Evaluating water resources carrying capacity of Pearl River Delta by entropy weight-TOPSIS model

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To understand the spatio-temporal changes in the water resources carrying capacity (WRCC) of Pearl River Delta (PRD), 19 indicators were selected from three subsystems (water resources, socio-economic, and eco-environment), and the entropy weight-TOPSIS model was employed to analyze the WRCC of each cities in PRD from 2015 to 2020. As the result shows, the water resources subsystem (WRS) had the largest weight in the evaluation system, followed by the socio-economic subsystem (SES), and the eco-environmental subsystem (EES); among these indicators, economic density, water resources per capita, annual precipitation, and new soil erosion treatment area had the highest weights; the PRD had a low WRCC score overall, with considerable regional differences; the capacity score changed with time, but the ranking of cities remained largely the same, with Shenzhen, Zhaoqing, and Huizhou marking higher scores, whereas Zhongshan, Foshan, and Zhuhai achieving lower scores. It was also found that Shenzhen had a high score for SES, which made up for the shortage of natural water resources there; cities like Huizhou, Jiangmen, and Zhaoqing which boast rich water resources and extensive development achieved high scores for WRS and EES. As the PRD develops, it is important to optimize dispatch of water resources, boost green economy, and promote ecological wellbeing.

Introduction

Water resources play a significant role in national economy and living-standard improvement. "Water resources-based planning" is a planning strategy that takes water resources as the primary constraint in control of urban area expansion and restructuring of industry layouts. Though cities often boast rich water resources in the early stage of development, problems like water shortage, water pollution, and ecological degradation rear their ugly heads as the economy takes off and the population grows, hobbling urban development (Wu et al., 2020). Researches show that there is no consensus on the definition of water resources carrying capacity (WRCC) among researchers, and relevant

studies often have varied focuses. For instance, Falkenmark and Lundqvist (1998) put forward the term "available water," and probed into the problem of water security from the perspectives of policy determination and human adaptation. Clarke (2002) maintained that WRCC is closely related to population growth and resource depletion. Milano et al. (2013) used the "water supply/demand ratio" to assess whether the water resources in the Ebro basin would meet the current and future demands of water in the region. Given our research goals, WRCC is defined as the capacity of water resources to meet the needs of human activities in a region within a given time frame, which is subject to impacts from comprehensive factors including water resources abundance, economic-technological strength, and ecological quality (Lin et al., 2020; Zhao et al., 2020; Wang et al., 2022). Evaluating the regional WRCC is a crucial step in urban planning and construction (Buckerfield et al., 2020).

WRCC has been extensively studied. In terms of the research object, most of these studies focused on regions with a certain economic scale like basins, provinces, cities, and economic circles, which rely heavily on water resources and are likely to suffer water shortage, whether rich or lack of natural water resources. As reported by Kang et al. (2019), the Haihe River basin has a low agricultural WRCC; the agricultural WRCC in Shanxi, Inner Mongolia, and Liaoning is also small, though there is no overload problem; the WRCC in Beijing, Tianjin, Hebei, Henan, and Shandong is overloaded, and hence it is necessary to optimize groundwater development and adjust the effective irrigation area. Magri and Berezowska-Azzag (2019) evaluated the water carrying capacity (WCC) of Oran, Algeria, based on four scenarios from the aspects of urban water resources sustainability, urban economy, society and environment, and believed that compared with improving water supply, rational development and recycling of water resources is the solution to maintain WCC. Wang et al. (2022) found that under the scenario of rapid economic development, the WRCC and coupling coordination degree of Guangzhou city are the worst, the water environment protection scenario and water conservation scenario are better, and the comprehensive scenario performs the best. Wang et al. (2021) analyzed the current and future WRCC of the Chang-Ji economic circle, and pointed out the major problems of water resources there—water shortage and poor water quality.

Studies that built WRCC evaluation indicator systems turn out to be similar as most involve indicators in the subsystems such as the water resources, the socio-economic, the eco-environmental and so on, though these indicators differ from each other in the natural and social conditions of the studied area or their research focuses (Li et al., 2021; Meng et al., 2021; Wei et al., 2021). Regarding the research methods, as WRCC evaluation involves many indicators that play varied roles in the evaluation system, researchers often need to assign weights to the indicators and then obtain a comprehensive WRCC score based on the weighted mean. Such methods are legion. Wang et al. (2014a) simulated the impact of economic advances and population growth on water consumption in Tongzhou District, Beijing by the system dynamics (SD) model, and found that the region suffered from severe water shortage and the current water supply could not meet the future needs. Peng et al. (2021) proposed the Driver-Pressure-Engineering water shortage-State-Ecological Basis-Response-Management (DPESBRM) concept, and employed the cloud model to calculate the weights of WRCC indicators, which fully considers the randomness and fuzziness of the evaluation object; their method was used to evaluate the WRCC of karst areas in Guiyang, China, and the evaluation results were found to be in line with the TOPSIS-based evaluation outcomes. Deng et al. (2021) quantified the WRCC of Han River basin in 2010–2016 by set-pair analysis, and forecasted the WRCC of the basin in 2035 by the soil and water assessment tool (SWAT) model. Other evaluation methods include analytic hierarchy process (AHP) (Lu et al., 2017), system dynamics (SD) models, neural networks (Wang et al., 2014b), and TOPSIS models (Lin et al., 2020).

