Intergating Qualitative and Quantitative Methods for Water Resources Carrying Capacity I: Conception and Method

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Abstract: Based on the analysis of existing concept of water resources carrying capacity (WRCC), “available water supply” was applied to define the conception of WRCC. Furthermore, modifications on research methods on WRCC were mated with analyzing the shortages of current research methods on WRCC. First of all, in order to solve the problems of uncertainty in qualitative assessment of WRCC, an assessment method based on dynamic feedback was suggested to qualitative assessment of WRCC. Secondly, in order to solve the disadvantage of existing quantitative assessment model of WRCC rarely consider the influence of spatial availability of water supply and spatial heterogeneity of water user, a distributed quantitative assessment model of WRCC was established. Contemporary, a calculation unit division method that by means of overlap analysis of DEM, land-use map and water user map was established. Finally, a qualitative and quantitative model of WRCC is established by coupling the qualitative assessment method based on dynamic feedback and distributed quantitative assessment model.

1. Introduction

The concept of water resources carrying capacity emerged in the mid-to-late 20th century alongside the development of sustainable development theory, as the close relationship between sustainable development and water resources became increasingly recognized [1,2]. In China, the concept of water resources carrying capacity was first explicitly proposed by Academician Yafeng Shi in the 1980s, subsequently garnering significant attention from the academic community and becoming a key focus and topical issue in water resources research [3,4]. After decades of research, two main categories of water resources carrying capacity concepts have been predominantly formed: “the maximum development capacity of water resources” and “the maximum scale of socio-economic development supported by water resources.” [5]. Additionally, two main categories of water resources carrying capacity research methods have been proposed: qualitative evaluation and quantitative calculation [6,7]. Existing research has made significant contributions to the development of water resources carrying capacity theory and the improvement of research methods. However, further improvements are still needed in the following areas: (1) The definition and connotation of water resources carrying capacity remain unclear, and a unified cognitive and theoretical system has yet to be formed.(2) Current research primarily focuses on qualitative evaluation or quantitative calculation from a single perspective, with few studies adopting a comprehensive integrated approach that combines qualitative evaluation and quantitative calculation to leverage the advantages of integrated and holistic analysis in studying the complex and large system of water resources carrying capacity.

In light of these issues, this paper aims to summarize the current concepts and research methods of water resources carrying capacity, supplement and improve its definition and calculation model, and establish a comprehensive integrated method for water resources carrying capacity that transitions from qualitative to quantitative analysis. This will further refine the theory of water resources carrying capacity and provide a reference basis for regional water resources optimization and sustainable development.

2. Analysis of the concept of water resources carrying capacity

The concept of water resources carrying capacity is generally only briefly mentioned in international studies on sustainable development and is often expressed as "sustainable water use", the ecological limits of water resources, or the natural system limits of water resources [8]. In China, there has been extensive discussion on the concept of water resources carrying capacity, yet no universally accepted definition has been established to date. This paper categorizes the definitions into two main types: water-focused type and determining the production based on water resources type.

(1) Water-focused type

This type of definition approaches water resources

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carrying capacity from the perspective of water resources characteristics, emphasizing water resources themselves and focusing on their maximum supply capacity, also referred to as exploitation capacity. According to this definition [9], water resources carrying capacity refers to the maximum exploitation capacity of water resources to supply water for industrial and agricultural production, human consumption, and ecological protection under certain technological, economic, and social conditions. This capacity represents the maximum exploitation potential of water resources, ensuring their natural circulation and renewal while enabling sustainable utilization for human benefit without causing deterioration.

(2) Determining production based on water resources type

This type of definition originates from the perspective of water resources as the principal factor but focuses on the objects supported by water resources. It emphasizes the maximum reasonable scale of the supported objects, which is a composite indicator typically comprising elements such as population, GDP, grain yield, irrigation area, and pollution load. According to this definition [6,10], water resource carrying capacity refers to the maximum capacity of water resources to support regional socio-economic development at a specific historical stage, based on foreseeable technological, economic, and social development levels, adhering to the principles of sustainable development, and under the condition of maintaining ecological and environmental sustainability through rational optimization and allocation.

