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# Calculation model and management system of WRCC based on grey water footprint calculation

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**ABSTRACT**

As the increasing population and rapid urbanization, the pressure on water resources has increased and water environment problems have become more serious. Traditional water resource management methods can no longer meet current and future needs, and new models need to be found. The gray water purification and reuse is an effective water-saving measure. Therefore, based on the regional water consumption and ash water pollution, the assessment model of water resource carrying capacity in this area is established. Then, it improves the elimination rate of gray water, increases the return flow of gray water resources, and thereby increases the carrying capacity of water resources. Finally, performance testing and simulation application analysis are carried out on the model. The results denote that the maximum error in the calculation of population carrying capacity of the model is 2%, with a fitness of about 99%. The stability of different environmental data testing is close to 100%, and the running time of data in D and F is about 30 and 10 min, respectively. And it is predicted that by 2040, when the gray water treatment rate in a certain region reaches 0.93 or above, the predetermined water resource carrying capacity of the region can be achieved. Based on the above data, it demonstrates high accuracy and adaptability, and can efficiently calculate the regional population resource carrying capacity. It has certain reference significance for further promoting the scientific and standardized management of gray water resources.

*Keywords:* Grey water footprint; Water resource carrying capacity; Ecological environment; Water resources management

## 1. Introduction

As the speed growth of social economy and population, water resources have become one of the scarce resources worldwide. The contradiction between supply and demand of water resources is becoming increasingly severe, and one of the most important issues is the recycling and utilization of gray water resources. Traditional water resource management methods often only focus on the balance between supply and demand of water resources, while neglecting the consideration of maximizing water resource utilization. To more effectively evaluate and manage water resources, more people are paying attention to the calculation and institutional design of water resource carrying capacity (WRCC) [1,2]. At present, there are huge problems in the calculation of WRCC, which requires a large amount of data, involving multiple fields and departments, and these data often come from different data sources. The parameter assumptions, calculation methods, and data quality in model calculations all have uncertainties. Calculation usually takes into account multiple factors such as geology, climate, ecology, and socio-economic factors, resulting in high computational complexity. The calculation results are closely integrated with the actual social, economic, and political environment [3,4]. For this reason, a simplified calculation model is studied. The total

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regional water consumption is water for social and economic development and water for ecological environment maintenance. Grey water footprint (GWF) is used to calculate grey water pollutants. On this basis, a calculation model of WRCC based on GWF is established. The relevant water resource protection and utilization policies are formulated based on specific issues using adaptive management strategies. The research is divided into four sections. The first section mainly explains the research on GWF and WRCC by many scholars both domestically and internationally; The second section mainly explains the calculation process of water resource usage and grey water pollution, and based on this, establishes a WRCC calculation model based on GWF; The third section mainly explains the testing methods and simulation applications related to model calculation accuracy, fitness, efficiency, and stability; The fourth section mainly analyzes the performance testing and simulation application results of the model.

## 2. Related works

Water resources are a fundamental condition for human survival and development, but currently there is a serious global shortage and pollution of water resources. The calculation of WRCC can make more reasonable and effective use of water resources. Therefore, many experts and scholars have conducted research on WRCC in general and achieved fruitful results. Chi et al. [5] used analytic hierarchy process and fuzzy discriminant analysis to predict WRCC, and conducted empirical research using a certain mining area as an example. The research findings indicated that this method could effectively predict the WRCC. Huang et al. [6] used system dynamics models to dynamically predict and regulate WRCC. Through model simulation of different water resource carrying capacities and comparative analysis, corresponding adjustment strategies were proposed. The research outcomes denoted that establishing dynamic prediction models and adjustment strategies could effectively improve water resource utilization efficiency and protect the environment, while achieving sustainable development and increasing WRCC. Yang and Yang [7] established a corresponding model and simulated the impact of factors such as water resource utilization, ecosystem status, and climate change on WRCC in the region. The experimental findings indicated that under the impact of climate change and human activities, the WRCC of the Koriya River Basin showed a clear dynamic trend of change. This study provided a scientific basis for scientific management and protection of water resources in the southern edge of Taklamakan Desert, as well as a reference for water resources management in other arid areas. Pu et al. [8] used multi-source remote sensing data and GIS technology to assess the carrying capacity of karst mountain resources. Through collecting remote sensing image data of different time scales, and applying GIS technology to process and analyze the data, a model for evaluating the carrying capacity of karst mountain resources was established. The experiment outcomes expressed that this method could accurately evaluate the resource and environmental carrying capacity of different regions. Yang and Yang [7] explored the dynamic WRCC of the Koliya River basin on the southern edge of the Taklamakan Desert. By analyzing factors such as water resource utilization, ecosystem status, and climate change in the region, corresponding models were established and simulated. It was found that under the impact of climate change and human activities, the WRCC of the Koriya River Basin showed a significant dynamic trend of change.

Grey water reuse is an effective water-saving measure, but due to the pollution problem of grey water, it is not widely used. Hossain et al. [9] used life-cycle assessment (LCA) framework and water footprint method to assess and analyze the water footprint of Australia's agricultural system. And it also explored the importance and challenges of water footprint assessment in sustainable agricultural development, and proposed suggestions to further improve the water use efficiency and sustainability of agricultural systems. Yao et al. [10] analyzed the effects of different nitrogen fertilizer application rates on nitrogen leaching and GWF, and the outcomes expressed that appropriate nitrogen fertilizer application rates could minimize nitrogen leaching and GWF while ensuring crop yield and quality. This research was of great significance to reduce agricultural pollution and protect water resources. To determine the GWF of groundwater resources in an area, Yapıcıoğlu and Yeşilnacar [11] investigated different recharge sources and analyzed the impact of groundwater recharge. The results indicated that different sources of supply would have an impact on the GWF. Yapıcıoğlu [12] used Monte Carlo simulation to evaluate the GWF of dye industrial wastewater treatment plants, and discussed the impact of wastewater reuse on minimizing the GWF. The research findings denoted that the main sources of GWF were the utilization of water resources and the discharge and treatment of sewage. Yan et al. [13] analyzed the dissolution and transport characteristics of different heavy metals and established a new model to calculate the GWF. This model could provide sustainable water resource management strategies for mining enterprises, effectively reducing the impact of mining wastewater on water resources. Cui et al. [14] utilized the water footprint assessment method to calculate the GWF of each economic zone, and used multiple regression analysis to evaluate the degree of influence of various factors on the GWF. The research outcomes provided a basis for formulating reasonable water resource management policies and strategies in various regions of China. Ansorge et al. [15] applied the water footprint assessment method to calculate and compare the GWFs of pollution point sources in two representative cities (Brno and Olomouc). The research findings indicated that sewage treatment plants were the main contributors to the GWF generated by pollution point sources in these two cities, accounting for over 70% of the total GWF. Yapıcıoğlu [16] studied the GWF of a dairy industrial wastewater treatment plant, and compared the traditional wastewater treatment technology with the new membrane filtration technology. The research findings meant that the degree of impact of gray water on the environment depends on the technology and management methods of wastewater treatment. Compared with traditional and new membrane filtration processes, the new membrane filtration process performed better in reducing the GWF.

From the research of domestic and foreign scholars mentioned above, evaluating WRCC requires considering multiple factors, and GWF is one of the important indicators for evaluating water resource utilization efficiency and environmental costs. It considers the relationship between the use of water resources and pollution generation, reflecting the efficiency of water resource utilization and environmental costs. Based on this, a WRCC calculation model based on GWF is proposed. It hopes to accurately calculate the regional WRCC, establish relevant policies and systems, strengthen water resource management, maintain social ecological environment, and promote sustainable development.

