Analysis of the ultimate water resources carrying capacity in Yancheng, China

Zengchuan Dong, Guang Yang, Shengnan Feng, Jiayi Ma and Bing Li

ABSTRACT

Unreasonable development and utilization of resources has caused serious environmental problems, especially water shortage and water pollution. Determining the largest population size and economic scale that water resources can support without destroying the ecological environment in a region, that is, ultimate water resources carrying capacity (UWRCC), helps to realize the sustainable utilization of water resources. UWRCC is a variable value which is easily affected by natural conditions, technical level and economic status. This study proposes a UWRCC research method that combines multi-objective optimization and scenario analysis. This method draws a diagram of UWRCC result sets based on multi-scenario UWRCC calculation, through which UWRCC values under different specific technical and economic levels are easily and quickly obtained. This method has been applied to Yancheng in this study and the quantitative relationship between technical level, economic level and UWRCC of Yancheng was analyzed. Taking Yancheng as the research area, this study analyzes the quantitative relationship between the technical level, economic level and UWRCC of Yancheng. The results show that according to existing government planning, Yancheng’s water resources will be sufficient to support socioeconomic development. But the districts of Yandu, Tinghu, and Binghai will experience population and gross domestic product overloading in future years. In addition, a diagram of the UWRCC sets of Yancheng was obtained and it provides a reference for local water resources management.

Key words | economic level, scenario analysis, technical level, ultimate water resources carrying capacity (UWRCC), water resources carrying degree, Yancheng

HIGHLIGHTS

- The characteristic indicators of ultimate water resources carrying capacity (UWRCC) are population and economic scale.
- A new analysis method of UWRCC is proposed.
- The UWRCC under different technical and economic levels of Yancheng were calculated.
- A diagram of the UWRCC result sets of Yancheng was drawn.
- Yancheng’s water resources will be sufficient to support development in the future.
INTRODUCTION

Since the 20th century, the global population has expanded rapidly and now exceeds 7.5 billion ($7.5 \times 10^9$). (Chen et al. 2020). With the development of technology and the economy, the living standard of human beings has been greatly improved. However, with the accompanying unreasonable exploitation and utilization of resources, the ecological environment has been seriously damaged. Major problems, including environmental pollution (Wang et al. 2020), ecological degradation (Shen et al. 2019), and resource shortages (Li et al. 2017) have gradually emerged. As an important part of natural resources, water is also confronted with over-exploitation (Liao et al. 2020). To ensure water security and to promote sustainable development of the social economy, scholars have conducted a wide range of research covering rational utilization and protection of water resources, and have gradually formed the concept of water resources carrying capacity (WRCC).

Until now, a major achievement of WRCC is the evaluation of water resources carrying status (WRCS) (Chi et al. 2019). WRCS refers to the overall status of the water resources system, the socioeconomic system and the ecological system in a particular region (Yang et al. 2020). It is evaluated by a comprehensive assessment system, which includes the degree of water resources development and utilization, the degree of social and economic development, the overall ecological health status of the region and other evaluation indicators. The commonly used evaluation methods range from fuzzy mathematics, to the binary index method, cloud model and ecological footprint theory (Dai et al. 2019; Yang et al. 2019; Wu et al. 2020; Zhang et al. 2020). The calculation method of WRCS is relatively simple and convenient for application (Peng & Deng 2020). However, the selection of evaluation indicators and the division of evaluation criteria have a significant impact on the calculation process, leading to a strong subjectivity on the final research results. Moreover, WRCS evaluation fails to offer the upper limit of population size and economic scale that the water resources can support in a region, which are critical values for any regional development strategy.

To break through the limitations of WRCS, research into ultimate water resources carrying capacity (UWRCC) is gradually increasing. UWRCC refers to the largest population size and Gross Domestic Product (GDP) scale that water resources can support in a region under specific economic and technical conditions, based on the premise of maintaining a healthy aquatic ecosystem (Yang et al. 2020). UWRCC is usually calculated using multi-objective programming models with the constraints of available water resources and water environmental capacity (Yan et al. 2019). Among them, Dou et al. (2015) proposed a distributed model that considers constraints like hydro-economic interactions, water supply, water quality, and socioeconomic development, which was applied to calculate the maximum population that the water resources can support in Henan Province. Li et al. (2016) established an optimization model based on approximate stochastic multiple objective programming, which was put to use for the optimization of industrial structures based on the water environmental carrying capacity in Huai River Basin in Shandong province. Meng et al. (2018) developed an inexact two-stage stochastic programming model to analyze the influence of flow level on the UWRCC of Yinma River Basin. Combined with an artificial neural network, Luo et al. (2019) presented an analysis model to predict maximum supportable population of water resources of the Beijing-Tianjin-Hebei region. These achievements provide scientific guidance for water resources management. However, UWRCC is a specific value under given economic and technical conditions. Indicators used to characterize economic and technical conditions, such as per capita GDP, water supply capacity of water conservancy projects, water use efficiency and sewage treatment level, will change during the development of a region, resulting in continuous dynamic changes of UWRCC. Therefore, instead of employing a single value, the UWRCC result sets under different economic and technical levels can provide better reference for the determination of regional development goals in the future.

