Pol. J. Environ. Stud. Vol. 32, No. 3 (2023), 1975-1986
DOI: *10.15244/pjoes/160199* ONLINE PUBLICATION DATE: 2023-03-07

Review

Research Progress on the Evaluation of Water Resources Carrying Capacity

Weizhi Li[1, 2, 3], Shanshan Liu[3], Wenjuan Chang[1, 2], Xin Zhang[3], Chenhao Li[3], Tianling Qin[3]*

[1]Engineering Research Center of Eco-environment in Three Gorges Reservoir Region, Ministry of Education, No. 8 Daxue Road, Xilin District, Yichang 443002, China
[2]College of Hydraulic & Environmental Engineering, China Three Gorges University, No. 8 Daxue Road, Xilin District, Yichang 443002, China
[3]State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, No. 1 Fuxing Road, Haidian District, Beijing 100038, China

Received: 1 September 2022
Accepted: 2 February 2023

Abstract

The imbalanced, maladjusted, and uncontrolled phenomenon in the regional water resources system is caused by the combined disturbances of climate change and human activities. The socio-economic and ecological systems are restricted, and the combined carrying capacity also changes accordingly. In order to explore the above changes, based on the influence mechanism of climate change, socio-economic system and ecosystem on water resources system, this paper systematically reviews the relevant research progress in water resources carrying capacity (WRCC), from the basic theory of water resources carrying capacity, the construction of evaluation index system, the classification criteria and evaluation methods, etc. This review provides basic theoretical and technical support for the study of generalized water resources carrying capacity considering the interlinked climate-ecology-society system, which is conducive to the promotion of water resources carrying capacity and the synergistic development of socio-economic and ecological environment under a changing climate.

Keywords: water resources carrying capacity evaluation, socio-economic system, ecosystems, climate change

Introduction

Water resources carrying capacity is a refined subfield of resource and environmental carrying capacity based on its components [1]. Water resources, an essential part of the natural environment, are closely related to socio-economic development and people's lives. [2, 3]. The subject of water resources carrying capacity is water resource, the object is human beings and the socio-economic systems and ecosystems in which they live. In a narrow sense, the water resources carrying capacity mostly reflects the following aspects: (1) Satisfy the demands and pressures of the object on the subject (2) Defining the water consumption

*e-mail: qintl@iwhr.com

thresholds of socio-economic and ecological systems in the water resources system (3) Determining the impact of human activities on the water resources system.

The study of water resources carrying capacity is a key scientific proposition for sustainable development. In the 1970s, due to the increasing contradictions in the development of human society and the rapid spread of resource shortage in many countries or regions around the world, intergovernmental international organizations carried out a series of resource carrying capacity projects [4]. Towards the end of the 20th century, the evaluation of the regional water resources carrying capacity was raised as an important scientific issue in the study of water security strategy and sustainable development [5, 6]. Scholars such as Wang G. [7] and Hui Y.H. [8] et al. took the lead in studying the water resources carrying capacity in Northwest China, which provides a basis for economic development decision-making in water deficient areas. International scholars mostly discussed the definition and basic criteria of water resources carrying capacity from the perspective of urban development and water security [9-12]. Since entering the 21st century, the research on water resources carrying capacity has begun to take shape, and has deepened from the discussion of concepts and methods to the application level. In 2006, Xia J. et al. established a WRCC model for urbanized areas based on the binary water cycle, with population as the target function, to provide a basis for the implementation of their sustainable development strategy. Later on, researchers have used this as a technical support to supplement and improve the physical process, establishing water resources carrying capacity evaluation models and indicator systems such as Control Objective Inversion model (COIM) [13], Pressure-State-Response (PSR) model [14] et al., and research has become more systematic, gradually incorporating ecosystems into the evaluation system [15]. In 2016, Ait-Aoudia M.N. et al. [16] determined the maximum population that can be supported by Algiers' water resources based on water supply and demand, using ecological water demand as a threshold. In the same year, Wang J.H. et al. [17] proposed a water resources carrying capacity evaluation method based on dynamic trial and error feedback from the perspective of water quality and quantity coupling, and applied this method to the national water resources carrying capacity monitoring and early warning mechanism construction work.

It can be seen that from theory to application, from static analysis to dynamic prediction, after half a century of exploration and research, the research on water resources carrying capacity has not only become one of the important basic tasks of national ecological civilization construction, but also provided a research basis for ensuring national water resources security and promoting comprehensive, coordinated and sustainable development [18].