## 3. Calculation model of WRCC based on GWF

The first section mainly analyzes the calculation method of water consumption and grey water pollutants required to construct a WRCC calculation model based on GWF. In the second section, based on the total water consumption, the total amount of environmental water resources and gray water purification water, the evaluation system of WRCC is constructed. And the nonlinear equation for carrying capacity calculation is constructed. Understanding these elements can help us better understand the WRCC and provide a basis for formulating corresponding water resource protection and management measures.

### *3.1. Analysis of water consumption and grey water pollution in water resources*

The precise calculation of WRCC can provide a clear understanding of the supply and demand status and sustainable utilization capacity of water resources in a certain region, and provide a basis for water resources management and protection and the formulation of relevant policies. The research mainly calculates the water resource usage in the area from two aspects: water for socio-economic development and water for ecological environment maintenance. The distribution of water resource usage is shown in Fig. 1.

As shown in Fig. 1, water for ecological environment maintenance includes water demand inside and outside the ecological environment of the water storage area (including all water areas such as rivers and lakes). The equation for calculating the amount of water required to maintain the normal operation of the ecological environment in the local water storage area is shown in Eq. (1).

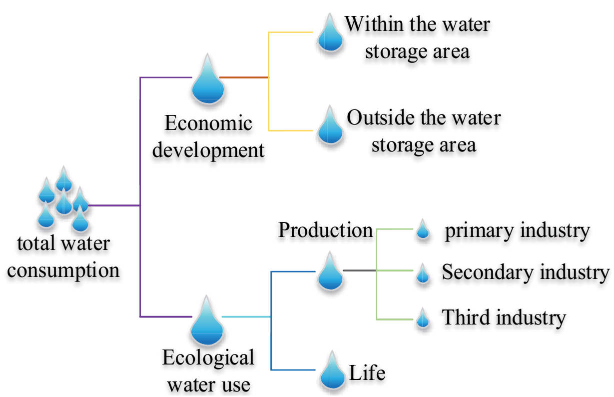


Fig. 1. Distribution of water resource usage.

$$W_1 = 24 \times 3600 \times \sum_{i=1}^{12} M_i \times Q_i \times P_i \tag{1}$$

where $W_1$ means the water demand for maintaining the normal operation of the water storage area; $Q_i$ denotes the average water flow rate of the month; $M_i$ expresses the actual number of days in the month; $P_i$ is the percentage of environmental water demand around the monthly storage area. The ecological environment water outside the local water storage area mainly includes urban environmental water, green vegetation construction water, and urban wetland environmental water. Urban environmental water usage helps improve the environment and hygiene, and its water consumption is shown in Eq. (2).

$$\begin{cases} W_2 = W_{2.1} + W_{2.2} \\ W_{2.1} = S_G \times q_G \\ W_{2.2} = S_c \times q_c \end{cases} \tag{2}$$

where $W_2$ represents urban environmental water use; $W_{2.1}$ indicates the water consumption of green space environment; $S_G$ refers to the area of urban green space; $q_G$ stands for the average water used for irrigation; $W_{2.2}$ denotes the water used for urban environmental sanitation; $S_c$ indicates the urban area; $q_c$ means the average water usage for urban sanitation per unit area. Green vegetation water can improve climate and maintain soil and water, and its water consumption $W_3$ is shown in Eq. (3).

$$W_3 = \sum_{i=1}^{n} S_{\text{pi}} \times q_{\text{pi}} \tag{3}$$

where $S_{\text{pi}}$ denotes the area of the *i*-th type of green vegetation; $q_{\text{pi}}$ means the average irrigation water used for the first planting. The water usage of urban wetland environment plays an important role in improving urban environment and ecological protection, and its water consumption $W_4$ is shown in Eq. (4).

$$\begin{cases} W_4 = W_{4.1} + W_{4.2} \\ W_{4.1} = 10 \times S_L \times (E_L - P) + F - R_L \\ W_{4.2} = 10 \times S_W \times (E_W - P) + F - R_W \end{cases} \tag{4}$$

where $W_{4.1}$ means the water consumption of constructed wetland; $S_L$ is the water surface area of the constructed wetland to be maintained; $P$ denotes the local average rainfall; $E_L$ expresses the water surface evaporation of constructed wetland; $F$ means the water permeability; $R_L$ indicates the runoff into constructed wetland; $W_{4.2}$ refers to the water consumption of natural wetlands; $S_W$ is the water surface area of the natural wetland that needs to be maintained; $E_W$ stands for the water surface evaporation of the natural wetland; $R_W$ represents the runoff into the natural wetland. The water used for social and economic development mainly includes two aspects: domestic and production water. Due to the significant differences in domestic water use between urban and rural residents, the study divided the domestic water use of residents into urban and rural areas, and the water consumption is shown in Eq. (5).

$$\begin{cases} W_5 = W_{5.1} + W_{5.2} \\ W_{5.1} = \text{Po}_1 \times \text{LQ}_1 \times 365 \\ W_{5.2} = \text{Po}_2 \times \text{LQ}_2 \times 365 \end{cases} \quad (5)$$

where it represents the total amount of domestic water used by $W_5$; $\text{LQ}_1$ and $\text{LQ}_2$, respectively mean the daily average total amount of water used by urban and rural residents, and $\text{Po}_1$ and $\text{Po}_2$ express the total number of residents. And residential production water includes production water for the first, second, and third industries. The study uses the quota method to calculate its water consumption, which sets the highest water consumption for each link based on the historical average water consumption. The primary sector of the economy is farm water, mainly including agriculture, forestry and fishery [17], and its water consumption is shown in Eq. (6).

$$\begin{cases} W_6 = W_{6.1} + W_{6.2} + W_{6.3} \\ W_{6.1} = \dfrac{\sum_{k=1}^{n} ZQ_{\text{ik}} \times A_{\text{ik}}}{\eta_{\text{ti}} \times \eta_{\text{si}}} \\ W_{6.2} = \text{FQ}_i \times A_{\text{Fi}} \\ W_{6.3} = \left(\text{XBQ}_i \times \text{PB}_i + \text{XSQ}_i \times \text{PS}_i\right) \times 365 \\ W_{6.4} = \text{YQ}_i \times A_{\text{ri}} \end{cases} \quad (6)$$

where $W_{6.1}$ denotes the water demand of crops in the $i$-th calculation area; $k$ refers to the type of crop; $\text{ZQ}_{\text{ik}}, A_{\text{ik}}$ represents the average water consumption and area for crop irrigation in the region; $W_{6.3}$ is the irrigation field utilization coefficient; $\eta_{\text{si}}$ indicates the irrigation water utilization coefficient; $W_{6.2}$ is the water demand for garden crops in the $i$-th calculation area; $\text{FQ}_i, A_{\text{Fi}}$ denotes the average water consumption and area for irrigation of garden crops in the region; $W_{6.3}$ expresses the water demand for animal husbandry in the $i$-th calculation area; $\text{XBQ}_i, \text{PB}_i$ refers to the daily average quantity and water consumption of large livestock; $\text{XSQ}_i, \text{PS}_i$ refers to the daily average quantity and water consumption of small livestock; $W_{6.4}$ is the water demand for fisheries in the $i$-th calculation area; $\text{YQ}_i, A_{\text{ri}}$ represent the limited replenishment amount and area of the region, respectively. The secondary sector of the economy mainly includes manufacturing and construction industries, while the tertiary sector of the economy mainly includes service industry, commerce, etc. Its water consumption is shown in Eq. (7).

$$\begin{cases} W_7 = W_{7.1} + W_{7.2} \\ W_{7.1} = S_e V_i \times \text{IQ}_i \\ W_{7.2} = \text{ThV}_i \times \text{TQ}_i \end{cases} \quad (7)$$

where $W_{7.1}$ means the water consumption of secondary industry of the economy in the $i$-th calculation area; $S_e V_i, \text{IQ}_i$ refers to the added value and limited water consumption of the secondary sector of the economy in the region; $W_{7.2}$ is the water consumption of tertiary sector of the economy in the $i$-th calculation area; $\text{Th}V_i \times \text{TQ}_i$ refers to the added value and limited water consumption of the secondary industry of the economy in the region. Another aspect of calculating the sustainable utilization of water resources is water pollution. A coupling model was selected to calculate and analyze the water pollution based on the GWF in the region. The overall technical flowchart for the design is shown in Fig. 2.