Yancheng is located on the east coast of China. It is one of the major cities involved in the ‘Great Development Strategy of Jiangsu Coast’ and is under a plan to further expand its socioeconomic scale. However, as agriculture is the leading industry in Yancheng, accounting for 80% of the total water consumption in 2015, the water use
efficiency of Yancheng is relatively low and the contradiction between water supply and demand is relatively sharp. To achieve the goal of sustainable development, it is necessary to analyze the rationality of the planned socioeconomic scale and to put forward suggestions on the socioeconomic development of Yancheng from the perspective of water resources utilization.

To obtain the maximum socioeconomic scale that the water resources can support long term under different conditions in Yancheng, this study constructs a UWRCC calculation model that takes the maximum population size and the maximum GDP scale of a region as the objectives and takes water quantity and water quality as the main constraints. Then, combined with 16 computing scenarios, this study first quantitatively analyzes the influence of technical level (water use efficiency and sewage treatment) and economic level (GDP per capita) for UWRCC. Meanwhile, combined with different UWRCC results under different conditions, a diagram of the UWRCC result sets of Yancheng is obtained. The information it provides can help decision makers set and adjust the sustainable social economic development mode from the perspective of water resources without tedious calculations.

METHOD

Framework of the study

This study is divided into four steps, as is shown in Figure 1. The first step is identifying major influence factors for UWRCC for the study area. The second step is constructing the UWRCC calculation model. The third step is setting computing scenarios and calculating. The last step is analyzing the UWRCC results and drawing a diagram of the UWRCC result sets.

Analysis of influencing factors of UWRCC

The main influencing factors of UWRCC are divided into three categories: natural conditions, technical level, and economic status, as is shown in Figure 2. Natural conditions mainly include precipitation, underlying surface, and the number of rivers, and channel morphology, determining the carrying capacity of the carrying subject. In this study, natural conditions are specifically reflected in the amount of water resources and the self-purification capacity of the rivers. The amount of water resources affects the amount of available water supply in a region which refers to the maximum

![Figure 1](http://iwaponline.com/ws/article-pdf/21/6/3099/932668/ws021063099.pdf)
amount of water resources that is supplied by water conservation projects from rivers on the premise of maintaining the ecological flow of the rivers. At the same time, to protect the river ecosystem and to maintain the sustainable development of a region, the amount of pollutant emissions must be within the rivers’ self-purification capacity. The rivers’ self-purification capacity is represented by water environmental capacity. For two similar regions, UWRCC is larger in the one with a larger available water supply and a stronger rivers’ self-purification capacity. Technical level refers to the level of water resources development, utilization and protection. The development level reflects the water supply capacity of water conservation projects, including the ability to intake local water resources and transit water resources. The utilization level reflects the water use efficiency of social and economic sectors. The protection level refers to the reutilization and treatment capacity of tail water. Generally speaking, the higher the technical level, the larger the UWRCC. Economic status mainly refers to the industrial structure and the per capita GDP level of a region. For the industrial structure, compared with regions dominated by agriculture, regions dominated by industry and services cause less water consumption per unit benefit and a smaller pollution emission amount per unit benefit, and correspondingly a greater UWRCC value. In addition, UWRCC is characterized by population size and GDP scale, through which per capita GDP can be obtained. The calculated per capita GDP needs to meet the requirements of the corresponding economic development stage. The above factors will directly affect the UWRCC of a region. When constructing a UWRCC calculation model, natural conditions are considered as constraints, while technical and economic factors are considered by setting scenarios with different technical and economic levels to analyze the impact of their changes on UWRCC.