The first type of definition, which defines water resources carrying capacity solely based on the exploitation capacity of water resources, has theoretical limitations in practical application. The ultimate goal of studying water resources carrying capacity is to provide theoretical and technical support for the coordinated economic development of a region, specifically determining the scale of society and economy that regional water resources can support. The same water resources exploitation capacity can yield different social and economic benefits depending on the water use objects and their allocation ratios. The second type of definition can clearly specify the development scale that water resources can support, making it more suitable for informing development decisions and aligning with the current mainstream water resource management approach of "determining production and urban development based on water resources." Therefore, this paper considers the second type of definition more appropriate. However, it also identifies an ambiguity in the definition of "water resources." Does it refer to the total regional water resources, the exploitable water resources, or the available water supply? This paper argues that it should refer to the available water supply for the following reasons:

1) Total water resources

Total water resources refer to the sum of renewable surface water and groundwater resources within the local watershed during the water cycle (W_{Local}). This measure represents the natural endowment of a region's water resources. However, a large W_{Local} does not necessarily indicate a high water resource carrying capacity, as only the portion of water that can be developed and utilized by humans contributes to socio-economic development.

2) Exploitable water resources

Exploitable water resources refer to the one-time, non-recyclable portion of water that can be utilized under conditions of economic feasibility, technical viability, and ecological and environmental sustainability. In principle, this can be estimated by subtracting the ecological water demand (W_{Eco}) from the total water resources, adjusted by a coefficient (a) representing the efficiency of engineering and technical measures: $W_s = aW_{Local} - W_{Eco}$. Exploitable water resources are the portion of locally generated water resources that can be developed and utilized as a one-time supply. This measure excludes both the reused water portion and water transferred from external basins. However, to address common issues such as water scarcity and uneven temporal and spatial distribution, reused and transferred water often become essential components of regional water supply systems.

3) Available water supply

Available water supply refers to the amount of water that can be utilized outside the river channels while meeting the ecological and environmental water requirements of river systems and groundwater systems. It is calculated based on water availability, the scale and layout of the water supply infrastructure, water demand, and the operational status of the supply system. The available water supply includes water from various sources such as surface water, groundwater, inter-basin water transfer, and unconventional sources (e.g., reclaimed wastewater, rainwater harvesting). It can be expressed as $W = W_{LPG} + W_T + W_{NG} - W_{Eco}$, where W_{LPG} is the local conventional supply capacity, W_T is the inter-basin water transfer volume, and W_{NG} is the unconventional water supply volume. It can be concluded that the available water supply is derived through systematic analysis based on the actual current engineering supply capacity, with adjustments for newly planned water resource projects, upgrades and modifications to existing infrastructure, and changes in supply capacity from ongoing project extensions. This process accounts for factors such as reduced inflow caused by infrastructure aging, reservoir sedimentation, and increased upstream water usage, as well as the water quality requirements of different users. The calculation integrates all water resources capable of generating social and economic value (excluding unused water and water that cannot be utilized by users) and considers temporal variations to ensure alignment with real-world conditions. Therefore, the term ‘regional water resources’ in the definition of the carrying capacity of water resources would be more appropriate to specify as ‘availability of regional water supply.’

Based on the above analysis, this paper defines water resource carrying capacity as: the maximum socio-economic development scale that the regional available water supply can support under certain socio-economic conditions, with the premise of maintaining ecological and environmental sustainability through rational allocation.

3. Review of research methods for water resources carrying capacity

Research methods for water resources carrying capacity can be categorized into two types: qualitative evaluation and quantitative calculation. Qualitative evaluation involves constructing an evaluation index system and using comprehensive evaluation methods to qualitatively determine whether the scale of socio-economic and environmental development exceeds the carrying capacity of water resources. Quantitative calculation, on the other hand, involves building more complex mathematical models to compute the socio-economic, environmental, and population scales that water resources in a specific region can support.

3.1. Qualitative evaluation methods

At present, many studies focus on the qualitative evaluation of water resource carrying capacity, employing various methods such as the fuzzy comprehensive evaluation method [7], principal component analysis [11]. While these studies utilize different techniques, their core logic and technical routes are consistent: construction of an evaluation index system → selection of an evaluation method → derivation of evaluation results（As shown in Figure 1）. These methods provide valuable references for water resource carrying capacity evaluation but also have notable limitations: (1) The construction of evaluation index systems involves a degree of subjectivity and does not fully adhere to scientific methods. (2) There is a lack of validation for the scientific and rational basis of the evaluation index systems, which directly relates to the level of scientific accuracy and rationality of the evaluation results. (3) The evaluation results are often expressed as vague intervals, making it difficult to determine the exact carrying capacity. Therefore, it is imperative to conduct research on water resource carrying capacity evaluation methods that integrate the construction of evaluation index systems with scientific validation.