As shown in Fig. 2, according to the method in the Water Footprint Assessment Manual, the GWF in this area is divided into four categories: industry, plantation, life and aquaculture. The pollution of plantation industry in this area is mainly caused by the unreasonable use of chemical fertilizer. Eq. (8) is the calculation method of GWF.

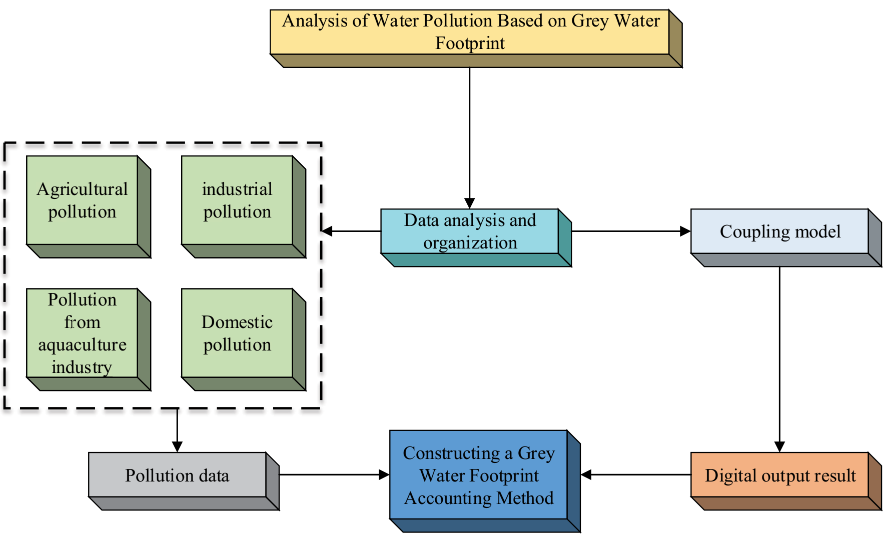


Fig. 2. Technical flow chart of grey water footprint pollution in the study area.

$$\begin{cases} \text{PGWF}_z = \dfrac{\alpha_z \times A_z \times V_z}{\left(C_{\max}^z - C_{\text{nat}}^z\right)} \\ \text{PGWF} = \max\left(\text{PGWF}_{\text{TN}}, \text{PGWF}_{\text{TP}}\right) \end{cases} \quad (8)$$

where PGWF denotes the GWF of plantation in the region; $\text{PGWF}_{\text{TN}}$,$\text{PGWF}_{\text{TP}}$ stands for the GWF of total nitrogen and total phosphorus, respectively; $\text{PGWF}_z$ refers to the GWF of the $z$-th pollutant; $C^z_{\max}$ indicates the maximum concentration of environmental pollutants; $C^z_{\text{nat}}$ refers to the natural local concentration of pollutants in the receiving water body; $\alpha_z$ denotes the parameter for fertilizer loss; $A_z$ is the area; $V_z$ means the amount of pure fertilization per unit area. The pollution in the aquaculture industry is mainly caused by animal excrement, and the calculation method for its GWF is shown in Eq. (9).

$$\begin{cases} \text{LGWF}_z = \dfrac{m \times t_1 \times n_{1z} \times \lambda}{\left(C_{\max}^z - C_{\text{nat}}^z\right)} - m\omega_z \\ \text{LGWF} = \max\left(\text{LGWF}_{\text{COD}}, \text{LGWF}_{\text{TN}}, \text{LGWF}_{\text{TP}}\right) \end{cases} \quad (9)$$

where $\text{LGWF}_z$ expresses the ash water footprint of the $z$-th pollutant in animal excrement; $m$ denotes the number of animals; $t_1$ stands for the feeding time; $n_{1z}$ represents the pollutant content; $\lambda$ expresses the rate of water loss of excreta; $\omega_z$ refers to the drainage standard value for the dry manure process in the aquaculture industry; LGWF means GWF of aquaculture industry; $\text{LGWF}_{\text{COD}}$ denotes the GWF of $\text{COD}_{\text{Cr}}$. Domestic pollution mainly comes from the discharge of sewage generated by residents during their daily lives, and the calculation method for their GWF is shown in Eq. (10).

$$\begin{cases} \text{HGWF}_z = \dfrac{\left(P_c \times W_{pc} \times n_{hz} \times \gamma - P_n \times W_{pc} \times n_{hz} \times \gamma\right) \times t_h}{\left(C_{\max}^z - C_{\text{nat}}^z\right)} - W_{dh} \\ \text{HGWF} = \max\left(\text{HGWF}_{\text{COD}}, \text{HGWF}_{\text{NH}_3-\text{N}}, \text{HGWF}_{\text{TP}}\right) \end{cases} \quad (10)$$

where $\text{HGWF}_z$ expresses the ash water footprint of the $z$-th pollutant in domestic pollution; $n_{hz}$ denotes the concentration of pollutants; $P_c$ refers to the urban population; $P_n$ refers to the rural population; $W_{pc}$ expresses the average rated water consumption in urban areas; $W_{pn}$ indicates the rated water consumption in rural areas; $\gamma$ is the pollution coefficient; $t_h$ stands for the time; HGWF means aquaculture industry's GWF; $\text{HGWF}_{\text{NH}_3-\text{N}}$ represents the GWF of $NH_3$–N. Industrial pollution mainly comes from wastewater generated during industrial production, and the calculation method for its GWF is shown in Eq. (11).

$$\begin{cases} \text{IGWF}_z = \dfrac{L_z}{\left(C_{\max}^z - C_{\text{nat}}^z\right)} - W_{dz} \\ \text{IGWF} = \max\left(\text{HGWF}_{\text{COD}}, \text{HGWF}_{\text{NH}_3-\text{N}}, \text{HGWF}_{\text{TN}}\right) \end{cases} \quad (11)$$

where $\text{IGWF}_z$ stands for the ash water footprint of the $z$-th pollutant in industrial pollution; $L_z$ means the wastewater load; $W_{dz}$ expresses the discharge amount of industrial wastewater; IGWF indicates the industrial GWF. The discharge amount of pollutants needs to meet the pollution capacity, and there is a certain linear relationship between the water pollution amount and the GWF, as shown in Eq. (12).

$$\begin{cases} \text{WC}_i \geq \text{PGWF} + \text{LGWF} + \text{HGWF} + \text{IGWF} \\ W_C = \rho W C_i \end{cases} \quad (12)$$

where $W_C$ is the water consumption for diluting and converting the pollutant $\text{WC}_i$ in the grey water; $p$ is a parameter.

## 3.2. Construction of WRCC calculation model and institutional management strategy

WRCC refers to the maximum economic and social development scale that a water resource system can support without damaging the water and ecological environment. The schematic diagram of regional water resource calculation is shown in Fig. 3.