**Model description**

As is shown in Figure 3, the UWRCC model constructed in this study is a multi-objective optimization model. To realize the optimal allocation of water resources in space, an intact
region is divided into different calculation units before model construction. The model sets two objectives: maximum sum of population size of each calculation unit and maximum sum of GDP scale of each calculation unit. The model constraints include water quantity constraint, water quality constraint and socioeconomic constraint. (i) Water quantity constraint predominantly indicates that total water use of all water users must be less than the available water supply in each calculation unit. Water users are divided into three categories: domestic, production, and ecological environment, with a further seven sub-categories (urban domestic, rural domestic, primary industry, secondary industry, tertiary industry, environmental sanitation, and landscape plants). The water supply sources are divided into local water and transit water. Transit water is the public water source, and the amount of transit water allocated to each calculation unit is obtained through the model. Contrary to transit water, local water is supplied to its own calculation unit. (ii) Water quality constraint indicates that pollutant emissions from production and domestic sources into rivers must be less than the water environmental capacity of the rivers in each calculation unit. According to the requirements of the ‘Three Red Lines Policy’ formulated by China’s Ministry of Water Resources, chemical oxygen demand (COD) and ammonia nitrogen (NH3-N) are selected as the pollutant indicators in this model. Water environmental capacity here refers to the maximum amount of COD and NH3-N that can be contained in a water body on the premise of not affecting its function. The pollution sources are divided into point source and non-point source. Point source pollution includes the wastewater from domestic, secondary industry, and tertiary industry sources, which is discharged after being treated by sewage treatment plants. The pollution from agriculture is considered as non-point source pollution. (iii) Socioeconomic constraint includes three sub-constraints: industrial structure constraint, food supply constraint and economic level constraint. Industrial structure constraint is used to ensure that the calculated industrial structure of each calculation unit is reasonable. Food supply constraint is used to guarantee that local grain production meets the demand of the residents in each calculation unit. Economic level constraint refers to a requirement that GDP per capita is reaches a certain level to ensure the fine economic condition of residents in each calculation unit.

**Mathematical expressions**

Water use of domestic sources $W_{domestic_k}$, water use of primary industry $W_{1,k}$, water use of secondary industry $W_{2,k}$, and water use of tertiary industry $W_{3,k}$ in the calculation unit $k$ are decision variables of the model.

**Objectives**

1. **Maximum sum of GDP scale of each calculation unit** ($GDP_k$). The objective is expressed by Equation (1) and the GDP scale in each unit is calculated by Equation (2).

   \[
   \text{Max } f_1 = \sum_{k=1}^{K} GDP_k 
   \]

   \[
   GDP_k = \sum_{i=1}^{3} \frac{W_{ih}}{w_{use \_per \_gdp \_ik}}
   \]

   where $K$ is the number of calculation units, $W_{ih}$ is the water use of the industry $i$ in unit $k$, $w_{use \_per \_gdp \_ik}$ is the per-10,000-yuan-GDP water use of the industry $i$ in unit $k$.

2. **Maximum sum of population size of each calculation unit** ($POP_k$). The objective is expressed by Equation (3) and population size of each unit is calculated by Equation (4).

   \[
   \text{Max } f_2 = \sum_{k=1}^{K} \text{POP}_k
   \]

   \[
   \text{POP}_k = \frac{W_{domestic_k}}{w_{use \_urban \_k} \times r_{urban \_k} + w_{use \_rural \_k} \times (1 - r_{urban \_k})}
   \]

   where $W_{domestic_k}$ is the domestic water use in unit $k$, $w_{use \_urban \_k}$ is the urban domestic water use per capita in unit $k$, $r_{urban \_k}$ is the urbanization rate of the unit $k$, and $w_{use \_rural \_k}$ is the rural domestic water use per capita in unit $k$.

**Constraints**

1. **Water quantity constraint**. This constraint is that the sum of domestic water use, production water use and eco-environmental water use ($W_{environ_k}$) must be less than the
available water supply in each calculation unit. The water quantity constraint is expressed by Equation (5). The available water supply includes the available local water supply \((W_{\text{avail,local}})_k\) and the available transit water supply \((W_{\text{avail,transit}})_k\). The sum of the available transit water supply in each calculation unit is less than the total amount of available transit water supply in the region \((W_{\text{avail,f}})\), which is expressed by Equation (6). Eco-environmental water use of each calculation unit is calculated by Equation (7), which is the sum of environmental sanitation water use \((W_{\text{san}})_k\) and landscape plant water use \((W_{\text{lan}})_k\).

\[
W_{\text{domestic}} + \sum_{i=1}^{3} W_{i} + W_{\text{environ}} \leq W_{\text{avail,local}} + W_{\text{avail,transit}} \tag{5}
\]

\[
W_{\text{avail,f}} \geq \sum_{k=1}^{K} W_{\text{avail,transit}}_k \tag{6}
\]

\[
W_{\text{environ}} = W_{\text{san}} + W_{\text{lan}} = POP_k \times w_{\text{use,san}} + area_{\text{lan}} \times w_{\text{use,lan}} \tag{7}
\]

where \(W_{1_k}\) is the water use of primary industry in unit \(k\), \(W_{2_k}\) is the water use of secondary industry in unit \(k\), \(W_{3_k}\) is the water use of tertiary industry in unit \(k\), \(W_{\text{environ}}\) is the eco-environmental water use in unit \(k\), \(W_{\text{avail,local}}_k\) is the available local water supply in unit \(k\), \(W_{\text{avail,transit}}_k\) is the available transit water supply in unit \(k\), \(W_{\text{avail,f}}\) is the total amount of available transit water supply in the region, \(W_{\text{san}}_k\) is the environmental sanitation water use in unit \(k\), \(W_{\text{lan}}_k\) is the landscape plant water use in in unit \(k\), \(w_{\text{use,san}}_k\) is the environmental sanitation water use per capita in unit \(k\), \(area_{\text{lan}}_k\) is the landscape plants area in unit \(k\), and \(w_{\text{use,lan}}_k\) is the landscape plants water use per unit area in unit \(k\).

