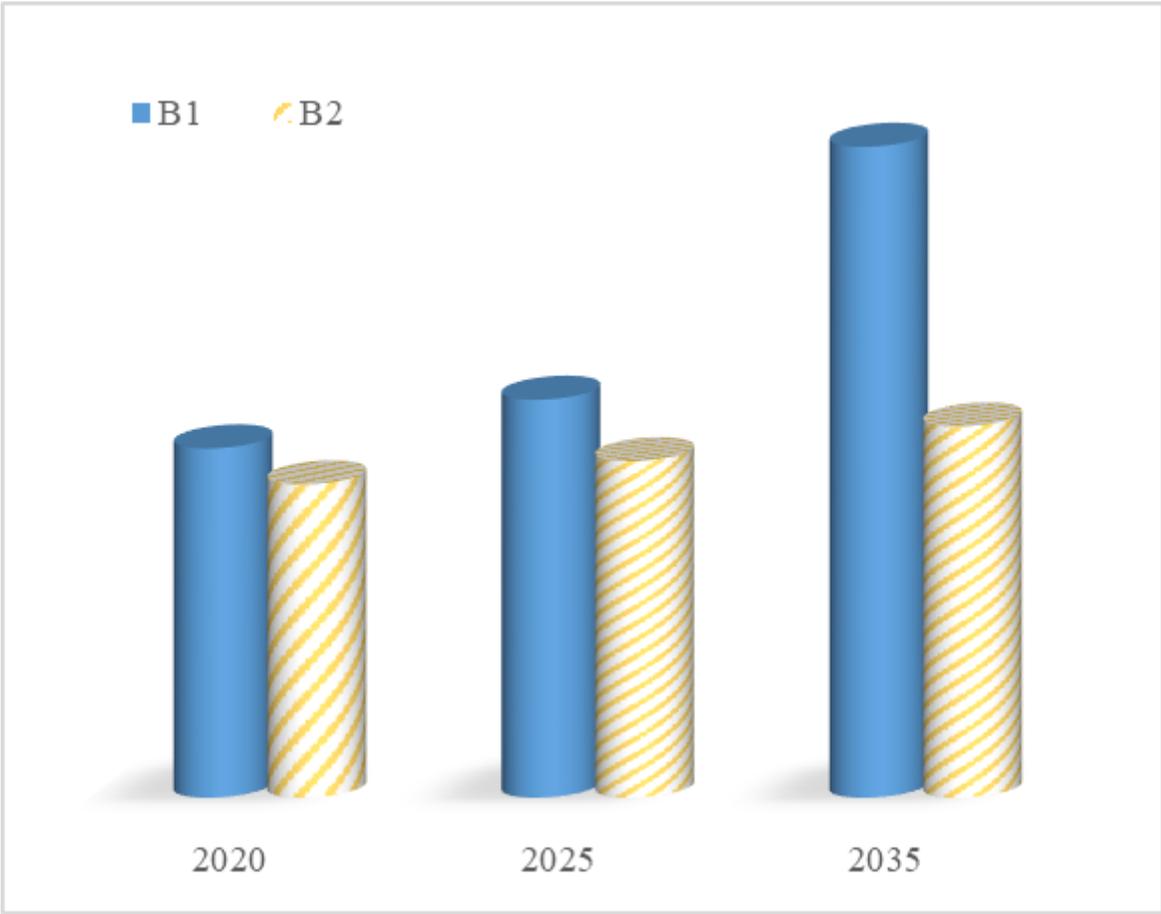


Figure 7

The calculation results of indices B1 and B2 in Qingdao