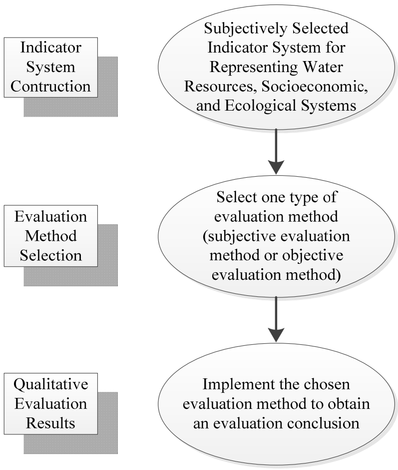

Figure 1. Traditional process flow of qualitative evaluation methods for water resources carrying capacity.

3.2. Quantitative calculation models

Quantitative calculation models for water resources carrying capacity aim to apply mathematical and hydraulic knowledge to characterize the relationships between water resources and social, economic, and environmental factors within a region. These models determine the maximum scale of socio-economic development that water supply systems can support while ensuring the sustainable development of regional ecosystems. However, this "maximum scale of development" is not an objective limit independent of socio-economic factors. The carrying capacity varies with different temporal and spatial scales. Its spatial heterogeneity is influenced by conditions such as the natural environment, water resources availability, water use structure, and the level of economic and technological development. Therefore, the quantitative calculation model for water resources carrying capacity is essentially a tool and method used to address questions such as "What socio-economic value will be generated after water supply?" and "How should a given amount of water be allocated to maximize socio-economic value?" In this sense, the quantitative calculation model for water resources carrying capacity is highly similar to watershed hydrological models. The key difference is that watershed hydrological models are tools or methods designed to answer hydrological science questions such as "What happens after rainfall?" under complex conditions involving precipitation, geology, topography, geomorphology, soil, vegetation, and land use.

Since the 1980s, numerous quantitative calculation models for water resource carrying capacity have been proposed by domestic and international scholars. Among the earlier and more representative models are the system dynamics model [6], and multi-objective decision analysis model [12]. These models have made significant contributions to the refinement of water resource-carrying capacity calculation methods. However, most of these models establish a mathematical relationship between the total water supply (total input) and the total socio-economic development scale (total output) and then use optimization algorithms or trial calculations to determine the water resource-carrying capacity of a region. This approach aligns with the core concept of lumped hydrological models, which simplify processes into a relationship between "input" and "output." As such, this type of quantitative calculation model can be collectively defined as a lumped water resources carrying capacity calculation model. Different lumped water resources carrying capacity calculation models employ varying solving methods. However, they inherently lack the ability to account for the impact of uneven spatial distribution of water resources and water use objects, which may lead to discrepancies between the results and real-world conditions.

Therefore, lumped water resources carrying capacity calculation models have the following inherent limitations: (1) They treat the spatially distributed water supply as a single aggregated input for the model. This approach implicitly assumes that the supply range of any water supply project within the study area can cover the entire region, meaning that any water supply project can deliver water to any point within the study area. This assumption clearly contradicts the actual situation, where the supply range of water supply projects is limited by economic and technical factors. (2) They simplify spatially heterogeneous water use objects into a few specific categories as aggregated outputs of the model. In reality, due to restrictions such as resources, ecology, location, and transportation, different areas within the study region (particularly large study regions) are functionally distinct. Some areas only include specific water use objects rather than all the aggregated outputs. Therefore, simplifying water use objects into a few specific categories as model outputs is inconsistent with the actual functional zoning of the region. Given these limitations, it is necessary to develop a distributed water resource carrying capacity calculation model that accounts for the spatial effectiveness of water supply and the spatial heterogeneity of water use objects.

4. Improvements in research methods for water resources carrying capacity

To address the limitations of traditional qualitative evaluation methods and quantitative calculation models for water resources carrying capacity, a dynamic feedback-based qualitative evaluation method and a distributed quantitative calculation model are proposed. By combining the strengths and advantages of these two approaches, an integrated evaluation method of water resources carrying capacity is established, where qualitative evaluation serves as the overarching control and quantitative evaluation provides refinement, with mutual feedback between the two approaches.

4.1. Dynamic feedback-based evaluation method for water resources carrying capacity

The primary principle of the dynamic feedback-based evaluation method is as follows: Based on the construction of a driving forces-pressure-state-impact-response (DPSIR) conceptual model for water resources carrying capacity evaluation, a preliminary regional water resources carrying capacity indicator system is proposed. Subjective and objective evaluation methods are then applied to verify the scientific validity of the indicators. If the indicators fail validation, feedback is used to adjust the indicator system until it passes validation. Finally, the validated indicator system is used to obtain the qualitative evaluation results of regional water resources carrying capacity. The specific technical framework is shown in Figure 2.