Despite the extensive studies on WRCC, few probed into the WRCC in the urban agglomeration of Pearl River Delta (PRD), and even less combined the spatial and temporal dimensions for comprehensive analysis (Xu et al., 2019). Compared with northern China, the PRD is rich in water resources, however, due to the large population, water resources-reliant industries, urban area expansion, and monotonous water sources in the eastern part, the PRD is plagued by water shortage as it develops. To strike a balance between water resources, environment, and economy, manage water resources in a scientific manner, and promote ecological wellbeing the PRD, we believe it is imperative to comprehensively analyze the spatio-temporal changes in the WRCC of the PRD. Based on the present work, collect data from 2015 to 2020 in the PRD, taking into account the differences in water resources, economic development and ecological environment, an WRCC evaluation index model was established, and the entropy weight-TOPSIS model was employed to perform empirical research from spatial and temporal dimensions. Suggestions were proposed based on the research findings and the differences of each cities, to provide a basis for sustainable and quality development of the PRD, and to expand the meaning of WRCC to a certain extent.

Research area overview

The PRD (111.35°E–115.43°E, 21.56°N–24.40°N), located in the mid-south of Guangdong province and the lower reaches of Pearl River (Figure 1), borders on South China Sea and is subject to the subtropical monsoon climate, with an annual average temperature of 21.4°C–22.4°C, and annual

FIGURE 1
Geographical location of the PRD.
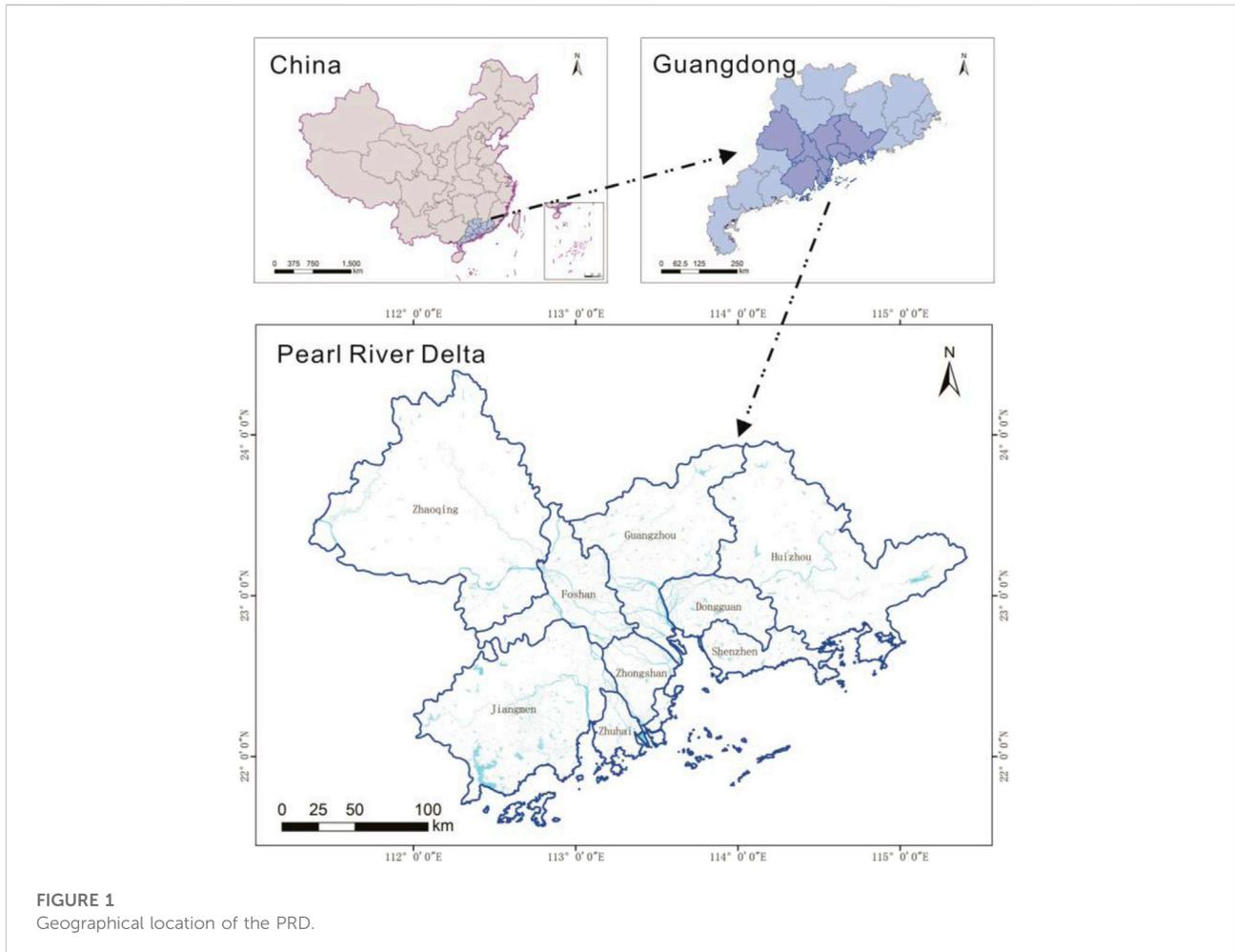
precipitation of 1,600–2,300 mm. The PRD accommodates nine cities, i.e., Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing, taking up an area of 55,400 km², which is less than one-third of the total area of Guangdong province. As one of the earliest regions that were opened up to the outside world in China, the PRD remains an economic hub for the country and the major part of the Guangdong-Hong Kong-Macau Greater Bay Area. In 2020, the PRD reached an urbanization rate of 85%, and the GDP there reached $1.4 trillion (over 80.8% of the total of Guangdong province). The PRD is at the confluence of Xijiang River, Beijiang River, and Dongjiang River, with rich dense network of waterways.