Research on the water resources carrying capacity is increasing due to its dynamicity, extreme limited, fuzzification, and the diversity of carrying modes [19]. The Web of Science (WOS) core database and the China Knowledge Network (CNKI) full-text database were searched for 2244 publications on "Water Resources Carrying Capacity" in the past 15 years, and relevant graphs and charts were drawn up using Excel and VOSviewer (Figs 1-3) to reveal the general research direction and trend of water resources carrying capacity.

As can be seen from Fig. 1, research on water resources carrying capacity (WRCC) has shown a clear upward trend in recent years, with most research being linked to socio-economics and less combining ecological service functions (EFS) and climate change. Most of the authors and organisations involved on WRCC research are from China (Fig. 2).

With the implementation of the national sustainable development strategy, the study of water resources carrying capacity has become one of the hot research

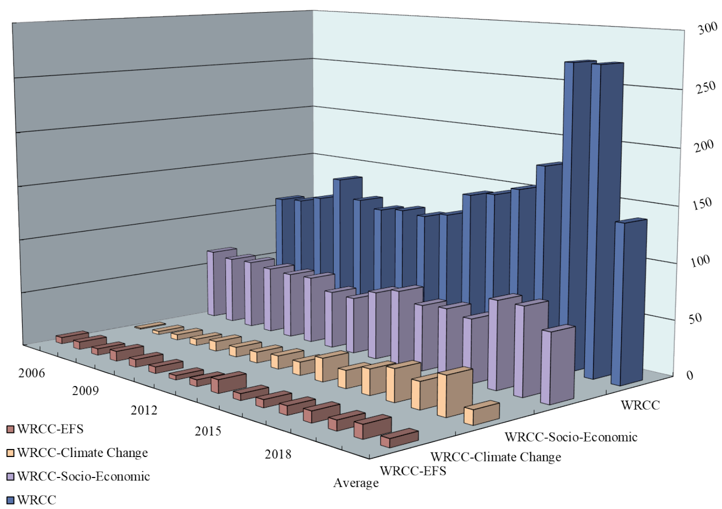

Fig. 1. Trends in the number of international publications on water resources carrying capacity and their related fields

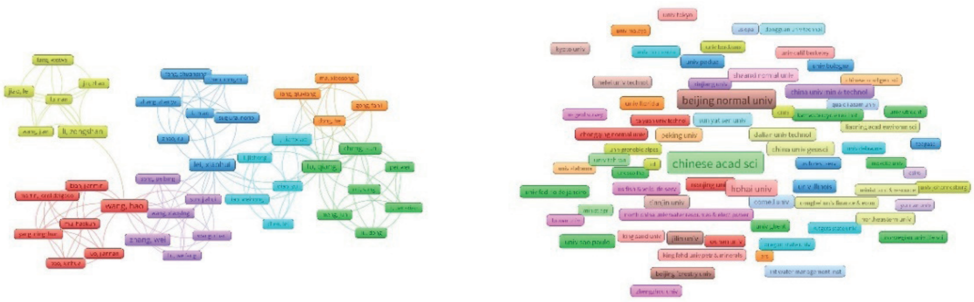

Fig. 2. Network of author and organization based on the co-authorship method on WRCC research from 2006 to 2020.

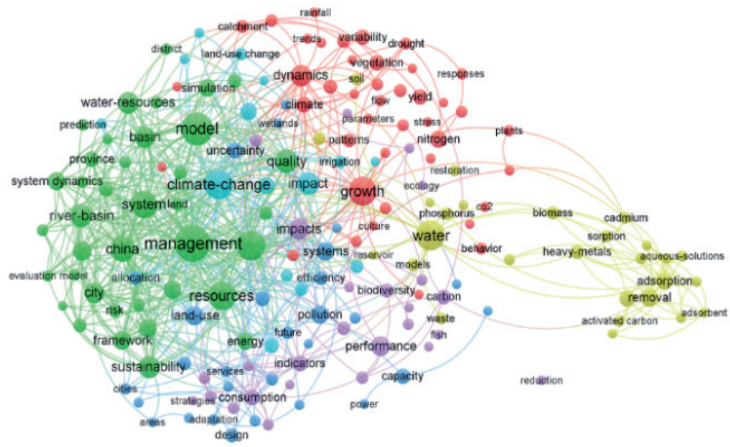

Fig. 3. Network of keywords based on the co-occurrence method on WRCC research from 2006 to 2020.