(2) **Water quality constraint.** This constraint is that pollutant emissions of COD and NH\(_3\)-N must be less than the water environmental capacity of rivers for each calculation unit. Because of the same calculation process, the study uses COD as an example to illustrate its specific mathematical expression. The constraint is expressed by Equation (8). The pollutant emissions of COD in unit \(k\) (\(COD_k\)) is calculated by Equation (9). The pollutant sources are divided into point source and non-point source. The pollutant emissions from point source, that is domestic source (\(COD_{\text{domestic}}_k\)), secondary industry source (\(COD_{\text{production}}_{2_k}\)) and tertiary industry source (\(COD_{\text{production}}_{3_k}\)), are calculated by Equations (10), (12), (13), respectively. The pollutant emissions from non-point source, that is agriculture source (\(COD_{\text{production}}_{1_k}\)), are calculated by Equation (11). The water environmental capacity of COD of unit \(k\) \((COD_{\text{environ}}_{\text{capa}}_k)\) is calculated by one-dimensional hydrodynamic model.

\[
COD_k \leq COD_{\text{environ}}_{\text{capa}}_k \tag{8}
\]

\[
COD_k = COD_{\text{domestic}}_k + \sum_{i=1}^{3} COD_{\text{production}}_{i_k} \tag{9}
\]

\[
COD_{\text{domestic}}_k = W_{\text{domestic}} \times r_{\text{pollinriver}}{3_k} \times r_{\text{poll,concen,cod}}_k \tag{10}
\]

\[
COD_{\text{production}}_{1_k} = \frac{W_{1_k}}{w_{\text{use,per,gdp}}_1 \times gdp \times perarea} \times poll_{\text{cod}} \times r_{\text{pollinriver,1,cod}}_k \tag{11}
\]

\[
COD_{\text{production}}_{2_k} = W_{2_k} \times r_{\text{pollinriver}}{2_k} \times r_{\text{poll,concen,cod}}_k \tag{12}
\]

\[
COD_{\text{production}}_{3_k} = W_{3_k} \times r_{\text{pollinriver}}{3_k} \times r_{\text{poll,concen,cod}}_k \tag{13}
\]

where \(COD_k\) is the pollutant emissions of COD in unit \(k\), \(COD_{\text{environ}}_{\text{capa}}_k\) is the water environmental capacity of COD of unit \(k\), and \(COD_{\text{domestic}}\), \(COD_{\text{production}}_{1_k}\), \(COD_{\text{production}}_{2_k}\), \(COD_{\text{production}}_{3_k}\) are the pollutant emissions from domestic, agriculture, secondary industry, tertiary industry in unit \(k\), respectively. \(r_{\text{pollinriver}}{3_k}\) is the proportion of_COD_3_k_ is the proportion of domestic and tertiary industry water that goes into the rivers after consumption and treatment in unit \(k\), \(r_{\text{poll,concen,cod}}_k\) is the COD concentration of domestic and tertiary industry tail water in unit \(k\), \(gdp\) and \(perarea\) is the output value per unit area of agricultural planting in unit \(k\), \(poll_{\text{cod}}\) is the COD emissions per unit area of agricultural planting in unit \(k\), \(r_{\text{pollinriver,1,cod}}_k\) is the proportion of COD produced by agricultural planting that goes into the rivers in unit \(k\), \(r_{\text{pollinriver,2}}\) is the proportion of the secondary industry...
water that goes into the rivers after consumption and treatment in unit $k$, $r_{poll.in.concen} \cdot cod_k$ is the COD concentration of the secondary industry tail water in unit $k$.

(3) Socioeconomic constraint. This constraint includes three aspects: industrial structure constraint, food supply constraint and economic level constraint.