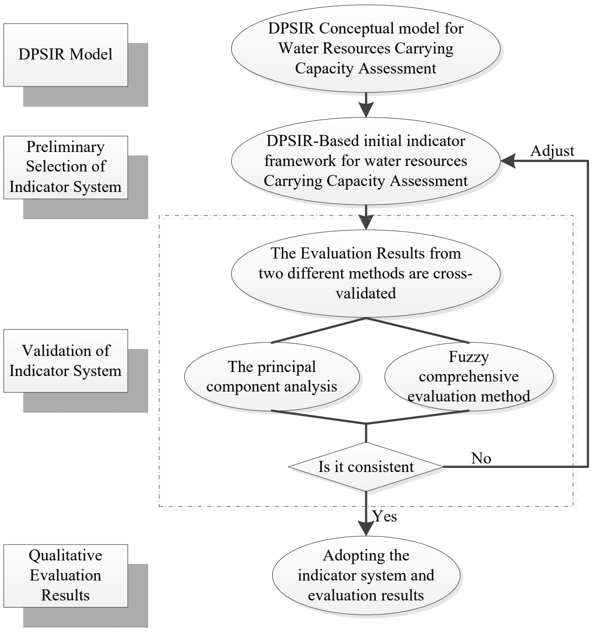

Figure 2. Framework of the dynamic feedback-based evaluation method for water resources carrying capacity.

(1) DPSIR model for evaluating water resources carrying capacity

The Water resources carrying capacity is a complex, integrated system encompassing the interactions among water resource systems, socio-economic systems, and ecological environment systems. It is a composite system formed through the interplay of these subsystems. Therefore, constructing an indicator system that reflects the interactivity among major systems and addresses the limitations of traditional indicator systems—such as subjective determination and isolation among indicators—has become a critical challenge for the qualitative evaluation of water resources carrying capacity. The introduction of the DPSIR conceptual model [13] provides a potential solution for addressing these interactive mechanisms. Due to its comprehensiveness, integrative nature, systematic approach, and flexibility, the DPSIR model has been widely applied in various fields, including environmental, ecological, and social evaluations.

The DPSIR model categorizes the evaluation indicators of a natural system into five components: Driving forces (D), Pressure (P), State (S), Impact (I), and Responses (R). Each component is further subdivided into specific indicators. The relationships among these components are dynamic and connected by causal links, breaking away from the static and isolated nature of traditional indicator systems. When applied to the evaluation of water resources carrying capacity, the DPSIR model interprets the causal chain of components as follows: socio-economic "driving forces" exert pressure on regional water resources and water ecology, leading to changes in the ‘state’ of regional water resources and the water environment, which subsequently ‘impacts’ socio-economic and environmental conditions, ultimately triggering a series of ‘response measures’ (as illustrated in Figure 3).

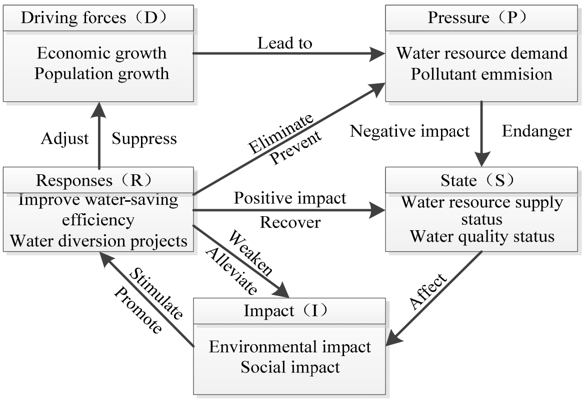

Figure 3. Schematic diagram of the DPSIR model for evaluating water resources carrying capacity.

(2) Preliminary selection of indicator system

To ensure the scientific validity of the indicators, the candidate evaluation indicators are primarily derived from indicators used in studies on water resources evaluation, ecological environment evaluation, and socio-economic evaluation published in authoritative domestic and international journals, as well as those adopted or recommended in standards and guidelines issued by various industries. Following the principles for determining an evaluation indicator system [13], and considering the research objectives and regional characteristics, a preliminary evaluation indicator system is selected.