areas of resources and environment. Chinese scholars have conducted a lot of research around the concept, connotation, characterization indicators and assessment methods of water resources carrying capacity, and have put forward many related concepts, connotations and methods. The international literature is biased towards the broader conceptual area of water resource management, of which water resources carrying capacity is only one aspect, and focuses more on the impact of external factors such as climate change on water resource systems and the construction of models (Fig. 3). At present, the model of water resources carrying capacity at home and abroad mainly takes population and economy as the carrying goal, but there is less research on the ability of water resources to maintain its own renewal and ecological environment, which has obvious limitations [20].

Research Progress on Key Issues of Water Resources Carrying Capacity Evaluation

Basic Theory of Water Resources Carrying Capacity Evaluation

The theoretical basis of the research on water resources carrying capacity mainly includes the theories of water resources, system engineering and sustainable development [21-23]. In different historical periods and based on different research purposes, the definition of water resources carrying capacity has different emphases. The definition of WRCC in the existing research can be roughly divided into "water resources development scale" and "water resources supporting sustainable development capacity". The scale of water resources development theory is based on the total amount of water resources, to obtain the maximum capacity of water resources can supply water for production and domestic use. Xu Y.P. [24], Gao Y.C. [25], et al. have argued that the surplus and deficit of water resources supply and demand and the potential for further exploitation of water resources represent the carrying capacity of water resources. The theory of water resources supporting sustainable development specifically refers to the maximum supporting capacity of water resources to support population and socio-economic development. The former starts from the level of water resources system and envisages a specific index to characterize the carrying capacity of water resources. The latter takes the socio-economic system as the anchor point and reflects the carrying capacity of local water resources in terms of population and socio-economic scale, which is more in line with the current situation of increasing water scarcity and constraints on coordinated socio-economic and ecological development, and has long-term significance and has been recognized by more scholars (Table 1).

Water Resources Carrying Capacity Evaluation Index System

Under the influence of climate change, human activities affect the regional water resources carrying capacity through the development and utilization of water resources through socio-economic development and ecological protection, so as to change the water resources carrying capacity. The resulting water resource overload includes the following four aspects: The first is the problem of excessive water intake and consumption. The water intake and consumption outside the river or groundwater exceeds the upper limit of water resources utilization, resulting in insufficient ecological water use in rivers and lakes, overexploitation of groundwater and other problems [38]. The second is the problem of over extraction and pollution discharge. The pollutants entering the river exceed the self-purification capacity or environmental capacity of the water body, resulting in the decline of water quality i.e., the problem of water environmental pollution [39]. The third problem is the over exploitation and occupation of water space leads to the shortage of natural water ecological space and the degradation of lake ecosystem. Fourth, the over exploitation of hydropower resources has caused excessive disturbance of natural hydrological process or excessive obstruction of natural flow pattern, resulting in the degradation of water ecosystem [40].

To quantitatively evaluate the water resources carrying capacity, it is necessary to select the elements and index factors affecting the water resources carrying capacity, so as to establish the evaluation index system and quantitatively evaluate the water resources carrying capacity through the evaluation model [41]. Constructing the evaluation index system of water resources carrying capacity is a basic work of water resources carrying capacity evaluation. This paper summarizes the relevant research results on the construction of evaluation index system of water resources carrying capacity at home and abroad, mainly based on the principles of scientific, systematic,

Table 1. Connotation classification and research content of water resources carrying capacity.