Research methodology

In the present work, WRCC evaluation index system is constructed, the entropy weight method is used to calculate the weight of each indicator, and the TOPSIS model is used to calculate the annual WRCC and scores of the three subsystems of each city from 2015 to 2020. The weights of indicators, the spatio-temporal changes in the WRCC, and the spatio-temporal changes in the subsystems are discussed, and suggestions for improving the WRCC of PRD is proposed.

Constructing the water resources carrying capacity evaluation index system

Water resources are a vital form of natural resources that social and economic advances hinge on. Developing and utilizing water resources need financial support, and a good environment is the foundation for regeneration of water resources. Thus, to assess regional WRCC, we need to build a multi-layered evaluation system that fully considers factors of water resources, economy, and the natural environment. By referring to relevant works (Xu et al., 2019; Lin et al., 2020; Zhao et al., 2020; Wang et al., 2022) and considering data availability, we constructed a WRCC evaluation indicator

TABLE 1 WRCC evaluation index system for PRD.

Objective layer	Rule layer	Indicator layer	Calculation	Code	Attri-bute
WRCC evaluation index system	Water resources subsystem (WRS)	Volume of water resources per capita (m3/person)	Total volume of water resources/total population	C1	P
		Water yield modulus (10,000 m^3/km^2)	Total volume of water resources/total area	C2	P
		Water supply per capita (m^3/person)	Volume of water supply/total population	C3	P
		Surface water ratio (%)	Volume of surface water resources/total volume of water resources	C4	P
		Water resources utilization rate (%)	Volume of water supply/total volume of water resources	C5	N
		Annual precipitation (100 million m^3)	—	C6	N
	Socio-economic subsystem (SES)	Population density (person/km^2)	Total population/total area	C7	N
		Natural population growth rate (‰)	—	C8	N
		GDP per capita (10,000 CNY)	GDP/total population	C9	P
		Economic density (100 million CNY/km^2)	GDP/total area	C10	P
		Urbanization rate (%)	Urban population/total population	C11	P
		Water consumption per 10,000 CNY of GDP (m^3)	Total water consumption/GDP	C12	N
		Water consumption per 10,000 CNY of industrial production (m^3)	Industrial water consumption/10,000 CNY industrial production	C13	N
		Urban domestic water consumption per capita (L/d)	Urban water consumption/total population	C14	N
	Eco-environmental subsystem (EES)	Water quality control rate of water functional zone (%)	—	C15	P
		Forest coverage rate (%)	—	C16	P
		Domestic sewage discharge per capita (L/d)	Volume of domestic sewage discharge/total population	C17	N
		Ecological water use rate (%)	Volume of ecological water use/total water consumption	C18	N
		New soil erosion treatment area (km^2)	—	C19	P

Note: P means positive, N means negative; "—" indicates that the indicator is directly extracted from relevant references.

system for PRD. PRD is the confluence of three rivers, where cities vary considerably from each other in terms of local water yield and inflow water volume, and it is challenging to develop inflow water resources, so the water resources subsystem discussed in the present work focuses on the volume and development potential of local water resources, with the volume of water resources per capita and water yield modulus as the evaluation indicators for this subsystem. Population growth and increased water consumption will pose pressure to water resources, but development of water resources utilization facilities and protection of water resources require large economic investment, so such indicators as population density and economic density as selected to assess the socio-economic subsystem of WRCC. Factors that affect water quality like water quality control rate of water functional zone and forest coverage are selected to assess the eco-environmental subsystem of WRCC. Table 1 shows the 19 indicators selected in the present work.

Determining indicator weight by the entropy weight method

A diverse and complex collection of factors contribute to WRCC. The weights should be assigned to the indicators in an objective manner to avoid subjectivity in calculation of weights. In the present work, the entropy weight method that could objectively reflect information in the indicators was employed to resolve the problem of subjectivity of weight assignment. Generally, a smaller entropy of the indicator means a larger entropy weight and hence more importance of the indicator (Kang et al., 2019). With the dimension of time considered, the weight of indicator is calculated as follows:

1) Normalization of the indicators

The primary evaluation matrix of regional WRCC is set as follows:

$$X = \left\{ x_{tij} \right\}_{p \times m \times n} \left(1 \leq t \leq p, 1 \leq i \leq m, 1 \leq j \leq n \right) \tag{1}$$

There are both positive and negative indicators for WRCC evaluation. These indicators are normalized as follows:

For positive indicators:

$$y_{tij} = \left(x_{tij} - \min x_j \right) / \left(\max x_j - \min x_j \right) \tag{2}$$

And for negative indicators:

$$y_{tij} = \left(\max x_j - x_{tij} \right) / \left(\max x_j - \min x_j \right) \tag{3}$$

where x_{tij} is the j-th indicator for the city i and the year t; $\max x_j$ and $\min x_j$ mean the maximum and minimum of the j-th indicator.

2) The weight of each indicator is:

$$Y_{tij} = y_{tij} \Big/ \sum_{t=1}^{p} \sum_{i=1}^{m} y_{tij} \tag{4}$$

3) The entropy of each indicator can be obtained by the following equation:

$$e_j = - \frac{1}{\ln(p \times m)} \sum_{t=1}^{p} \sum_{i=1}^{m} Y_{tij} \ln Y_{tij} \tag{5}$$

And if $Y_{tij} = 0$, then $Y_{tij} \ln Y_{tij} = 0$.

4) The weight of each indicator can be obtained by the following equation:

$$W_j = \left(1 - e_j \right) \Big/ \sum_{j=1}^{n} \left(1 - e_j \right) \tag{6}$$

where W_j means the entropy weight coefficient; a larger W_j means more information the corresponding indicator conveys, and a more important role this indicator plays in comprehensive evaluation.