As shown in Fig. 3, based on the schematic diagram of water resource calculation, the indicators of regional WRCC can be obtained as shown in Eq. (13).

$$\begin{cases} Q_{\text{can}} = \psi Q_{\text{self}} + Q_{\text{in}} + Q_{\text{again}} \\ W_{\text{lost}} = W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W_c \\ I = \dfrac{W_{\text{lost}}}{Q_{\text{can}}} \end{cases} \quad (13)$$

where $W_{\text{lost}}$ expresses the total water consumption; $Q_{\text{can}}$ is the available water resources; $\psi$ stands for the comprehensive coefficient of available water; $Q_{\text{self}}$ refers to the total amount of water resources; $Q_{\text{in}}$ denotes the total amount of water transferred from outside the region; $Q_{\text{again}}$ indicates the available amount of purified gray water resources; $I$ refers to an indicator of WRCC. If $I > 1$, it indicates that it exceeds the WRCC of the area; If $I = 1$, it indicates that it is in a critical state; If $I < 1$, it indicates that the WRCC of the area has not been exceeded. To quantify the calculation of the WRCC indicators mentioned above, it is necessary to first establish a water resource cycle transformation equation for the region, as shown in Eq. (14).

$$\begin{cases} Q_{\text{Can}} = \psi Q_{\text{self}} + Q_{\text{in}} + Q_{\text{again}} \quad 14.1 \\ Q_{\text{Can}} = W_{\text{Indu}} + W_{\text{Arg}} + W_{\text{Life}} + W_{\text{other}} + \Delta W \quad 14.2 \\ W_{\text{Indu}} + W_{\text{Arg}} + W_{\text{Life}} + W_{\text{other}} = W_{\text{Cons}} + W_{\text{Ret}} \quad 14.3 \\ W_{\text{Cons}} = E_I + E_A + E_L \quad 14.4 \\ W_{\text{Ret}} = C_{\text{Ret}} + Q_{\text{Ret}} \quad 14.5 \end{cases} \quad (14)$$

where 14.1 is the calculation equation for available water resources; 14.2 expresses the available water distribution equation; 14.3 indicates the water resource utilization consumption equation; 14.4 denotes the calculation equation for water resource energy consumption; 14.5 refers to the equation for calculating the regression quantity after water

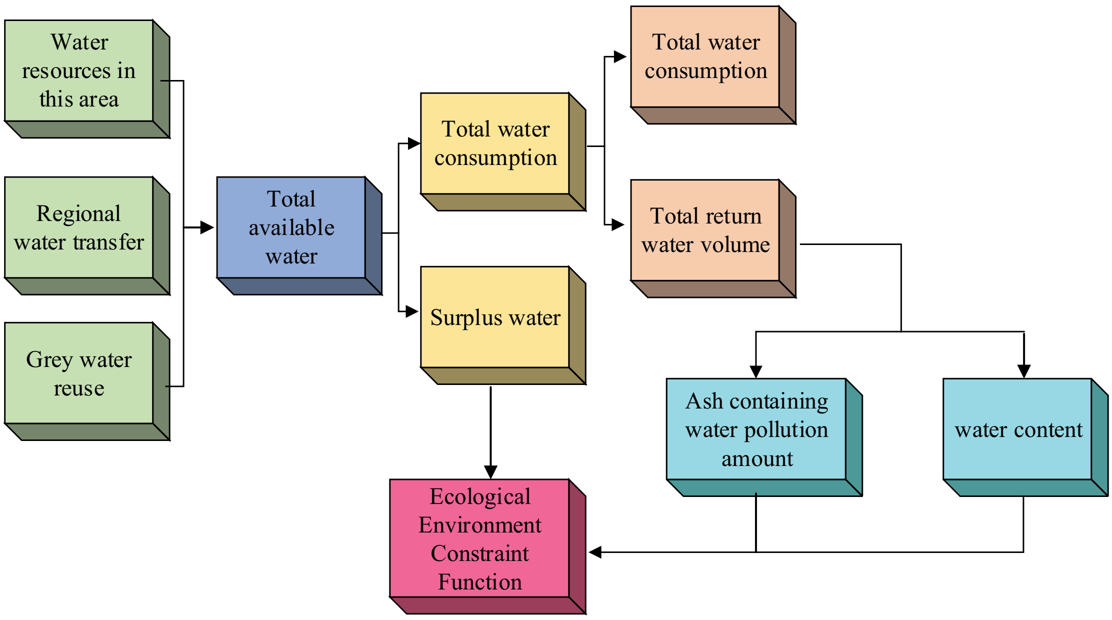


Fig. 3. Schematic diagram of regional water resource calculation.

resource utilization. Then, a cycle transformation equation based on the GWF pollutants is established. To facilitate description and calculation, the research model selects the water surface of a single river flow area as the research object, as shown in Fig. 4.

According to the water quantity and quality model in Fig. 4, the cyclic transformation process of pollutants based on GWF is calculated as shown in Eq. (15).

$$Q_m C_m = Q_1 C_1 + W_D - K\left(Q_1 C_1 + W_D\right) \quad (15)$$

where $Q_m$ represents the river cross-sectional runoff; $C_m$ means the concentration of pollutants; $Q_1$ and $C_1$ represent the upstream water volume and average concentration of pollutants, respectively; $W_D$ denotes the total amount of discharged gray water pollutants; $K$ expresses the pollutant elimination parameter. Afterwards, because water resources, population, economy, environment, etc. are closely related, it is necessary to establish a constraint function based on social and economic relations to calculate WRCC, denoted as SubMod(SESD). Finally, the calculation of WRCC also needs to ensure a virtuous cycle of the environment in the study area, so it is necessary to establish an ecological constraint equation as shown in Eq. (16).

$$\begin{cases} Q_m \times C_m \le W_s & 15.1 \\ C_m \le C_s & 15.2 \\ Q_m \ge Q_s & 15.3 \end{cases} \quad (16)$$

where 15.1 refers to the total amount control of water resource ecosystems, with the main purpose of setting requirements for the total amount of pollutant emissions in the region; 15.2 means the concentration control of the water resource ecosystem, which mainly constrains the water in the area to not exceed the self-purification standard of the water body itself; To meet the water resource ecosystem water use standards, $Q_s$ denotes the minimum standard for water flow in the region. At this point, all the equations required for the calculation model of WRCC in the region have been completed. According to the above introduction, the meaning of WRCC is the maximum economic and social development scale that the water resource system can support. There are many characterization indicators for the maximum economic and social development scale, such as the total population, industrial and agricultural output value, etc. The relationship between the characterization indicator system is shown in Fig. 5.

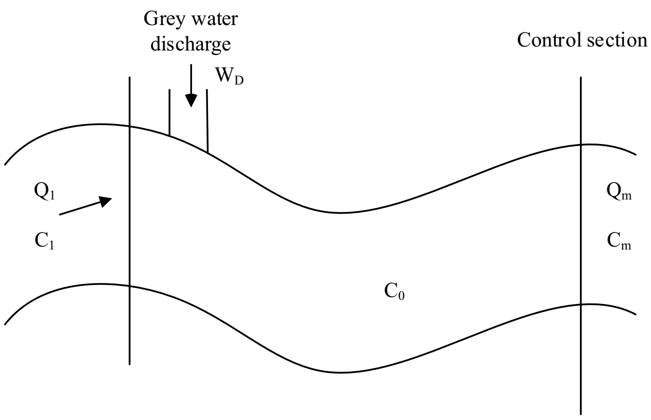


Fig. 4. Schematic diagram of water quantity and quality model.