Classification	Research Content	Reference
Maximum development capacity of water resources	On the premise of ensuring life and ecosystem, the regional water resources can accommodate the largest agricultural, industrial, urban scale and population capacity.	[7]
	Under certain social conditions, water resources can provide the maximum capacity of water for industrial and agricultural production, people's life and ecological environment protection.	[24, 26]
Maximum capacity of water resources to support socio-economic development	Under the condition of maintaining a certain living standard and ecological environment quality, the available water supply of natural water resources can support the maximum coordinated development of population, environment and economy.	[27-29]
	On the basis of meeting ecological water use, water resources can maintain the maximum socio-economic scale of limited development goals.	[1, 12]
Maximum capacity to support socio-economic development within the context of rational use and optimal allocation of water resources	Under the socio-economic and technological conditions of different stages in the region, on the premise of rational development and utilization of water resources, the regional natural water resources can maintain and support the population, economy and environmental scale.	[30, 31]
	According to the foreseeable stage of technological and socio-economic development, taking sustainable development as the principle and maintaining the virtuous circle of ecological environment as the condition, after reasonable and optimal allocation, the water resources in this area play the greatest supporting role in the local socio-economic development.	[32]
	When the water management and social economy are optimized, the regional water ecosystem itself can carry the maximum sustainable development level.	[33]
Maximum size of the water system that can support socio-economic development and the number of people with a certain standard of living	On the premise of maintaining a virtuous ecological cycle and sustainable development, water resources can support the scale of social and economic activities and the scale of population with a certain living standard.	[34]
	The maximum population capacity that can be supported by regional socio-economic development under the conditions of rational allocation and efficient utilization of water resources, based on the predictable stage of technological and socio-economic development, based on the principle of sustainable development and on the premise of maintaining the benign development of ecological environment.	[35-37]

dynamics, quantifiable and reflecting the factors of human water relationship coordination. According to the structure of "Target layer - Rule layer - Element layer - Index layer" (Table 2.), taking water resources carrying capacity as the target layer, based on social-economic system, the evaluation index system of water resources carrying capacity is designed by selecting some relevant indexes at the criterion level of ecosystem and water resources system (Fig. 4.).

Evaluation Standard of Water Resources Carrying Capacity

The development and utilization of water resources in human society mainly includes taking and consuming water resources, discharging and receiving pollutants, occupying water space and developing and utilizing water energy resources. The resource attributes of development and utilization are water resources, water environment capacity, water space and water flow state [61, 62].

The essence of the water resources carrying capacity evaluation is to judge this capability status from four elements [10, 62]: water resources, water environment capacity, water space, and water flow state according to the indicator measurement standard. Here, water space refers to spatial information indicators such as water surface area, aquatic habitat area, etc. And water flow state refers to Characteristic information indicators such as water system connectivity, flow velocity, etc.

Table 2. Water resources carrying capacity Main evaluation indicators.

Target Layer	Rule Layer	Element layer	Index Layer	Reference
Water Resources Carrying Capacity	Economic System	Economic Development Level	Industrial & agricultural economic density, per GDP, GDP growth rate, Cultivated land area, Irrigation area, total grain yield, etc.	[42-44]
		Industrial Structure	The proportion of three industries in GDP, the proportion of paddy and dry land, the proportion of output value of agriculture, forestry, animal husbandry and fishery, etc.	[43-45]
	Social System	Population status	Total population, urbanization rate, natural population growth rate, population flow, population density, etc.	[43, 44, 46]
		Scientific and technological level	Enterprise investment in science and technology, water saving level, proportion of output value of high-tech industries, proportion of expenditure on science and technology, etc.	[47, 48]
		Social technology level	Per capita water consumption, Water consumption per 10000-yuan GDP, Average irrigation water consumption per mu, Sewage discharge, Irrigation water utilization coefficient, Water elasticity coefficient, Pollutant inflow coefficient, Sewage diameter ratio, etc.	[49, 50]
		Water resource allocation capacity	Proportion of ecological water use, Proportion of water used by the three industries, Proportion of water storage and transfer, Flood regulation and storage capacity, Reservoir regulation capacity index, Water shortage ratio, etc.	[49, 51]
		Policies, regulations and management ability	Proportion of water conservancy investment, Proportion of agricultural expenditure, Proportion of irrigation investment, Water price, Improvement rate of policies and systems, etc.	[52]
	Ecosystem (Ecological Service Function)	Supply service	Total water resources, Average biomass of aquatic organisms, Water conservation, etc.	[53, 54]
		Adjust service	COD discharge, total wastewater discharge, urban sewage treatment rate, Water self-purification index, Reduce the amount of dust, etc.	
		Culture service	Water landscape distribution, water leisure tourism person times.	
		Support service	Water area ratio, chlorophyll concentration, biodiversity index, etc.	
	Climate System	Weather conditions	Average annual precipitation, average annual temperature, drought index, evaporation index, etc.	[55,56]
		Water resource endowment	Total water resources, water production coefficient, runoff coefficient, variation coefficient of water resources, drainage density, etc.	[56, 57]
		Development and utilization degree of water	Water resources development and utilization rate, water area and coastline development and utilization degree, water resources supply and demand balance index, runoff regulation and storage capacity, groundwater overexploitation, etc.	[58-60]