The industrial structure constraint is expressed by Equation (14). The upper limit ($r_{ind}^{\text{max},ik}$) and lower limit ($r_{ind}^{\text{min},ik}$) of the proportion of industry $i$ in GDP in unit $k$ are determined by actual values in previous years, and the proportion of industry $i$ in unit $k$ ($r_{ind}^{\text{cal},ik}$) is calculated by formula (15).

\[
r_{ind}^{\text{min},ik} \leq r_{ind}^{\text{cal},ik} \leq r_{ind}^{\text{max},ik}
\]

\[
r_{ind}^{\text{cal},ik} = \frac{W_{ik}}{w_{use} \cdot dp_{ik} \cdot \text{GDP}_k}
\]

The food supply constraint is expressed by Equation (16), which refers to grain production ($food_{cal,k}$) being larger than food demand ($food_{demand,k}$) in unit $k$. The grain production is calculated by Equation (17) and the food demand is calculated by Equation (18). However, because the cultivated land of unit $k$ ($cultiarea_k$) is limited, the maximum grain production, that is the planting area ($plantarea_{cal,k}$), is constrained, which is expressed by Equation (19). The planting area is calculated by Equation (20).

\[
food_{cal,k} \geq food_{demand,k}
\]

\[
food_{cal,k} = \frac{W_{ik}}{w_{use} \cdot dp_{ik} \cdot \text{GDP}_k} \times \text{per.area}_{k}
\]

\[
food_{demand,k} = \text{POP}_k \times \text{dem.capital}
\]

\[
plantarea_{cal,k} \leq cultiarea_k
\]

\[
plantarea_{cal,k} = \frac{W_{ik}}{w_{use} \cdot dp_{ik} \cdot \text{GDP}_k \times \text{index.multiprop}}
\]

where $food_{cal,k}$ is the grain production in unit $k$, $food_{demand,k}$ is the food demand in unit $k$, $food_{per.area}$ is the grain yield per unit area in unit $k$, $food_{dem.capital}$ is the food demand per capita, $plantarea_{cal,k}$ is the planting area in unit $k$, $cultiarea_k$ is the cultivated land area of unit $k$, and $index_{multiprop}$ is the multiple cropping index, which refers to the average planting times on the same cultivated land in one year.

The economic level constraint refers to GDP per capita ($GDP_{per.capital,k}$) which is required to reach a certain level ($GDP_{per.capital,k}$) to ensure the fine economic conditions of residents in each calculation unit, which is expressed by Equation (21). The GDP per capita is calculated by Equation (22).

\[
GDP_{per.capital,k} \geq GDP_{per.capital,k}
\]

\[
GDP_{per.capital,k} = \frac{\text{GDP}_k}{\text{POP}_k}
\]

where $GDP_{per.capital,k}$ is the calculated GDP per capita in unit $k$, and $GDP_{per.capital,k}$ is the required value of the GDP per capita in unit $k$.

Model solution

As is shown in Figure 4, a genetic algorithm (GA) is used to solve the UWRCC model (Chang et al. 2010). Specifically, the first step is to generate the initial population of the aforementioned decision variables. The initial population size is 40. The second step is to construct the fitness function, which is expressed by formula (23):

\[
F(x) = \sum_{m=1}^{M} \rho_m f_m(x)
\]

where $F(x)$ is the fitness function and $\rho_m$ is the weight of the objective $m$. In this study, the objectives in the model are considered to be equally important, so the weight of each objective is $1/M$, that of $1/2$. $f_m(x)$ is the normalized objective function of the objective $m$ after eliminating the influence of the objective’s dimension.

The third step is to use the initial population and the fitness function to finish the genetic operations (i.e., selection, crossover and mutation) of the GA method. When the difference in fitness between neighboring generations is <0.1, the iteration is terminated and the population with the
maximum fitness is selected as the solution of the decision variables. Finally, the UWRCC value of the region is figured out by the calculated decision variables.

STUDY AREA AND COMPUTING SCENARIOS

Study area

Yancheng, Jiangsu Province, China, was selected as the research area in this study. Yancheng is located in the lower reaches of the Huai River, in the middle east of North Jiangsu Plain, between 32°34′-34°38′ N and 119°27′-120°54′ E. The mean annual precipitation is 1,016.6 mm and the value decreases from south to north inside Yancheng. The mean annual runoff is 4,317 million m³ and the equivalent runoff depth is 254.0 mm. Yancheng has jurisdiction over 9 districts and counties. By 2015, the total population of the city was 8.28 million, of which 4.56 million were an agricultural population, accounting for 55.13%, and 3.72 million were a non-agricultural population, accounting for 44.87%. The GDP of the whole city was 380 billion yuan, and the industrial structure ratio was 13.6: 47.0: 39.4 (primary to secondary to tertiary industry). Yancheng is one of the major cities involved in the ‘Great Development Strategy of Jiangsu Coast’ and its socioeconomic scale is planned to be further expanded.

This study divided the research area into 9 calculation units based on the county-level administrative districts, namely Tinghu, Yandu, Dongtai, Dafeng, Xiangshui, Binghai, Funing, Sheyang and Jianhu. The geographical location of Yancheng is shown in Figure 5.