TOPSIS model

The technique for order of preference by similarity to ideal solution (TOPSIS) model is a comprehensive evaluation method which can make the best of all primary information to accurately reveal the gaps between different evaluation schemes. The TOPSIS modelling process is as follows:

1) Positive processing is performed on the primary evaluation matrix: $x_{ij} \rightarrow x'_{ij}$ and the normalized decision-making matrix b_{ij} can be obtained by the following equation:

$$b_{tij} = x'_{tij} \Big/ \sqrt{\sum_{i=1}^{m} x'^2_{tij}} \tag{7}$$

2) The weighted normalization matrix can be obtained as follows:

$$c_{tij} = w_j \cdot b_{tij} \tag{8}$$

3) The positive ideal solution and the negative ideal solution can be calculated:

$$c_j^+ = \left\{ \max c_{tij} \right\} \tag{9}$$

$$c_j^- = \left\{ \min c_{tij} \right\} \tag{10}$$

4) The Euclidean distance is employed to calculate the distance of the evaluation object from the positive ideal solution and the negative ideal solution:

$$s_{ti}^+ = \sqrt{\sum_{j=1}^{n} \left(c_{tij} - c_j^+ \right)^2} \tag{11}$$

$$s_{ti}^- = \sqrt{\sum_{j=1}^{n} \left(c_{tij} - c_j^- \right)^2} \tag{12}$$

5) The closeness between the evaluation object and the positive and negative ideal solutions is calculated as follows:

$$f_{ti} = s_{ti}^- \Big/ \left(s_{ti}^- + s_{ti}^+ \right) \tag{13}$$

And the closer f_{ti} is to 1, the better the evaluation object is, which means the score of WRCC is higher.

Data source

The data used in the present work are from the water resources bulletins, annual statistical year books for cities in the PRD, as well as the water resources bulletins, and soil and water conservation bulletins of Guangdong Province in 2015–2020. The calculation method of some indicators is in Table 1.

Results and analysis

Indicator weight

Based on primarily processed data, the entropy weight method was employed to calculate the weight of each indicator, as shown in Table 3. The weights for the WRS, the SES, and the EES are 0.4052, 0.3470, and 0.2478, respectively. The WRS has the largest weight, which means the natural reserve of water resources and water supply engineering capacity are the major contributors to the WRCC of the PRD, and although the geographical distribution of natural water resources cannot be changed, a reasonable WRCC can be maintained through scientific development of water resources and control of population; the SES has the second largest weight, only

TABLE 2 Weights of the 19 indicators for WRCC evaluation of the study area.

Indicator	C1	C2	C3	C4	C5	C6	C7
Weight	0.1169	0.0386	0.0384	0.0550	0.0489	0.1078	0.0128

Indicator	C8	C9	C10	C11	C12	C13	C14
Weight	0.0184	0.0640	0.1496	0.0320	0.0214	0.0347	0.0140

Indicator	C15	C16	C17	C18	C19
Weight	0.0196	0.0622	0.0475	0.0245	0.0939

FIGURE 2
Ranking of WRCC evaluation indicators for the PRD.
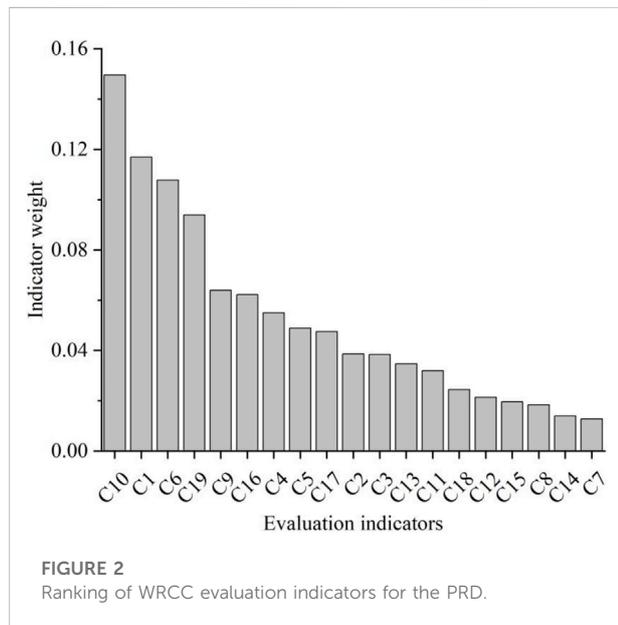
0.06 less than WRS, which means economic growth not only relies on the natural reserve of water resources, but plays a role in improving the regional WRCC; the EES has the smallest weight, which may be because the impact of changes in the ecological environment on the WRCC is lagging, but a good ecology can sustain the regular water cycle and promote rational development of water resources, and hence the EES is an indispensable part in WRCC evaluation. Indicators with the largest weights in each subsystem are C1, C10, and C19. In this logic, rational development of water resources, acceleration of economic growth, and ecological improvement initiatives are effective measures to improve WRCC.

Table 2 shows the 19 indicators selected in the present work for WRCC evaluation; these indicators are sequenced, as shown in Figure 2. The top-ranking six indicators, C10, C1, C6, C19, C9, and C16, are positive indicators, and two for each subsystem. The weight of C10 is the largest, and C9 ranks fifth, indicating that in the relatively developed PRD, economic investment is particularly important for the utilization and protection of water resources.

C1 and C6 take the second place, indicating that natural water resources are the most basic component of WRCC. The treatment of soil erosion and the improvement of forest coverage are conducive to maintaining a good watershed ecology and normal hydrological cycle. That is to say, to improve the WRCC of PRD, we need to fully consider the three subsystems.