(3) Validation of the scientific and rational basis of the indicator system

The DPSIR conceptual model provides a solid theoretical foundation and a complete technical framework for constructing the evaluation indicator system for water resources carrying capacity. However, during the specific process of constructing the indicator system, the selection of corresponding indicators for the five components still largely depends on subjective judgments by decision-makers. Therefore, whether the constructed indicator system can comprehensively and objectively reflect the coordination between regional water resources and socio-economic and ecological development requires further scientific and reasonableness validation. A scientifically sound and rational indicator system should fully represent the essential characteristics of the study system. Consequently, its evaluation results should not vary drastically with different evaluation methods, demonstrating robust consistency. Conversely, if the evaluation results diverge significantly, the indicator system may not adequately capture the system's characteristics, potentially leading to contradictory conclusions. To validate the scientific and rational basis of the indicators, multiple evaluation methods can be employed, and their results cross-verified. If the results exhibit high consistency, the indicator system does not require adjustment. If inconsistencies are observed, certain indicators are adjusted until the evaluation results achieve robust consistency. The technical framework for this process is illustrated in Figure 2.

Based on the analysis, a combination of two typical evaluation methods currently used in water resource carrying capacity assessments, namely subjective evaluation methods and objective evaluation methods, can be adopted. The subjective evaluation method, represented by the fuzzy comprehensive evaluation method [7], relies heavily on expert judgment to determine indicator weights. While this approach incorporates expert experience, its evaluation results often reflect the subjective biases of the experts. Conversely, the objective evaluation method, exemplified by principal component analysis[11], extracts objective information from the decision matrix through purely mathematical computations. This method does not depend on decision maker’s subjective judgments, thus ensuring greater objectivity. By cross-verifying the results of these two methods, it is possible to balance the benefits of decision maker experience while minimizing subjective biases, leveraging the strengths of both subjective and objective evaluation methods to validate the scientific and rational basis of the evaluation indicators and results. Fuzzy comprehensive evaluation and principal component analysis are representative methods of their respective categories and have been successfully applied in numerous cases. Therefore, the combination of these methods is used for scientifically evaluating regional water resource carrying capacity.

To reduce the subjectivity of the fuzzy comprehensive evaluation method and ensure that evaluation results are more reasonable and aligned with real-world conditions, this method is further refined. Specifically, the geometric mean of the weight values from the subjective weighting method (analytic hierarchy process, AHP) [14] and the objective weighting method (entropy weight method) [14], known as the combined weight, is used for the fuzzy comprehensive evaluation indicators.

(4) Evaluation of water resources carrying capacity

Using the indicator system constructed based on the above principles, regional water resources carrying capacity is qualitatively evaluated by applying principal component analysis and the fuzzy comprehensive evaluation method.

4.2. Development of a distributed water resources carrying capacity calculation model

The conceptual framework for constructing a distributed water resources carrying capacity calculation model is as follows: The study area is discretized into multiple subunits (which can be further subdivided as needed). The lumped water resources carrying capacity model is then applied to each subunit to calculate its individual water resources carrying capacity. These results are subsequently aggregated to determine the overall water resources carrying capacity of the entire region. The construction of the distributed water resources carrying capacity calculation model primarily involves three processes: subunit division, calculation of available water supply, and model development. The detailed structure is illustrated in Figure 4.