Construction of computing scenarios

To make the calculated UWRCC meet the concept of long-term and stable support, the available water supply in an extremely dry year (after frequency analysis of long series data of annual water resources using the P-III distribution curve, the water quantities of an extremely dry year correspond to the 90% frequency on the P-III distribution curve) of Yancheng was selected as the water quantity input of the model. To compare the influence of different economic levels and technical levels on the UWRCC results, different computing scenarios were set in this study. The influencing factors of technical level included three types of water supply capacity of water conservancy projects, water use efficiency and sewage treatment level. In this study, water supply capacity was not considered in scenario analysis because the water supply capacity of water conservancy projects exceeds the amount of water resources in Yancheng. The technical level in this study was considered from two aspects: water use efficiency and sewage treatment level. It was characterized by a series of parameters and they could also be divided into four grades: basic, medium, relatively high, and high. They referred to the level that Yancheng can reach in 2015, 2020, 2025 and 2030, respectively. Economic level was characterized by the indicators of per capita GDP and industrial structure, which were both divided into four grades: basic, medium, relatively high, and high. The above four economic levels correspond to the economic situation of Yancheng in 2015, 2020, 2025 and 2030, respectively. Combining the above different technical levels and economic levels, 16 different scenarios were obtained. The scenario numbers and the corresponding

Figure 4 | Model solution process.
technical levels and economic levels are shown in the Table 1. Among them, Scenarios I, V, IX, and XIII represented the actual scenario in 2015 and the planned scenarios in 2020, 2025, and 2030 of Yancheng, respectively.

### Data

The data for this study were mainly collected from three sources. Water Resources Bulletin of Yancheng offered water supply and water use data. Water Resources Integrated Planning of Yancheng included the data of the existing and planning water supply projects. Socio-economic data, such as current and planning population, economic level of different years and available cultivated area were collected from Statistical Yearbooks and related socio-economic development planning. The parameter values of the model which could reflect different technical and economic levels were calculated on the basis of the collected data, as is shown in Table 2.
RESULTS

The UWRCC results of 16 computing scenarios for Yan- cheng are shown in Table 3. Scenario XIII (economic level: basic, technical level: high) has the largest population of each calculation unit, with a total population of 14.17 million, and a GDP of 712.39 billion yuan. Scenario IV (technical level: basic, economic level: high) has the smallest population of each calculation unit, with total population of 4.37 million, only one third of scenario XIII, and a GDP of 864.77 billion yuan. Meanwhile, Scenario XVI (economic level: high, technical level: high) has the largest GDP of each calculation, with total GDP of 1,756.81 billion yuan, and a population of 8.87 million. Scenario I (technical level: basic, economic level: basic) has the smallest GDP of each calculation unit, with total GDP of 313.59 billion yuan, and a population of 6.87 million. Overall, for four different economic scenarios with the same technical level, the higher the economic level, the smaller the population size and the larger the GDP scale in UWRCC. For four different technical scenarios with the same economic level, the higher the technical level, the larger the population size and the GDP scale in UWRCC.

The technical level and economic level of Scenarios I, VI, XI, and XVI correspond to that of 2015, 2020, 2025 and 2030, respectively. The populations of the four scenarios in UWRCC for Yancheng are 6.87 million, 7.50 million, 8.86 million and 8.87 million. The GDP of the four scenarios in UWRCC are 313.59 billion yuan, 733.28 billion yuan, 1,324.66 billion yuan and 1,756.82 billion yuan. It is thus clear that the population size and economic scale are on the rise.

DISCUSSION

Analysis of water resources carrying degree in Yancheng

The relationship between the actual socioeconomic size and the UWRCC value in Yancheng in 2015, 2020, 2025 and 2030 is analyzed based on water resources carrying degree (WRCD), which is calculated according to formula (24):

\[
r = \frac{P}{P_{\text{max}}} + \frac{\text{GDP}}{\text{GDP}_{\text{max}}} - \frac{1}{2}
\]

where \( r \) is the value of WRCD, \( P \) is the actual population size and \( P_{\text{max}} \) is the population size in UWRCC, \( \text{GDP} \) is the actual GDP scale and \( \text{GDP}_{\text{max}} \) is the GDP scale in UWRCC. Among them, the \( P \) value and GDP value of 2015 refer to the ‘Yancheng Economic Development Bulletin’. The \( P \) values and GDP values of 2020, 2025, and 2030 were calculated by referencing ‘Yancheng Socioeconomic Development Planning’ (Yancheng Government, undated). When \( r > 1 \), the region is in an overloaded state and when \( r \leq 1 \), the region is in a sustainable state.