Analysis of water resources carrying capacity evaluation results of Pearl River Delta

1) The TOPSIS model was employed to calculate the mean scores of WRCC of the PRD in 2015–2020. The natural breaks method is used to divide the nine cities into three grades according to the scores. With reference to Lin et al. (2020), the connotation and status of WRCC of each grade are explained, as shown in Table 3 and Figure 3 presents the annual changes in WRCC there. As Table 3 reveals, the overall WRCC of the PRD remained small, and the mean score of each city ranges from 0.137 to 0.479; only Shenzhen and Zhaoqing scored higher, followed by Huizhou, Jiangmen and Guangzhou, while Dongguan, Zhuhai, Foshan, and Zhongshan scored relatively lower. As Figure 3 shows, cities along the borders of the PRD including Zhaoqing, Huizhou, Jiangmen, and Shenzhen had the highest WRCC, whereas the five cities in the central region of the PRD had a lower WRCC, demonstrating considerable regional differences. Shenzhen, due to its economic strength, reaches the highest score (0.497), and Zhaoqing, with its rich reserve of water resources and good ecology, has the second largest score of WRCC (0.425), whereas Zhongshan has the lowest score (0.137), and Foshan has the second smallest score (0.174). As Figure 4 shows, in 2015–2020, despite the changes in the WRCC of each city, the ranking of cities remained the same; Foshan, Zhaoqing, and Guangzhou showed stable changes, whereas Shenzhen, Dongguan, and Haizhu presented an upward trend in the evaluation score. As the PRD witnessed a normal and relatively dry year in 2020, with the annual precipitation staying at merely 1,609 mm, all cities in the PRD had a smaller WRCC score in 2020 than in 2019; except Shenzhen and Zhongshan, all other cities had a larger WRCC in 2016 and 2019 than in other years, which is attributed to the rich rainfall in these 2 years and hence a high volume of water resources per capita. The WRCC of the PRD is positively correlated to the precipitation, especially in Guangzhou, Huizhou, Zhongshan, Jiangmen and Zhaoqing, the correlation coefficient is more than 0.72, while Zhuhai is 0.57. To resolve the problem of overdependence of WRCC on natural rainfall, we need to reserve water in the wet years to resolve water shortage in the dry years.

2) The TOPSIS model was used to calculate the score of each subsystem in the WRCC evaluation system for the PRD, and the mean score from 2015 to 2020 was obtained: the mean score for

TABLE 3 Mean WRCC of cities in the PRD from 2015 to 2020.

City	Evaluation score	Evaluation level	Ranking	Connotation	Capacity
Shenzhen	0.497	I	1	Reasonable supply of water resources	The WRCC is moderate, and there is still some potential for further development
Zhaoqing	0.425	I	2	Reasonable supply of water resources	
Huizhou	0.352	II	3	Water shortage	The WRCC reaches the warning threshold, and the potential for further development is limited
Jiangmen	0.332	II	4	Water shortage	
Guangzhou	0.271	II	5	Water shortage	
Dongguan	0.195	III	6	Severe water shortage	The WRCC reaches the upper limit, and there is very limited potential for further development
Zhuhai	0.179	III	7	Severe water shortage	
Foshan	0.174	III	8	Severe water shortage	
Zhongshan	0.137	III	9	Severe water shortage	
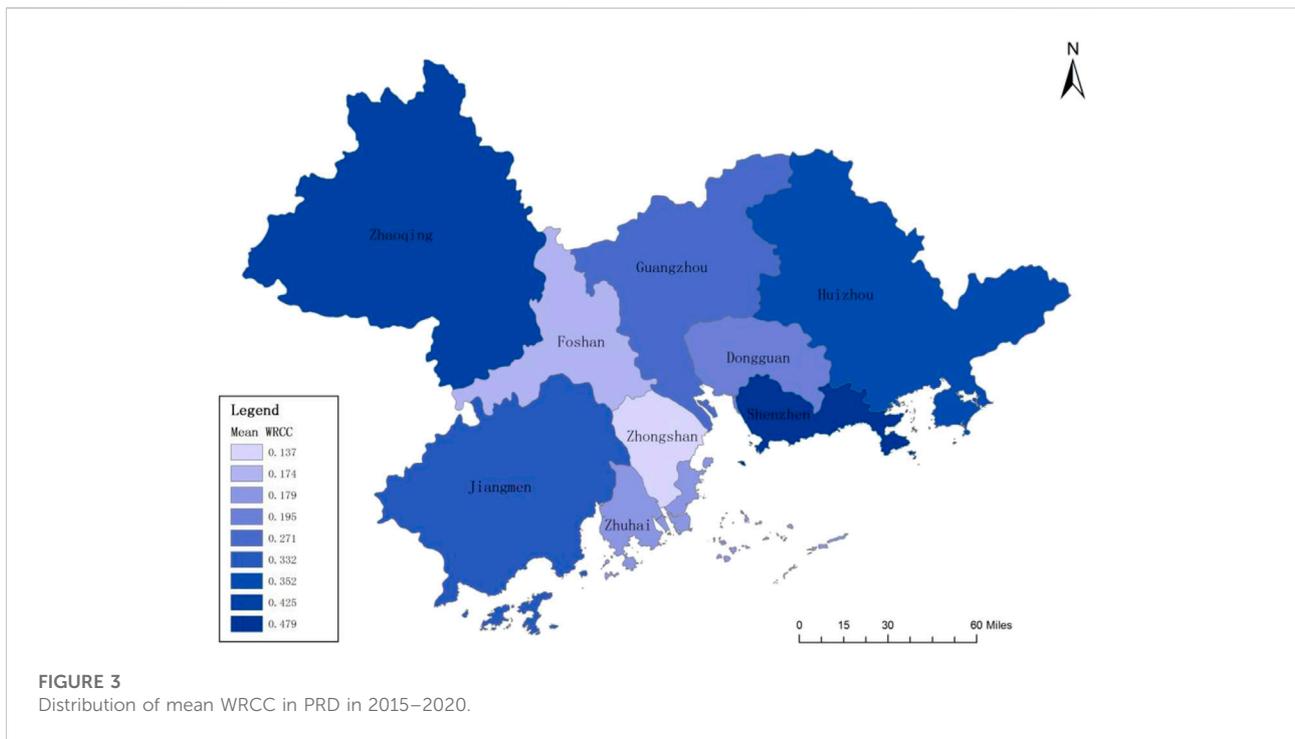
FIGURE 3
Distribution of mean WRCC in PRD in 2015–2020.