According to the hierarchical relationship in Fig. 5, the WRCC should be $F = \{f_1, f_2, \ldots, f_n\}$; $F$ refers to the WRCC of the region, and $f_1, f_2, \ldots, f_n$ represents the characteristic indicators. For the convenience of expression, the study selects the single indicator of total population as the calculation standard for the WRCC of the region, and determines the

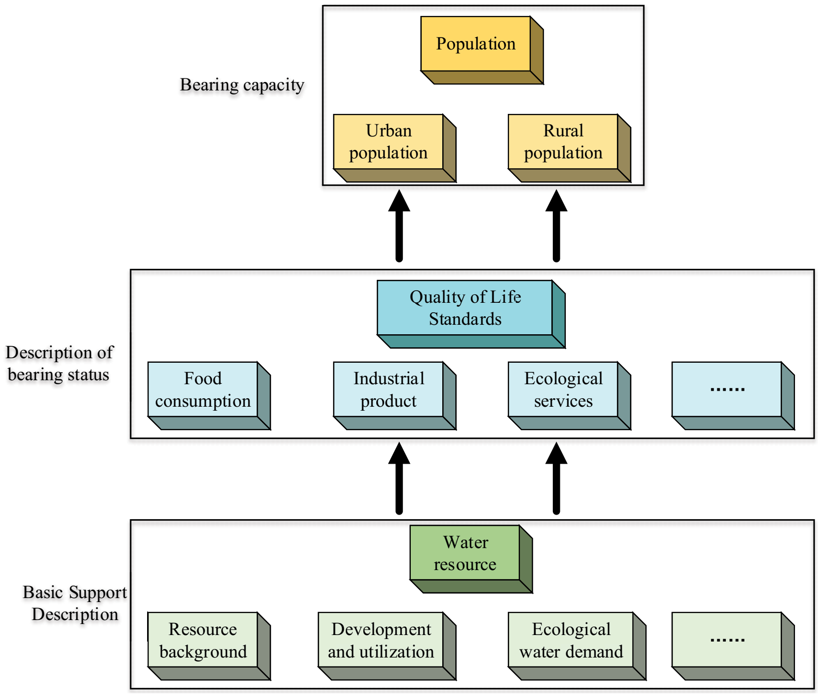


Fig. 5. Hierarchy structure of water resource characterization.

objective function, Max($P$); $P$ means the total population. In fact, the constraint function SubMod(SESD) established above, which is linked by socio-economic relations, has already determined the relationship between various indicators of WRCC. That is, if the total population that the region can carry is determined, indicators such as industrial and agricultural output value are also determined. The model constructed by the research institute is based on socio-economic development and ecological environment maintenance water use, considering water pollution based on GWF, and maintaining a virtuous cycle of social ecology as constraints. The ultimate goal is to solve the WRCC. In the face of such complicated nonlinear objective function, numerical iterative method is used to find the optimal solution [18], and the calculation is shown in Fig. 6.

The approximate process of constructing a WRCC model from the research institute in Fig. 6 is as follows: first, it sets the parameters of each calculation formula; Next, it selects a certain area to set half of the population as the initial value and set the step size; Then, it substitutes the initial value and step size into the constraint equation calculation to determine whether the calculated value meets the conditions, and if it does not, it needs to continue iterating until the optimal solution is found. The optimal solution obtained is the WRCC in the region. The purpose of evaluating and analyzing the WRCC is to maintain the sustainable utilization of water resources to meet the sustainable development needs of the region. By continuously delving into the connection between limited water resources and the current economic, environmental, and social situation of cities, it can identify bottleneck factors in water resource utilization, improve water resource management efficiency, and achieve the goal of optimizing resource allocation and promote sustainable urban development [19]. Therefore, adaptive management models can be used to formulate corresponding policies and regulations to improve the WRCC.

As shown in Fig. 7, in response to the issue of WRCC, the study first identifies the cause of the problem; Then it designs and implements corresponding solutions based on specific problems; Next, it supervises and comprehensively evaluates the implementation plan, and finally makes adjustments. This forms a closed-loop management model that can formulate effective policies, save water, and improve water resource utilization, thereby enhancing WRCC.

## 4. Performance testing and simulation application of WRCC calculation model

The first section mainly set up the model running environment, and tests were conducted on the accuracy, fitness, stability, and running time of the model built by the research institute, and satisfactory results were obtained. The second section mainly used the model to calculate the current and future WRCC of a certain city for the next 20 y, and proposed corresponding management measures based on this.

### *4.1. Performance testing of WRCC calculation model*

To verify whether the constructed model meets the expected requirements, the study analyzed the performance of the regional water resource calculation model from several aspects such as computational accuracy and efficiency. Firstly, it set the operating environment for water resource calculation. Its configuration and parameters are shown in Table 1.

Next, the study selected relevant data from regions A and B from 2010 to 2020 as parameters, and compared the results calculated using historical estimation methods and

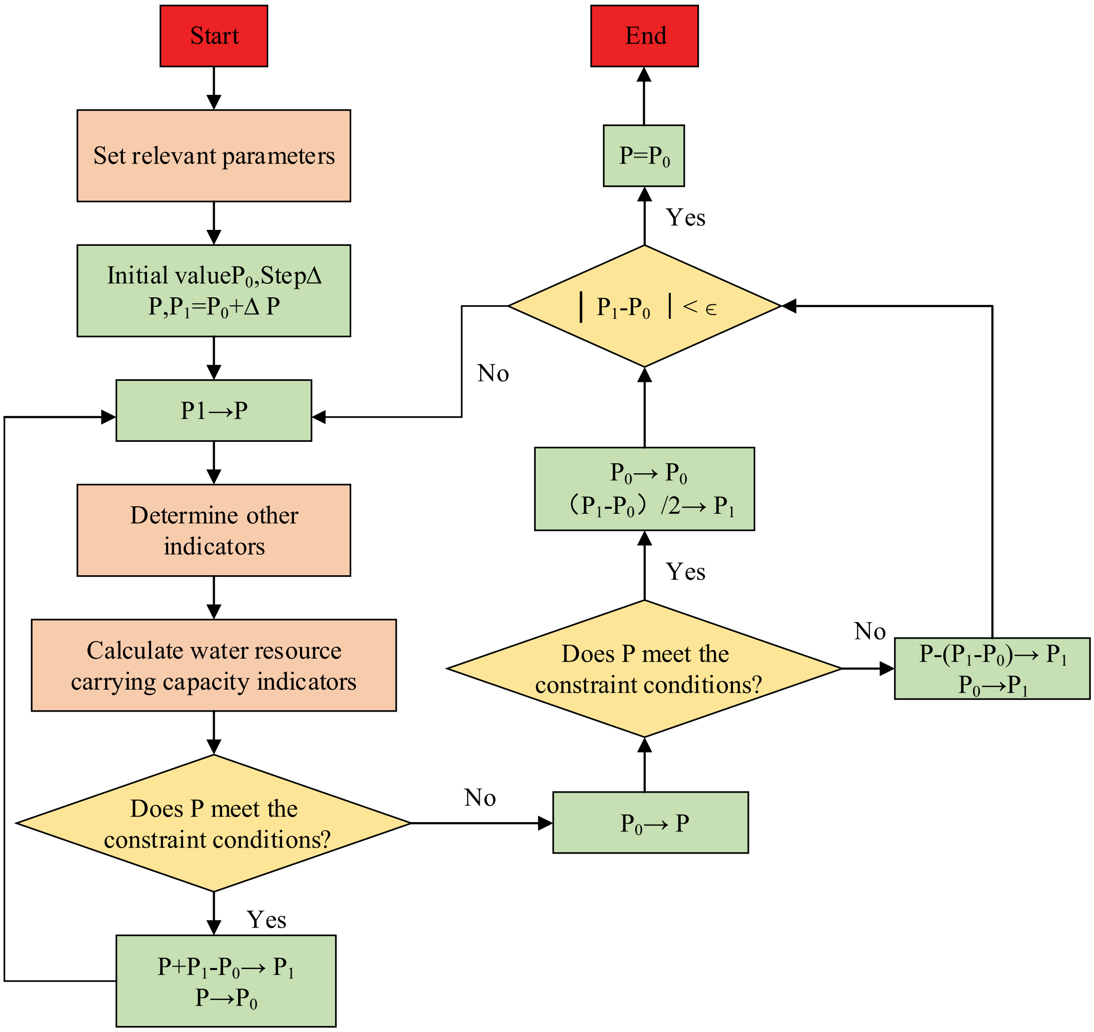


Fig. 6. Flow chart of iterative algorithm for solving WRCC.

hydrological geographic analysis methods under the same experimental conditions. Firstly, the accuracy of the model's WRCC calculation was tested. The results are shown in Fig. 8.