Table 2 | Numerical values of the parameters of each economic level and technical level

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter values</th>
<th>Basic</th>
<th>Medium</th>
<th>Relatively high</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>Per capita GDP (10^4 yuan/person)</td>
<td>4</td>
<td>9</td>
<td>14</td>
<td>19</td>
</tr>
<tr>
<td>Technical</td>
<td>Per-10,000-yuan-GDP water use of the primary industry (m³/10^4yuan)</td>
<td>250</td>
<td>200</td>
<td>135</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Per-10,000-yuan-GDP water use of the secondary industry (m³/10^4yuan)</td>
<td>20</td>
<td>16</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Per-10,000-yuan-GDP water use of the tertiary industry (m³/10^4yuan)</td>
<td>5</td>
<td>4</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Urban domestic water use per capita (m³/person)</td>
<td>90</td>
<td>100</td>
<td>105</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Rural domestic water use per capita (m³/person)</td>
<td>70</td>
<td>75</td>
<td>85</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>The COD concentration of point source after treatment (mg/L)</td>
<td>100</td>
<td>60</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>The TN concentration of point source after treatment (mg/L)</td>
<td>25</td>
<td>8</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>The proportion of urban water use into the rivers</td>
<td>0.9</td>
<td>0.8</td>
<td>0.7</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Proportion of COD produced by agricultural production into the rivers</td>
<td>150</td>
<td>135</td>
<td>120</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>Proportion of TN produced by agricultural production into the rivers</td>
<td>30</td>
<td>27</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>The COD emission amount per area of agricultural production (kg/hectare)</td>
<td>0.3</td>
<td>0.25</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>The TN emission amount per area of agricultural production (kg/hectare)</td>
<td>0.3</td>
<td>0.25</td>
<td>0.2</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Table 3 | The UWRCC calculation results of each scenario in Yancheng

<table>
<thead>
<tr>
<th>Calculation unit</th>
<th>POP</th>
<th>GDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiangshui</td>
<td>48.80</td>
<td>208.38</td>
</tr>
<tr>
<td>Binghai</td>
<td>98.10</td>
<td>406.13</td>
</tr>
<tr>
<td>Funing</td>
<td>85.40</td>
<td>569.78</td>
</tr>
<tr>
<td>Sheyang</td>
<td>90.90</td>
<td>415.41</td>
</tr>
<tr>
<td>Jianhu</td>
<td>82.30</td>
<td>481.46</td>
</tr>
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<td>Binghai</td>
<td>98.10</td>
<td>406.13</td>
</tr>
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<td>481.46</td>
</tr>
</tbody>
</table>

Note: POP refers to the maximum population size; its unit is 10^4 persons. GDP refers to the maximum GDP scale, its unit is 10^8 yuan.
The WRCD calculation results are shown in Figure 6. From 2015 to 2030, the WRCD value of Yancheng dropped from 1.05 to 0.9, which meant the water resources carrying status changed from overloaded to sustainable. It showed that in accordance with the government’s planning of water resources utilization and socioeconomic development, Yancheng’s water resources would be sufficient to support the population and GDP in the future. From the perspective of districts, the variations of WRCD values were different. The WRCD values of Binghai and Tinghu showed a clear upward trend. Binghai was in a sustainable state in 2015 and then deteriorated into an overloaded state in subsequent years, while Tinghu remained overloaded for all four years. The districts showing a downward trend in WRCD values were Xiangshui, Jianhu, Yandu, Dongtai, and Dafeng. In these districts, except Yandu, water resources were in a sustainable state in future years. Although different in the changing trend of WRCD value, water resources carrying condition of Yandu and Tinghu were similar, overloaded for all four years. For Funing and Sheyang, WRCD values changed insignificantly each year, fluctuating around 1. In order to cope with the possible overload situation in Yandu, Tinghu, and Binghai in the future, further measures should be taken on the basis of existing plans. Specifically, for Yandu and Tinghu, because of the concentration of industry and the relatively large economic scale, the population and major industries should be guided to move to other sustainable districts by adjusting the industrial distribution in the future. For Binghai, water use efficiency and the reutilization and treatment capacity of wastewater should be improved.

Explanation and application of the diagram of UWRCC result sets

The diagram of the UWRCC results of Yancheng and its explanation

Points in Figure 7 represent the calculated population size of different computing scenarios. The points of the same technical level were fitted into a curve and finally four curves were obtained.

Two characteristics of the diagram need to be noted. First, with the increase in per capita GDP, the curves in the diagram show a downward trend. This means that with the increase of regional economic demand, the population size that water resources can carry will gradually decrease. This is due to the competition relationship between domestic water use and production water use. If we assume that the population of a region is $X$, the per capita GDP is $Y_1$, the domestic water use per capita is $D_d$, and the per-10,000-yuan-GDP water use is $D_e$, then, the total water use of the social economy $Z_1$ can be expressed by Formula (25). When calculating the UWRCC in this study, the value of $Z_1$ is set as the maximum available socioeconomic water supply, which is a constant. When the technical level, namely the water use efficiency indicators $D_d$ and $D_e$, are also constants, the increase in the economic level, that is, the per capita GDP $Y_1$, will inevitably lead to a decrease in the population size $X$.

$$Z_1 = X \times D_d + X \times Y_1 \times D_e$$ (25)
The second characteristic to be noted is that the higher the technical level is, the higher the position of the corresponding curve in the diagram. This shows that for the same economic level, when the technical level improves, the population that water resources can carry in Yancheng will increase. Moreover, multiple curves representing different technical levels are parallel to each other. Assuming that two curves representing different technical levels intersect, there will inevitably be a situation that a smaller population can be carried under a higher technical level. That is to say, the increase in water use efficiency and sewage treatment level will lead to a decrease in population, which is obviously wrong. That is why the curves in the diagram cannot intersect.