WRS, SES, and EES was 0.329, 0.220, and 0.331, respectively. Figure 5 shows the mean WRCC score of each city in the PRD from 2015 to 2020. For cities including Guangzhou, Zhuhai, Foshan and Zhongshan, the score for each subsystem shows little difference; for Shenzhen, however, the SES has a far larger score than the other two subsystems; for Huizhou, Jiangmen, and Zhaoqing, the scores for WRS and EES are far higher than that for the SES. Though Shenzhen had a low volume of water resources per capita (C1), a small annual precipitation (C6), a high population density (C7), and a high ecological water utilization rate (C18), it ranked top among all cities in the PRD in terms of the economic density (C10), urbanization rate (C11), water use volume per 10,000 yuan of GDP (C12), and water use volume per 10,000 yuan of industrial production (C13), which makes up for the lows in WRS and EES. In future urban planning of Shenzhen, it is necessary to better allocate water resources, maintain water diversion projects, improve the ecology, and seek new sources of water supply. For Huizhou and Zhaoqing, the score for SES is far smaller than that for WRS and EES. Thus, these two cities should make the fullest of their rich water resources and good environment

FIGURE 4
Changes in WRCC of cities in the PRD in 2015–2020.

FIGURE 5
Mean score of subsystems in WRCC evaluation of cities in PRD.
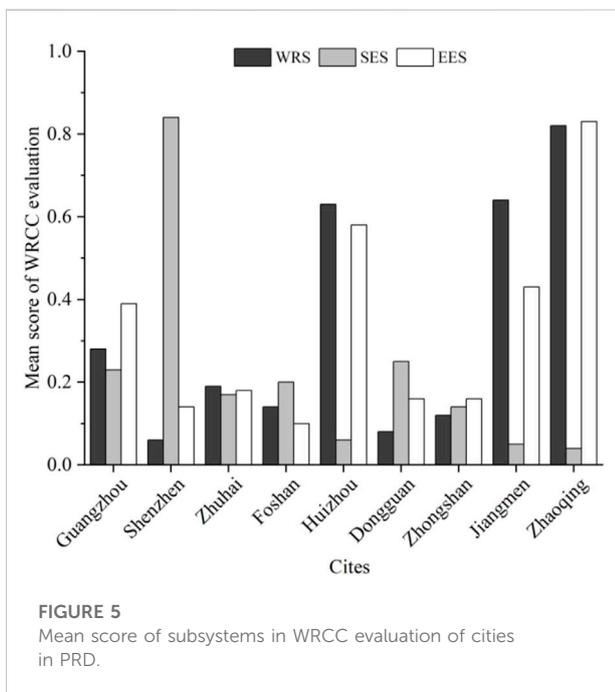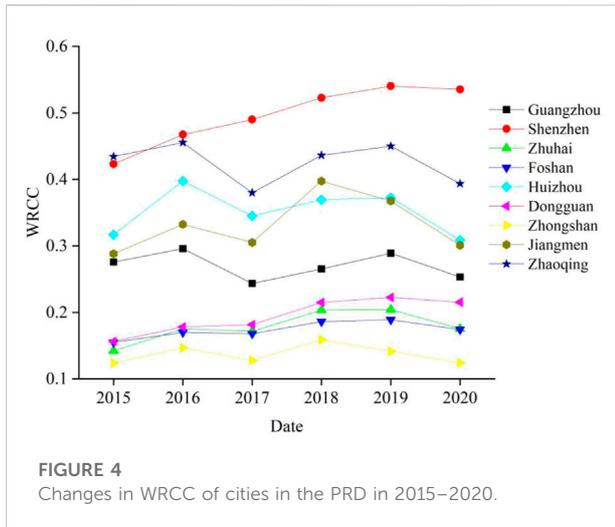
to restructure the industries and boost economic growth. In sum, cities in the PRD, which constitute one the most important urban agglomerations in China, should cooperate with each other to achieve optimized transfer of industries and resources, and join hands to improve the natural environment.

3) The subsystems for WRCC evaluation in the PRD show considerable differences, which implies the problems like uneven distribution of water resources, unbalanced economic growth, and varied efforts for ecological improvement in this region. By the score of the WRS in WRCC evaluation, the cities are ranked as follows: Zhaoqing > Jiangmen > Huizhou > Guangzhou > Zhuhai > Foshan >

Zhongshan > Dongguan > Shenzhen, and the gap between the maximum (0.817) and the minimum (0.063) is 0.754, which shows varied possession of water resources among cities. Zhaoqing, Huizhou, and Jiangmen boast rich rainfall, with the volume of water resources per capita reaching 3,700, 2,700, and 2,900 m^3/person; besides, with a low water resources utilization rate, the score for the WRS in these three cities is higher than in other cities, indicating the great potential for development of water resources in these cities. For Guangzhou, despite the high precipitation and water supply per capita, the volume of water resources per capita there is only half that of the PRD, and the water utilization rate is high, so the city achieves a score merely at 0.275. Zhuhai, because of its low volume of water resources per capita and small annual precipitation, reaches a score of mere 0.188 in WRCC evaluation. Foshan, Zhongshan, Dongguan, and Shenzhen feature a low annual precipitation and large population, with a volume of water resources per capita at merely 190–590 m^3/person, and hence achieving small scores in WRCC evaluation, at 0.136, 0.121, 0.080, and 0.063, respectively.