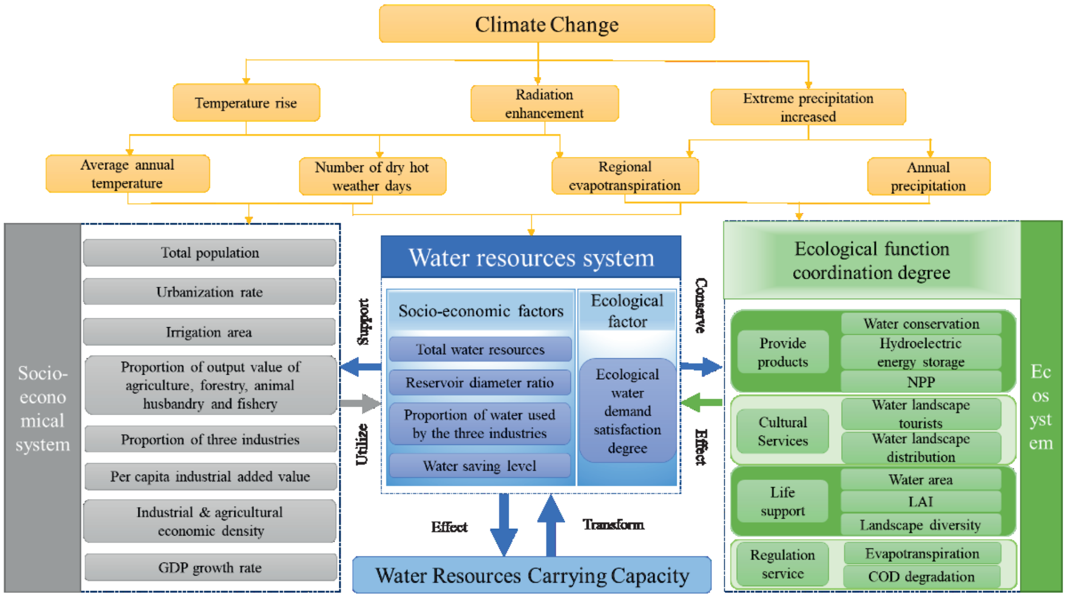

Fig. 4. Impact of socio-economic and ecosystem evolution on the carrying capacity of water resources in the context of climate change.

Water Resources

The support of water resources to the water resources carrying capacity is reflected in the elements related to the total amount of regional water resources available, the size of the total amount of regional water resources available determines to a certain extent the carrying status of regional water resources. When the amount of water used to maintain human production and life, ensure socio-economic development and sustain the ecological environment exceeds the amount of water available for renewal in the regional water cycle, it will cause frequent conflicts between human society, economic development and the ecological environment and water resources, bringing about problems such as over-exploitation of ecological water and groundwater, which are obstacles to These problems are important factors that hinder human life, constrain regional economic development and damage the ecological environment.

Water Environment Capacity

The water environment capacity supports the water resources carrying capacity by reflecting the elements related to the pollution carrying capacity of the water resources system. The process of human production and economic development will produce a certain number of pollutants, causing a decline in the quality of water resources. When the number of pollutants entering the river exceeds the pollution carrying capacity of the water body, it will cause the loss of the function of the water body. The water resources without guaranteed water quality are then less able to meet the functions related to human life, economic development, agricultural irrigation and maintenance of the ecological environment.

Water Space

The support of water space for the water resources carrying capacity is reflected in the functions required by the regional ecological environment to maintain the habitat of flora and fauna in the region. With the accelerated urbanisation process and the gradual transformation of nature by human beings, the constant demand for water space and the large-scale artificial disturbance to the physical habitat have caused the original aquatic habitats to be squeezed and destroyed to varying degrees, and the greater the degree of disturbance and destruction, the worse the carrying capacity of the regional water resources.

Water Flow State

The water flow state supports the water resources carrying capacity by providing a relatively unobstructed water flow channel in the basin, which acts as a carrier of material transport, energy transfer and information transfer within the water flow system, and is also the basis for all ecological processes. The connectivity of the water flow system is not only reflected in the renewal of water flow in the context of the large-scale water cycle, but also in the structural characteristics of the water flow in the deep pool-shallow system at the river segment scale. As human activity intensifies, the construction of dykes and over-abstraction of water sever the hydraulic connections between water bodies, blocking the three-way connectivity of rivers and disrupting the original hydrological rhythms. The higher the degree of temporal and spatial blockage of water flow channels to meet social services such as water supply and power generation, the poorer the water resources carrying capacity.