**Application of the diagram of UWRCC result sets**

The diagram of UWRCC result sets for Yancheng reflects the relationship between the three variables of technical level, economic level and the largest population size that can be carried by water resources. In the case that any two variables are known, the unknown variable can be quickly and directly derived from this diagram. Specifically, when the future population size of Yancheng is determined, a straight line representing the determined population size parallel to the abscissa can be drawn in the diagram of UWRCC result sets. The points where the line intersects the curves represent several different socioeconomic development modes for the determined population size. Each development mode corresponds to a certain economic level and technical level. On the other hand, if the economic level and technical level of Yancheng are determined, the optimal population size can be found using in the diagram.

The diagram is an intuitive presentation of the UWRCC result sets of Yancheng, which provides a concise and straightforward assistant for decision makers to set and adjust the socioeconomic development mode from the perspective of water resources without tedious calculations. Certainly, the diagram can be further refined from the following two aspects: firstly, for each technical level, more economic level scenarios can be set up to increase the point density to better fit the curve, so as to make the fitting results more credible; secondly, more technical level scenarios can be added to increase the number of curves and expand the applicability of the diagram.

**Applicability and limitations**

The method proposed in the study seeks the largest socioeconomic scale of a region under different economic and technical levels from the perspective of the sustainable utilization of water resources. Two aspects should be paid attention to when applying this method to other areas. The first aspect is parameter determination of the UWRCC calculation model, such as values of available water supply.
and water environment capacity, which need lots of preliminary work. The second is that, before applying the scenario analysis method, it is necessary to identify the major factors of UWRCC to reduce calculation.

The UWRCC research can be improved in the future as follows. Firstly, the calculation step length in the model is one year, which does not take into account the uneven distribution of precipitation (Zhan et al. 2018) and socioeconomic water demand during the year. Especially for grain planting, there are some differences in the water demand in different periods of the planting cycle (Cao et al. 2019). In later research, the calculation step length could be set as a month to reflect the above influence. Secondly, the water exchange brought by grain trade between regions is not considered. Yancheng is the main grain base of Jiangsu Province, whose production fully meets the local grain demand, so its impact is not considered. In regions with high socioeconomic development and dominated by industry and services, local grain yield is low. These regions meet the residents’ grain demand mainly by purchasing grain from other regions and the virtual water contained in the purchased grain reduces the agricultural water demand (Zhao et al. 2020), which has an impact on the UWRCC values. This issue can be studied combining with virtual water theory in future UWRCC research.

CONCLUSION

To help decision makers set and adjust the sustainable socioeconomic development mode from the perspective of water resources, this paper proposed an UWRCC calculation method combined with multi-programming model and scenario analysis. By applying this method to Yancheng, the UWRCC results under different technical levels and economic levels are obtained. Generally, for different economic scenarios with the same technical level, the higher the economic level, the smaller the population size and the larger the GDP scale in UWRCC, for different technical scenarios with the same economic level, the higher the technical level, the larger the population size and the GDP scale in UWRCC. In addition, the calculation results of Scenarios I, VI, XI, and XVI corresponded to the UWRCC values of Yancheng in years 2015, 2020, 2025, and 2030, which are 6.87 million persons and 313.59 billion yuan, 7.50 million persons and 735.28 billion yuan, 8.86 million persons and 1,324.66 billion yuan and 8.87 million persons and 1,756.82 billion yuan, respectively. Analyzing the WRCD of these four years showed that Yancheng’s water resources would be sufficient to support the population and GDP in the future. However, as far as districts are concerned, Yandu, Tinghu, and Binghai would experience population and GDP overloading in future years. Based on the UWRCC result, a diagram of the UWRCC result sets under different technical and economic levels in Yancheng was drawn in this study. This diagram reflected the quantitative relationship between the three variables of technical level, economic level and the maximum sustainable population size. Decision makers can get information about UWRCC directly and conveniently from this diagram. Some aspects could still be improved. Firstly, the calculation step length in the model can be changed from year to month. Secondly, virtual water theory can be introduced to analyze the impact of grain trade of UWRCC.

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DATA AVAILABILITY STATEMENT

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

REFERENCES


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