By the score of the SES in WRCC evaluation, the cities in the PRD are sequenced as follows: Shenzhen > Dongguan > Guangzhou > Foshan > Zhuhai Zhongshan > Huizhou > Jiangmen > Zhaoqing. The top ranking four cities have a high urbanization rate, all with a rate higher than 90% except Guangzhou, and the rate in Shenzhen even approaches 100%. Besides, these four cities have a high economic density and a high GDP per capita; in particular, Shenzhen has an economic density of $186 million/$km^2$, and a GDP per capita of $28,000/year; besides, the city's strong initiatives towards green economy and low-carbon economy have contributed to coordinated development of water resources and economy. Zhaoqing, which ranks the last among all the cities in the PRD with a score at mere 0.042, has an urbanization rate lower than 50%, and a per-capita GDP of merely $8,000/year, less than 1/3 of that in Shenzhen. These can be attributed to the low GDP in Zhaoqing, the large area of land, its irrational industrial layout, defective industrial chains for the manufacturing and service sectors, and a low water utilization rate of industries. Therefore, in future planning of Zhaoqing, it is necessary to balance resources and economic growth.

By the score of EES in WRCC evaluation, the cities in the PRD are ranked as follows: Zhaoqing > Huizhou > Jiangmen > Guangzhou > Zhuhai > Zhongshan > Dongguan > Shenzhen > Foshan. The cities have varied degrees of environmental quality and ecological treatment efforts, and cities with a higher score often have a larger area. Jiangmen and Zhaoqing have water functional areas with a high water quality control rate; Zhaoqing and Huizhou has a large forest coverage rate and large areas of new soil erosion treatment. Cities with lower scores generally have a smaller area: Foshan, Zhuhai, and Guangzhou have a high domestic sewage discharge per capita; Zhongshan, Foshan, and Zhuhai have a small forest coverage rate. Therefore, cities with a high score in WRCC evaluation need to maintain good environment, strengthen pollution treatment, and promote the pollution accountability systems; for cities with a large

FIGURE 6
Changes in the score of the WRS, SES, and EES in regional
WRCC evaluation of cities in PRD from 2015 to 2020.
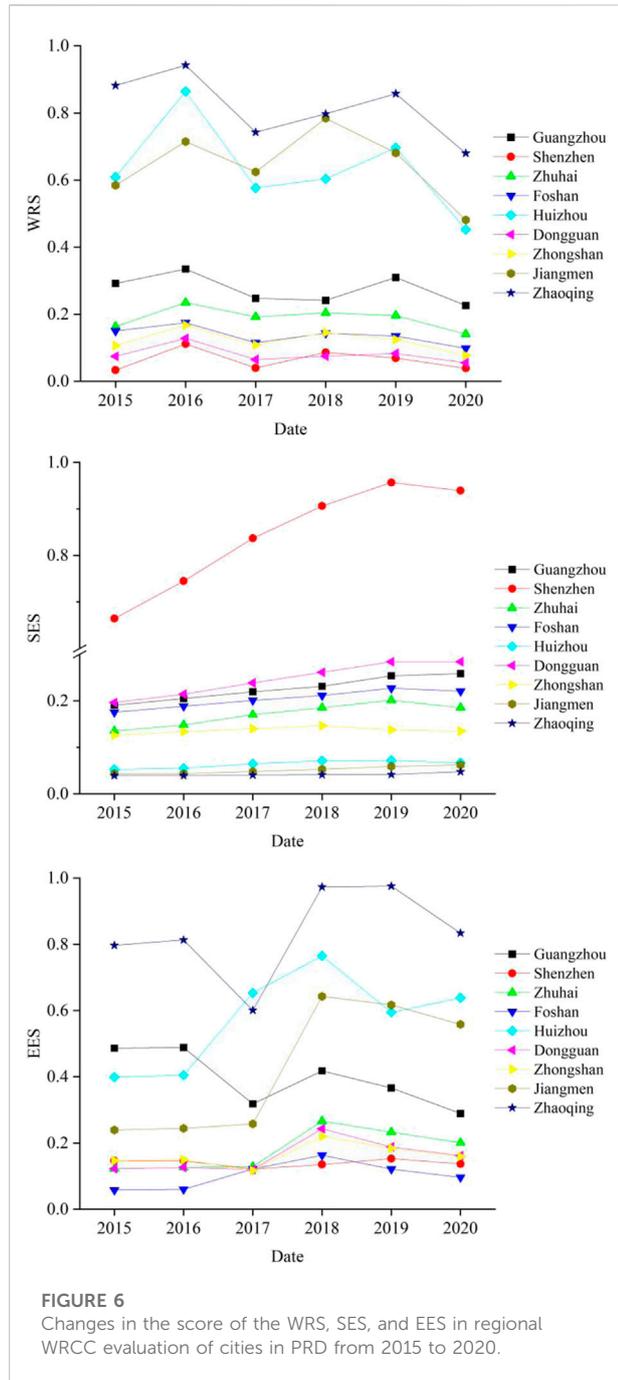
population and a small area of land, ecological improvement can only play a limited role in increasing the regional WRCC, so it is necessary to find new solutions for environmental treatment and achieve harmony between human and nature.