Table 3. Key driving indicators of water resources carrying capacity.

Essential	Index Classification		Key Driving Indicators
Water Resources	Total Water Quantity	Capacity Indicators	Precipitation, Total water resources, Storage Capacity of Medium and Large Reservoirs, Unconventional water consumption, irrigative water use efficiency
		Load Indicators	Population density, Urbanization rate, Water consumption per 10000-yuan GDP, Water consumption of 10000-yuan industrial added value, Development and utilization rate of water resources
	Ecological Water Quantity	Capacity Indicators	Basic ecological flow, Ecological base flow guarantee rate
		Load Indicators	Total water consumption outside the river, eco-environment water consumption, Annual runoff
Water Environment Capacity	Load Indicators		Total ammonia nitrogen emission, COD emission, urban sewage treatment rate
Water Space	Capacity Indicators		Precipitation, Annual runoff, drainage density
	Load Indicators		replenishment of rivers and lakes, Landscape fragmentation, Soil erosion rate, Vegetation Coverage, Hydrological connectivity
Water Flow State	Capacity Indicators		Annual runoff, Total water resources, Average velocity of river
	Load Indicators		Hydropower development and utilization rate, River cut-off length ratio, Annual runoff change rate

The supply, use, consumption and discharge of water resources interact with the ecological environment. Water resources carrying capacity is to meet the demand and pressure of socio-economic system and ecosystem on water resources. It is necessary to define the thresholds between the two major systems, socio-economic and ecological, in terms of water quantity, water quality, water space, and water flow state, and determine whether the impact of human economic activities on ecosystem service functions is excessive.

Through relevant research and practice at home and abroad, a total of 26 key driving indicators were selected from four elements: water quantity, water quality, water space and water flow status, after correlation analysis, principal component analysis (PCA), entropy weighting method (EWM) and DEMATEL method to analyze the indicator weights in each element (Table 3).

In addition, with reference to the "Urban Water System Planning Guidelines" (SL431-2008), "Surface Water Environmental Quality Standards" (GB3838-2002) and other national or industry standards and norms promulgated in the fields of water conservation, ecology and other related literature [62-67], some index grading standards were compiled, and the degree of influence of each index on WRCC was divided into 3 levels (Table 5).

Evaluation Method of Water Resources Carrying Capacity

The existing evaluation methods of water resources carrying capacity can be divided into two categories. The first category is constructing the indicator system from the phenomenon analysis of the water resources carrying capacity. Due to the neglect of interrelationships

Table 4. Water resources carrying capacity evaluation criteria.

Essential	Load	Capacity	Carrying Condition Evaluation			
			Severe Overload	Overload	Critical State	No Overload
Water Resources	Total regional water consumption on W	Regional available water W_0	$W \geq 1.2W_0$	$W_0 \leq W < 1.2W_0$	$0.9W_0 \leq W < W_0$	$W \geq 0.9W_0$
Water Environment Capacity	Number of pollutants entering the river in water function area P	Sewage carrying capacity of water functional area	$P \geq 3\ P_0$	$1.2P_0 \leq P < 3P_0$	$1.21P_0 \leq P < 1.2P_0$	$P < 1.1P_0$
Water Space	Actual water area rate S	Natural water area ratio	$S < 0.9S_0$	$S_0 > S \geq 0.9S_0$	$1.21S_0 > S \geq S_0$	$S \geq 1.2S_0$
Water Flow State	Total regulation capacity of reach reservoir R	Annual runoff of river reach	$R \geq 0.9R_0$	$0.6R_0 \leq R < 0.9R_0$	$0.4R_0 \leq R < 0.6R_0$	$R < 0.4R_0$

Table 5. Water resources carrying capacity of some indicators grading standards.