As shown in Fig. 8a, the population of region A has shown a rapid growth state, from over 14.3 million in 2010 to over 17.2 million in 2020, an increase of approximately 3 million people. According to historical data analysis and calculation, the standard carrying population fluctuated between 17.5 million and 20 million, indicating that the WRCC of the region was relatively small. Through the visual analysis of the line chart, the broken line track of the calculation model built by the research institute had little difference from the standard carrying population. The biggest difference was in 2017, which was about 2%. However, traditional models, because they were calculated based on historical data, had a lag in calculation results and relatively large errors. The maximum error was in 2020, with a difference of about 14%. The hydrogeological model predicted that the carrying population has been declining, indicating that the ecological water resources in the region have been decreasing. Fig. 8b shows the results of data testing in region B, indicating that the population growth in the region was relatively slow and the standard carrying population was much larger than that of the region, indicating that the region was relatively rich in water resources. Through the visual analysis of the line chart, the difference between the calculated results of the model built by the institute and the standard carrying population was about 1% at most, while the difference between the calculated results of the traditional model and the standard was about 10%. The hydrogeological model predicted that the carrying population fluctuated between 18 million and 19 million, indicating that the total amount of ecological water resources in the region was relatively stable. The findings denoted that the model constructed by the research institute had high accuracy. Next, the adaptability of the model was tested using the GDP and grain production indicators of regions A and B. The results are shown in Fig. 9.

As shown in Fig. 9a, the agricultural production in region A was relatively stable and the output value was relatively low, fluctuating between 11.5 million and 12 million kg. Through the visual analysis of line chart, it was found that the grain yield calculated by the model built by the institute

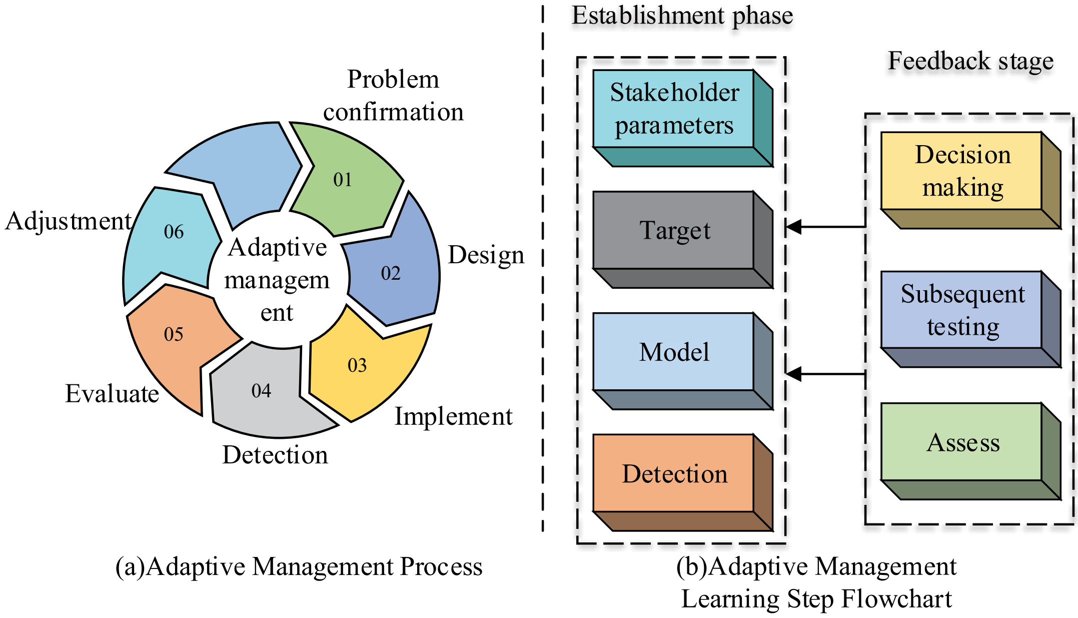


Fig. 7. Adaptive management strategy. (a) Adaptive management process and (b) adaptive management learning step flowchart.

Table 1
Calculation model operating environment and parameter selection

| Type | Parameter selection |
|---|---|
| Operating system | Windows 10 Professional |
| Processor | Intel Core i9-11900K 3.5GHz 8-Core 16 Thread |
| Memory | 64GB DDR4-3600MHz RAM |
| Storage | 1TB NVMe SSD+4TB SATA HDD |
| Graphics card | NVIDIA GeForce RTX 3080 10GB GDDR6X |
| Data analysis such as software | MATLAB, CAD |
| Programming language | Python |

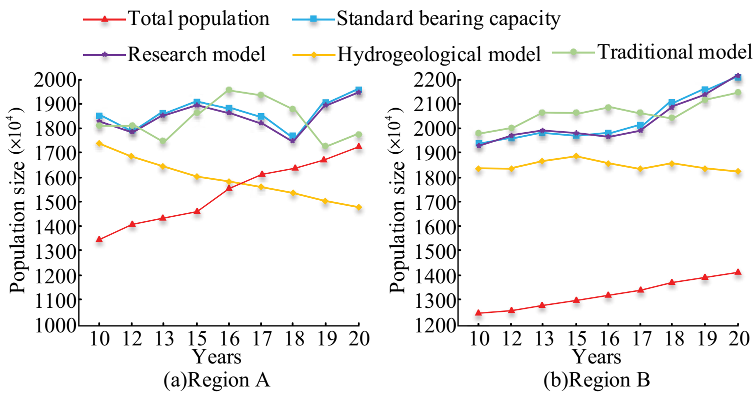


Fig. 8. Population carrying capacity test results for regions (a) A and (b) B.

was almost consistent with the standard grain yield obtained by real-time data analysis of the year, with the difference not exceeding 1%. However, the GDP output value of region A has rapidly increased, increasing by about 1,700 billion yuan in just 10 y. The GDP output value growth calculated by the model constructed by the research institute was also consistent with the standard GDP. In Fig. 9b the GDP output value remained relatively stable, fluctuating between 800 billion and 1,200 billion yuan, while grain production continued to rise, reaching 42 million kg in 2020. Similar to

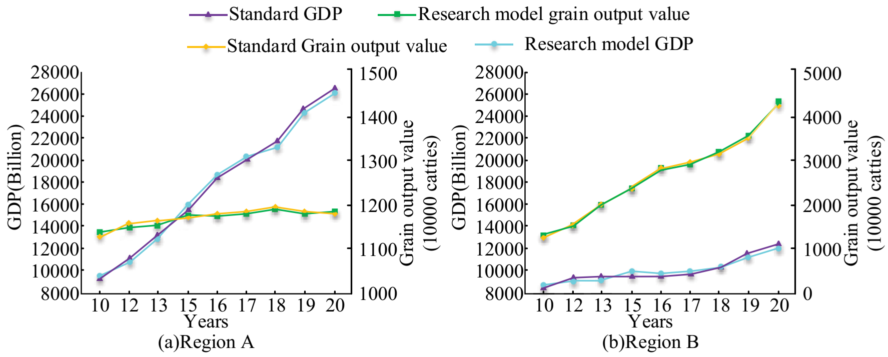


Fig. 9. GDP and grain production test results for regions (a) A and (b) B.

region A, the calculation results of the model constructed by the research institute were almost consistent with the standard results. The above results indicated that using different data and environments did not have a significant impact on the accuracy of the research model, indicating that the model had high adaptability and credibility. Then, the stability of the model constructed by the research institute was tested. For this purpose, data from regions A, B, and C were selected as calculation parameters. The model was then calculated 30 times, and the average value was calculated every 10 times as the result, as shown in Fig. 10.