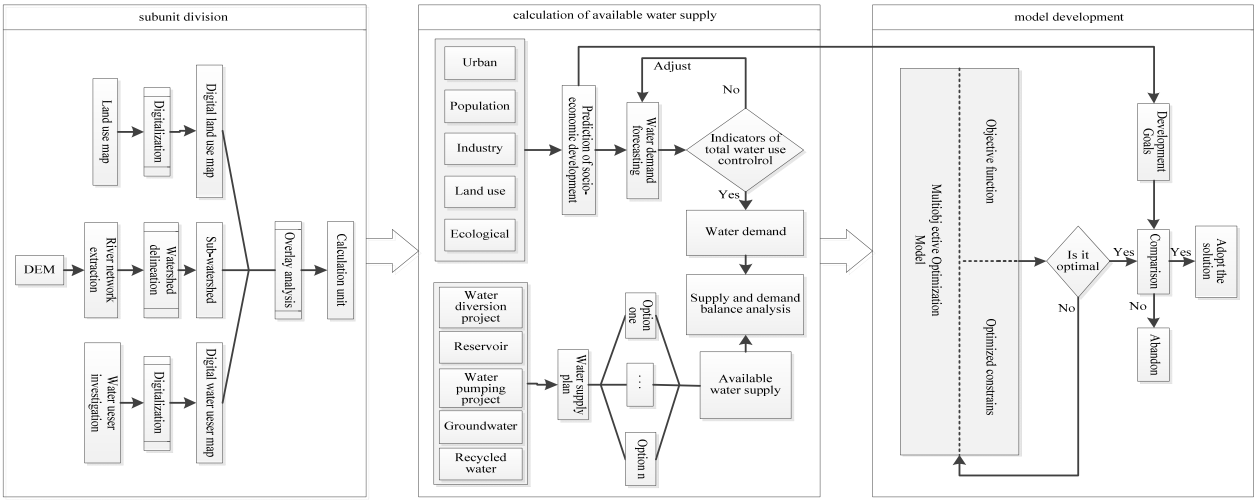

Figure 4. Structural diagram of the distributed water resources carrying capacity calculation model.

(1) Division of calculation units

As analyzed above, the distributed water resources carrying capacity calculation model primarily aims to reflect the impact of spatial heterogeneity in water supply and water use objects on the regional water resources carrying capacity. Therefore, the division of calculation units must emphasize the spatial independence of water supply and the spatial heterogeneity of water use objects.

A watershed represents the fundamental geomorphological unit formed under internal geodynamic forces and modified by external forces and human activities, defined by clear physical boundaries (watershed). It serves as the basic spatial unit for terrestrial water cycles and ecosystems. Watershed act as significant barriers for many organisms and often insurmountable obstacles for human activities. Consequently, socio-economic activities and human interventions within a watershed, such as hydraulic engineering construction, are relatively independent. Thus, the calculation unit division for the distributed water resource carrying capacity calculation model can be conducted by discretizing the study area into natural subwatersheds to ensure relative independence in water supply. These subwatersheds are then further divided into calculation units that are relatively consistent with the water use objects within them.

In this study, the division of calculation units follows the hydrological response unit (HRU) division method. The primary data used include a digital elevation model (DEM), land use maps, and water use object investigation maps. The process for subunit division is as follows (illustrated in Figure 4): based on the DEM, the study area is first discretized into several natural subwatersheds. Then, spatial overlay analysis is conducted by combining the subwatersheds with land use maps and water use object investigation maps. Finally, the subwatersheds are further subdivided into multiple calculation units where water use objects are relatively uniform.

(2) Calculation of available water supply

The available water supply of a region is derived through a comprehensive analysis based on the available water supply calculations for individual projects (such as storage, diversion, and water lifting projects). A rational arrangement of water supply schemes for various water sources and engineering types is then conducted to obtain the final available water supply. The calculation principles for the available water supply of different types of projects are as follows:

1) Diversion and water lifting projects

$$W_k = \min\left(D, Q_{\max}, Y_{up} - Y_{down}\right) \tag{1}$$

where W_k represents the available water supply from the diversion project, D is the water demand of the user, Q_{max} denotes the maximum supply capacity of the diversion and water lifting project, Y_{up} refers to the water inflow to the river channel, and Y_{down} indicates the water demand downstream of the river channel, including ecological water requirements.

2) Storage projects

The calculation of the available water supply from storage projects differs depending on whether the project involves large and medium-sized reservoirs or small-scale storage facilities. For large and medium-sized reservoirs, the available water supply is generally calculated using either the typical year regulation method or the multi-year series regulation method. These processes are relatively complex and are not elaborated here due to space limitations; for details, refer to *Hydrological and Hydraulic Calculations* [15].

For small-scale storage facilities, the available water supply is typically calculated using the repeat storage index method:

$$W_k = n \cdot V_{usable} \tag{2}$$

where n is the repeat storage index, usually greater than 1.0, and is influenced by factors such as catchment area, inflow volume, and effective storage capacity. V_{usable} represents the usable storage capacity of reservoirs and ponds.

3) Groundwater projects

The available water supply from groundwater projects is calculated as:

$$W_k = \sum_{i=1}^{n} q_i \Delta t_i \tag{3}$$

where q_i represents the pumping capacity of the well, measured in m^3/s, Δt_i is the operating time of the well, measured in seconds (s), and *i* denotes the number of wells.

(3) Model construction

Water resource carrying capacity involves multiple objectives related to water resources, society, economy, and ecology. In water-scarce regions, these objectives are often interdependent and mutually constraining, making it impossible to achieve optimal solutions for all objectives. Instead, only relatively optimal solutions can be attained. In this study, the outputs of the model are selected as the maximum industrial added value (*Ind*), maximum population (*Pop*), and maximum agricultural irrigation area (*Area*).