Analysis of the three subsystems in WRCC evaluation show that cities including Shenzhen, Dongguan, Zhongshan, and Foshan need to make better use of their limited water resources and optimize spatial and temporal allocation of water resources; cities like

Zhaoqing, Jiangmen, Huizhou, and Zhongshan should promote industry upgrading, encourage green production and boost economic growth; Cities including Foshan, Shenzhen, Dongguan and Zhongshan need to curb blind expansion of urban areas and reserve more area for the "lucid waters and lush mountains."

4) As Figure 6 shows, as the time proceeds, the score of the WRS in WRCC evaluation varied from 2015 to 2020, registering a slight decrease overall. The scores for Zhaoqing, Jiangmen, and Huizhou varied considerably, whereas the scores for other cities remained stable. The score for the SES remains stable, with a slight increase; the score for Shenzhen saw a rapid rise, followed by Dongguan and Guangzhou. Under the impact of the Covid-19 pandemic, however, the score for all cities stayed low in 2020. For most cities in the PRD, the score for EES in WRCC evaluation presented an upward trend, though with slight fluctuations; Guangzhou, however, witnessed a dropped score due to its reduced new soil erosion treatment area and increased utilization rate of water for ecological purposes. Though economic growth and ecological treatment can improve regional WRCC, uneven distribution of water resources and increased water demand along with economic growth will still reduce the regional WRCC. Therefore, we need to proceed with strict water resources management policies, encourage water-saving efforts, and transfer water resources in water-rich regions to water-short areas to achieve coordinated development among regions.

Conclusion and suggestions

Conclusion

In the present work, the WRCC of cities in PRD was discussed, and the following conclusion were reached:

1) The three subsystems are sequenced as follows by the weight they have in WRCC evaluation: WRS > SES > EES. Indicators including economic density, C10, C1, C19, C9, and C16 contribute considerably to the regional WRCC of the PRD. Rationally developing water resources, boosting economic growth, and improving the environment are effective measures to improve the regional WRCC.

2) From 2015 to 2020, the WRCC of the PRD remained low overall, with significant regional differences. Cities along the borders of the PRD like Zhaoqing, Huizhou, Jiangmen, and Shenzhen reached a high score in WRCC evaluation, whereas cities in the central area of the PRD achieved a lower score. Though the WRCC of each city changed over time, the ranking of cities by the score of WRCC remained largely the same. The WRCC was found to be positively correlated to precipitation. The scores of WRS, SES, and EES were 0.3288, 0.2202, and 0.3306, respectively. For cities including Guangzhou, Zhuhai, Foshan and Zhongshan, the subsystems achieved similar scores in WRCC evaluation; in Shenzhen, SES achieved a far higher score than the other two subsystems in WRCC evaluation; for Huizhou, Jiangmen, and Zhaoqing, WRS reached a far higher score in WRCC evaluation than the other two subsystems.

3) As further analysis of the three subsystems shows, Zhaoqing, Huizhou, and Jiangmen boast a rich reserve of water resources and considerable potential for further development; Shenzhen, Dongguan, Zhongshan, and Foshan are in short supply of water; Shenzhen, Dongguan, Guangzhou, and Foshan enjoy considerable economic strength, which contributes to coordinated development of the water environment and economy. Zhaoqing, which ranks last in the WRCC evaluation, is less developed than other cities. Zhaoqing, Huizhou, and Jiangmen have a large area of land and good ecology, whereas other cities should pay more attention to promote coordinated development between economic growth and ecological wellbeing.

Suggestions

As the construction of the Guangdong-Hong Kong-Macau Greater Bay Area moved forward, the PRD is bound to see population and economic growth, which will pose tangible challenges to the sustainable development of water resources. In the future, cities in the PRD should cooperate with each other to optimize spatial and temporal allocation of water resources. For example, optimizing the allocation of water resources in the Dongjiang River, and transferring water to water scarce cities in the eastern PRD by Xijiang River diversion project. In order to drive the social-economic development of Zhaoqing, Jiangmen, and Huizhou, green economy and industry configuration should be encouraged. On the basis of comprehensively promotion of the pollution accountability systems, and pursue ecological wellbeing, we should attach importance to the governance of urban rivers in Guangzhou, Zhongshan, and Foshan, and strengthen the monitoring and assessment of environmental health risks. Furthermore, we should push forward the initiatives to build a water-saving society, taking advantage of the economic of the PRD, with further improvement of water resources utilization efficiency. We can also incorporate more data and set thresholds for the evaluation indicators to capture changes in regional WRCC, thereby providing a scientific basis for sustainable development of water resources, economic growth, and ecological improvement in PRD.

Contributions, limitations, and future research

In the present work, 19 indicators were selected, and the entropy weight-TOPSIS model was employed to calculate the WRCC score of cities in the PRD from 2016 to 2020 with relation to WRS, SES, and EES. The distribution pattern of WRCC was analyzed, and contributing factors to regional WRCC were explored on the temporal and socio-economic dimensions. Moreover, suggestions were proposed to promote harmony between water resources and human in PRD.

Nonetheless, there are some limitations in our work. First, the water resources system is complex and constantly changing,

and WRCC has such characteristics as diversity, dynamic changes, and fuzziness. Evaluation of WRCC in our work, however, is static evaluation based on historical data and a limited set of indicators; the interactions between subsystems are overlooked; and the results are applicably only to the years between 2015 and 2020. In future works, it is necessary to improve the evaluation indicator system by introducing new indicators related to water conservation and the water environment, increase the basis data to make the research result more scientific and practical; in addition, scientific methods should be adopted to predict the impacts of different urban development plans on the future WRCC of PRD.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YZ and QY conceived the conceptualization, acquired the funding and administrated the project; ZL and BZ conducted the investigation, analyzed data and refined the methodology; YZ wrote the original draft; QY reviewed and YZ editing the final paper.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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