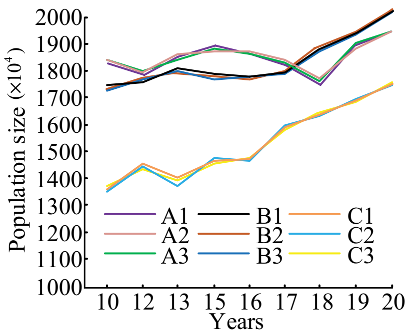


Fig. 10. Population carrying capacity test results of regions A, B, and C.

As shown in Fig. 10, the average values of the three population carrying capacity calculations for regions A, B, and C were all close, indicating that the model had good stability. This was because the stability of the calculation model referred to the relatively small change in output results when there were slight changes in input parameters, which could produce stable and reliable results. In this case, due to the close proximity of data from the three regions, it indicated that the model constructed by the research institute had good stability against changes in input parameters. Finally, the computational efficiency of the model was tested, and data from regions D and F were still selected as parameters to test the running time of the model (Model 1) built by the research institute. It ran the data 100 times, took the average value every 10 times as the statistical result, and used machine learning based hydrological prediction model (Model 2), GIS based water resource assessment model (Model 3), and traditional statistical calculation model (Model 4) as reference. The results are shown in Fig. 11.

As shown in Fig. 11, Fig. 11a shows the calculation time results of using region D data in four models. Model 1 had the lowest calculation time, about 30 min. Among the other three models, Model 4 had the most running time and was unstable, with significant time differences between different runs. The running time of Models 2 and 3 was relatively stable, with approximately 60 and 73 min, respectively.

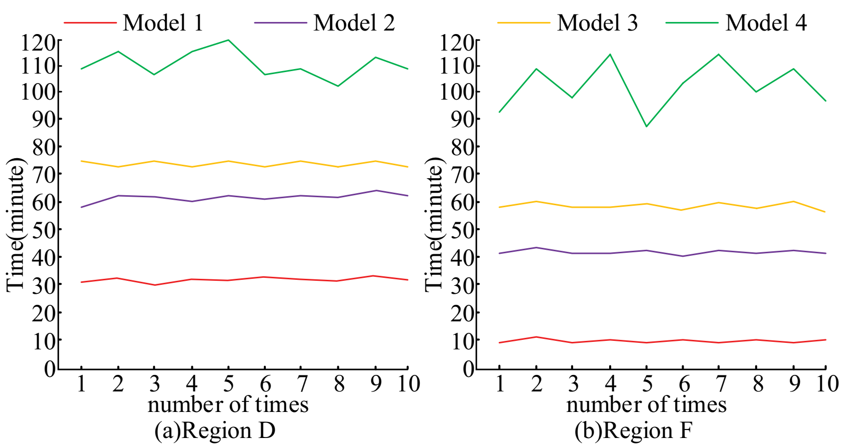


Fig. 11. Model operation time result test: regions (a) D and (b) F.

Fig. 11b shows the calculation time results of using region F data in four models, which were similar to (a) and still had the lowest calculation time of about 10 min in model 1. The calculation time for Models 2 and 3 was approximately 42 and 60 min, respectively. Model 4 was still unstable, with a significant difference in runtime. The above data once again indicated that the research model had extremely high stability and high computational efficiency.

### *4.2. Example application analysis of WRCC calculation model*

To better manage and utilize water resources, it is necessary to quantitatively assess and calculate the WRCC. The parameters of WRCC varied depending on different regions and situations. The study selected a certain city as the application analysis object of the model. The water distribution of the city is shown in Fig. 12.

According to Fig. 12, the distribution of water features in the city was characterized by more in the south and less in the north. It divided the evaluation criteria for WRCC into five indicators, and calculated the WRCC status of the region according to the model, as shown in Fig. 13.

From Fig. 13, the vast majority of the city was still in a state of water shortage, especially in the northern part of the city, where there was more water shortage. In this regard, relevant departments needed to pay attention to the introduction of external water transfer and increase the intensity of grey water treatment rate to effectively alleviate the crisis. To make the sustainable use of water resources come true, it could refer to the city's water resources announcement to know the city's surface, ground and total water resources and other parameters. The external water transfer was calculated according to the relevant policy report, while other industrial and farm water used parameters were set according to the development planning report of the city government. The predicted WRCC and grey water treatment rate for 2030 and 2035 are shown in Fig. 14.

As shown in Fig. 14a, with the increase of gray water treatment rate, both urban and rural populations have steadily increased, but they have not reached the calculated carrying capacity. This was because the current increase in ash emissions and low treatment rates have led to ineffective control of water environmental issues, resulting in WRCC

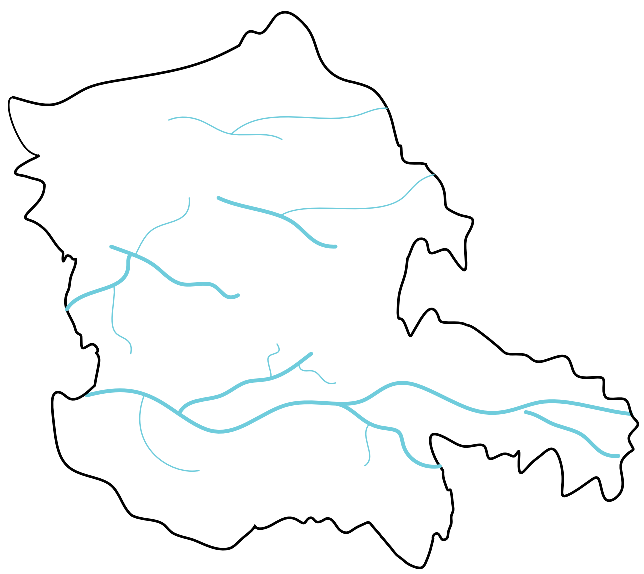

Fig. 12. Water area distribution map of a city.

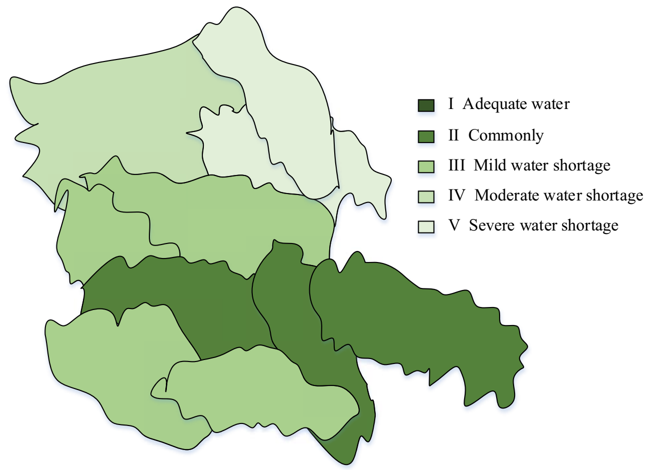


Fig. 13. Current water resource carrying status of a city.