The objective function is defined as follows:

$$Obj = Opt.\left\{\max(Ind), \max(Pop), \max(Area)\right\} \quad (4)$$

Assuming the study area is divided into *n* calculation subunits, the water resource carrying capacity WC of the entire study area in year *t* is:

$$WC(t) = \sum_{i=1}^{n} Obj_i(t) \quad (5)$$

where WC(t) represents the water resources carrying capacity as a vector expressed as $WC(t) = (Ind(t), Pop(t), Area(t))$. $Obj_i(t) = (Ind_i(t), Pop_i(t), Area_i(t))$ represents the water resources carrying capacity of each calculation subunit. For a subunit without arable land, $Obj_i(t) = (Ind_i(t), Pop_i(t), 0)$, and other scenarios follow similarly.

The constraints of the model include water resources constraints, socio-economic constraints, ecological environment constraints, and non-zero variable constraints.

1) Water resources constraints

a. Water balance constraint

$$W_i(t) = w_{Ind\,i}(t) + w_{Pop\,i}(t) + w_{Area\,i}(t) \quad (6)$$

where $W_i(t)$ is the available water supply in the *i*-th calculation subunit in year *t*, and $w_{Ind\,i}(t), w_{Pop\,i}(t), w_{Area\,i}(t)$ represent the industrial water consumption, domestic water consumption, and agricultural water consumption, respectively, in the *i*-th calculation subunit in year *t*.

b. Water supply project constraint

$$W_i(t) \le W_{\max i}(t) \quad (7)$$

where $W_{\max i}$ is the maximum water supply capacity of the water supply project in the *i*-th calculation subunit in year *t*.

2) Socio-economic constraints

a. Population constraint

$$\begin{cases} Pop_i(t) = w_{city\,i}(t) f_{city\,i}(t) + w_{country\,i}(t) f_{country\,i}(t) \ge Pop_i(t-1) \\ w_{city\,i}(t) + w_{country\,i}(t) = w_{Pop\,i}(t) \end{cases} \quad (8)$$

where $Pop_i(t)$ is the total population of the *i*-th calculation subunit in year *t*, $Pop_i(t-1)$ is the total population of the *i*-th calculation subunit in year *t*-1. $w_{city\,i}(t)$ and $w_{country\,i}(t)$ represent the urban and rural domestic water consumption, respectively, in the *i*-th calculation subunit in year *t*. $f_{city\,i}(t)$ and $f_{country\,i}(t)$ are the unit water resource support capacities for urban and rural residents, respectively, in the *i*-th calculation subunit in year *t*, expressed as the reciprocal of the water quota (people/m^3).

b. Urbanization constraint

$$w_{city\,i}(t) f_{city\,i}(t) \ge \left[w_{city\,i}(t) f_{city\,i}(t) + w_{country\,i}(t) f_{country\,i}(t) \right] B_{cty\,i}(t) \quad (9)$$

where B_{cti} is the urbanization rate of the *i*-th calculation subunit in year *t*.

c. Industrial output constraint

$$w_{Ind\,i}(t-1) f_{Ind\,i}(t-1) / Pop_i(t-1) \le w_{Ind\,i}(t) f_{Ind\,i}(t) / Pop_i(t) \quad (10)$$

d. Agricultural irrigation area constraint

$$w_{Area\,i}(t) f_{Area\,i}(t) \le TArea_i(t) \quad (11)$$

where $f_{Area\,i}(t)$ is the unit water resource support capacity for agriculture in the *i*-th calculation subunit in year *t*, expressed as the reciprocal of the water quota (mu/m^3). $TArea_i(t)$ represents the total cultivated land area of the *i*-th calculation subunit in year *t*.

3) Ecological and environmental constraints

In this study, off-channel ecological and environmental water use is included in urban domestic water consumption, while in-channel ecological and environmental water use is deducted during the calculation of available water supply. According to the *Guidelines for Water-draw and Utilization Assessment on Construction Projects* (SL 322-2013) and other relevant regulations regarding in-channel ecological and environmental water use, the standard is set at 30% of the multi-year average inflow during the flood season and 10% of the multi-year average inflow during the non-flood season.

4.3. Integration of qualitative and quantitative methods for water resources carrying capacity

Qualitative evaluation and quantitative calculation are two fundamental research paradigms in the field of water resources carrying capacity. Qualitative evaluation involves the analysis and study of the qualitative aspects of phenomena. In the context of water resources carrying capacity research, it examines how regional water resources support local socio-economic development. This process typically involves analyzing the background of water resources carrying capacity (the three systems), establishing the relationships between each system and the water resources carrying capacity (represented by selecting evaluation indicators), investigating and collecting data to calculate indicator values, and finally applying specific analytical methods (such as fuzzy comprehensive evaluation or principal component analysis) to draw conclusions. Qualitative evaluation has the advantages of being comprehensive and interpretable, but since the researcher serves as the primary analytical tool, it is inevitably influenced by subjective factors, resulting in conclusions that may exhibit drawbacks like fuzziness and uncertainty.

Quantitative analysis focuses on the measurement and study of the quantifiable aspects of a phenomenon. Applied to water resource carrying capacity research, it involves investigating the maximum socio-economic development scale that regional water resources can support. Typically, this process entails analyzing the background of water resources carrying capacity (the three systems), identifying causally related variables (decision variables), constructing mathematical relationships between these variables (objective functions and constraint equations), and finally deriving conclusions through calculation. Quantitative analysis offers advantages such as rigor, precision, and objectivity. However, it reduces the relationships among the three systems to quantifiable mathematical expressions, which overlooks the influence of numerous non-quantifiable factors on water resources carrying capacity. Moreover, issues such as unreliable statistical data and improperly defined constraints may result in drawbacks like incomplete research conclusions.

In summary, neither of the two methods can be considered inherently superior or inferior, as each has its own unique advantages and limitations. These methods simply approach the research subject from two different perspectives. They are not mutually exclusive but are, to some extent, interrelated and even complementary. Since quality and quantity represent two facets of the same phenomenon, combining the two methods can enrich research outcomes and enhance the comprehensiveness of the study. Therefore, this paper proposes an integrated qualitative and quantitative research method for water resources carrying capacity. The specific approach is as follows: Based on the previously proposed dynamic feedback-based water resource carrying capacity evaluation method and the distributed water resource carrying capacity calculation model, socio-economic indicator values, water demand, and available water supply from the quantitative calculation model are used to compute the indicator values representing the three systems (socio-economic, water resources, and ecological environment) in the qualitative evaluation. The results of the qualitative evaluation are then utilized to assist in guiding decision-making for the multi-objective model in the quantitative calculations. This integration achieves the coupling of qualitative and quantitative methods, enabling mutual validation and supplementation of the results from the two approaches (as shown in Figure 5).

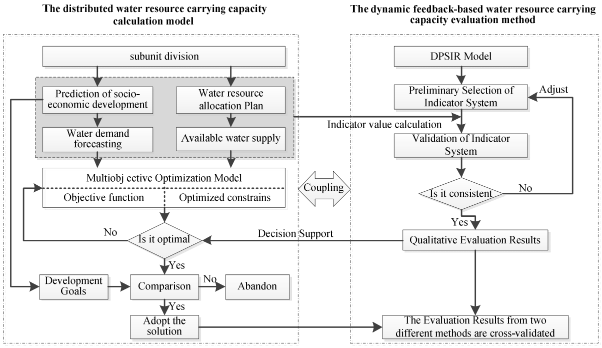

Figure 5. Evaluation of water resources carrying capacity by integrating qualitative and quantitative methods.

5. Conclusions

(1) Based on a comprehensive review of domestic and international studies on water resources carrying capacity, this paper thoroughly analyzed the current concept and defined regional water resources carrying capacity as the maximum socio-economic development scale that the available water supply of a region can support under certain socio-economic conditions, with the premise of maintaining ecological and environmental sustainability through rational optimization and allocation. This definition fully considers the practical realities of regional water supply infrastructure and provides a reference for achieving optimal water resource allocation and sustainable development in the region.

(2) To address the limitations of existing quantitative calculation models for water resources carrying capacity, which treat regions as homogeneous wholes, this paper proposed a distributed water resources carrying capacity calculation model that accounts for the spatial effectiveness of water supply and the spatial heterogeneity of water use objects, along with a method for dividing calculation units.

(3) In response to the subjectivity in constructing evaluation indicator systems for qualitative evaluation of water resources carrying capacity, the lack of adherence to certain scientific methods, and the absence of scientific validation of the indicator systems, a dynamic feedback-based evaluation method for water resources carrying capacity was proposed.

(4) Based on the improved quantitative calculation method, namely the distributed water resources carrying capacity calculation model, and the qualitative evaluation method, specifically the dynamic feedback-based water resources carrying capacity evaluation method, a comprehensive evaluation method for water resources carrying capacity is established. This method integrates the strengths and advantages of both approaches, with qualitative evaluation serving as the total control and quantitative evaluation providing refinement, while enabling mutual feedback between the two approaches.

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