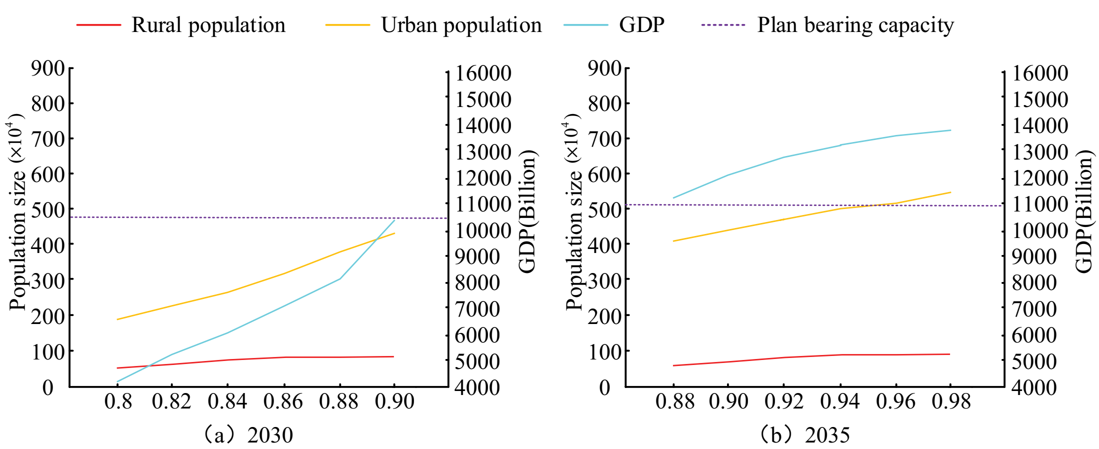


Fig. 14. Relationship between WRCC and grey water treatment rate in (a) 2030 and (b) 2035.

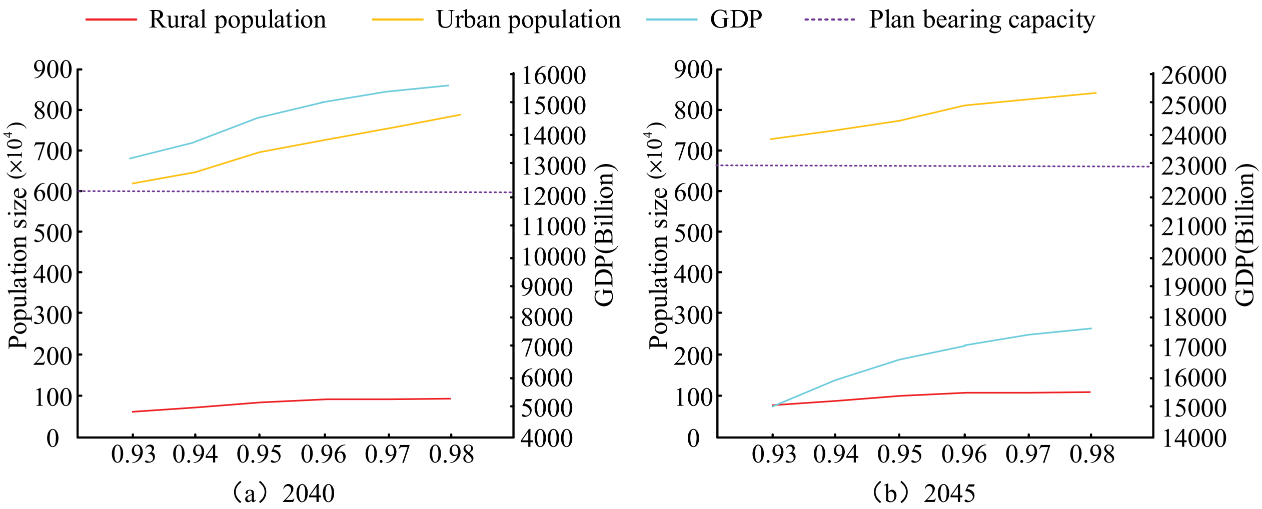


Fig. 15. Relationship between WRCC and grey water treatment rate in (a) 2040 and (b) 2045.

exceeding the range. As shown in Fig. 14b, when the grey water treatment rate reached 0.945, the WRCC could reach the planned scale of 5.08 million people. Along the rise of future water conservancy projects and the increase of planned external water diversion, the relationship between WRCC and grey water treatment rate in 2040 and 2045 would continue to be predicted.

From Fig. 15a in 2040, the grey water treatment rate increased, the total available water resources increased, and there was no water shortage phenomenon. The WRCC reached the expected level. According to calculations, if the grey water treatment rate reached 0.93, the city's water resource carrying population was 6.11 million. From Fig. 15b, in 2045, with further optimization of water resource management, the carrying population of water resources in the city further increased to 7.23 million at a grey water treatment rate of 0.93. In summary, the current development scale of the city has exceeded its WRCC, manifested by severe water shortage and gray water pollution, and low treatment rate. However, with the introduction of relevant policies, the introduction of external water transfer, and the improvement of gray water treatment rate, the WRCC of the city would greatly improve in the next two decades. Therefore, for the water resource management based on GWF, the paper put forward several suggestions: it strengthen gray water resource management plan, including GWF assessment, gray water resource carbon footprint and water footprint calculation; People were encouraged to use low-carbon and low water consumption gray water treatment facilities; It supported the development of low-carbon and low water consumption grey water treatment technologies, such as bubble based systems and systems that utilize plants and microorganisms to purify grey water; People were encouraged to take measures to self-filter and collect gray water, and actively participate in the process of gray water treatment and utilization; It promoted sustainable management of gray water resources through government subsidies, tax policies, environmental monitoring, and enforcement measures.

## 5. Conclusion

Water resources utilization is a decisive factor that limits the growth of human society and economy. A WRCC calculation model based on GWF was established for this purpose. This model took the WRCC as the research object, comprehensively analyzed the water consumption and gray water pollution, and proposed to eliminate gray water to improve the amount of return water resources. And considering the relationship between social development and ecological virtuous cycle, a goal constraint function was established. The results showed that the testing errors of the research model in regions A and B were 2% and 1%, respectively, while the errors of the traditional model were 14% and 10%, respectively; By using different objective functions, the research model could still perform accurate calculations with a maximum error of 1%; The study repeatedly calculated data from different regions, resulting in a maximum error of 4%; The data running time in regions D and F was about 30 and 10 min, respectively, while the other three models had the fastest running time of 60 and 42 min, respectively. In the case analysis, the model could accurately calculate the regional WRCC and predict that when the grey water treatment rate in the region reached 0.945 in 2035, it could reach the expected WRCC of 5.08 million people. When the water treatment rate reached 0.93 in 2040, it could reach the WRCC of 611. The above data indicated that the research model could efficiently and accurately calculate WRCC, and had high stability and adaptability. The simulation prediction results indicated that it was necessary to improve the management system of grey water resources to promote grey water reuse and reduction management, alleviate water resource pressure, and ensure the health of water ecological environment, to further improve WRCC. However, this study only considered the main sources of gray water pollution and could not achieve a more refined analysis. Meanwhile, the total amount of water resources was also a rough estimate that needed further research and optimization.

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