Index	Unit	No Overload	Critical State	Overload	Index	Unit	No Overload	Critical State	Overload
Surface water utilization rate	%	<20	20-40	>40	Wetland protection rate	%	>90	50-90	<50
Water quality standard rate	%	>80	60-80	<60	Ecological water use rate	%	>25	15-25	<15
Dissolved oxygen concentration	mg/L	>5	2-5	<2	COD concentration	mg/L	<20	20-40	>40
Per capita water consumption	L/per	<120	120-180	>180	Percentage of primary industry	%	<12	12-15	>15
Biodiversity Index	\	>0.8	0.7-0.8	<0.7	Groundwater exploitation coefficient	\	<0.7	0.7-1.0	>10
Average irrigation water consumption per mu	m^3/mu	<300	300-400	>400	Water consumption per unit of GDP	m^3/10000yuan	<60	60-80	>80

Table 6. Main evaluation methods of water resources carrying capacity.

Evaluation Method	Research Content	Advantages	Improvements	Reference
Conventional trend method	The upper limit of the total industrial and agricultural output value, irrigated area, and population development scale under the condition of meeting the minimum requirements of maintaining the ecological environment.	The method is easy and intuitive.	Difficult to reflect the complex relationship of water resources carrying capacity system	[7]
System dynamics method	The ability of water resources to sustainably support social systems, as expressed in the value of industrial and agricultural output.	Can better solve the quantitative relationship between the factors influencing the carrying capacity of water resources	Involving many model parameters, large data requirements, and difficult to choose the covariates.	[68-70]
Fuzzy comprehensive evaluation method	The capacity of water resources to supply water for production, living and ecological environmental protection, i.e., the maximum capacity of water resources development and utilization.	A more comprehensive picture of the water resources carrying capacity.	The problem of subjective arbitrariness in the evaluation.	[68, 72, 73]
Principal component analysis method	Regional water resources allowed to develop the amount of water to maintain the population, socio-economic development support capacity, water resources development potential.	Objective determination of weights to avoid subjective arbitrariness.	Unclear meaning of single indicator composite of multidimensional objectives.	[16, 73, 74]
Ecological footprint method	Quantifying the degree of sustainable use of natural resources by introducing ecologically productive land	Highly manipulable, intuitive calculation results, reflecting regional comparability	There are problems such as imperfect theoretical foundation and no recognized bearing capacity index system	[53]

Table 6. Continued.

Prediction-Simulation-Optimization-Based Control Object Inversion Model (PSO-COIM)	Establishing quantitative links between „climate change" factors and „water resources system" factors; calculating predictions of future evolution of land surface water resources systems based on climate model outputs	Better reflect the dynamic carrying capacity of water resources under climate change, suitable for the calculation of dynamic carrying capacity of water resources in complex basins	Some processes have been simplified in the modeling, so there is still room for improvement in calculation accuracy	[13]

among various factors, the subjectivity of researchers is enhanced, and it is mostly used for macroscopic qualitative judgments. Common methods include fuzzy comprehensive evaluation (FCE) [63], principal component analysis (PCA) [64], projection pursuit (PP) [65], Set pair analysis (SPA) [66] and analytic hierarchy process (AHP) [67], etc. Secondly, starting from the interaction relationship between factors in the water resources carrying capacity system and focus on the factor linkage between phenomena, such as conventional trend method [7], multi-objective decision analysis method [34], etc. (Table 6). How to reasonably establish the "socio-economic-ecological-climatic" composite system of water resources carrying capacity evaluation method is the biggest difficulty in this field, and there is still a lack of solid basic theoretical support, which needs to be explored in depth.

Conclusion

At present, certain progress has been made in the research related to water resources carrying capacity evaluation, but the basic theoretical results still need to continue to be studied in depth, and generally for the formation of a unified caliber of "water resources carrying capacity" evaluation connotation. The application of a single evaluation method of water resources carrying capacity has limitations and is often limited to each factor in the water resources carrying capacity system, and is more subjective in the selection of the index system and evaluation criteria. Future research will focus on the following two aspects.

First, the study of water resources carrying capacity involves interdisciplinary research in hydrology, ecology, economics and system science, and requires comprehensive consideration of the interaction of multiple systems such as regional socio-economic, resources, ecology and climate. Climate change and human activities interfere with and affect the water resources system excessively, easily causing an imbalance in the development and evolution of the three systems of "water resources - socio-economic - ecology", resulting in water resources overload. Therefore, the basic theoretical research on the components, connotation and extension, and the bearing mechanism of the general water resources carrying capacity (GWRCC) is an important trend of current research.

Second, using "big data" technology, "3S" technology, artificial intelligence, etc., new methods are proposed for the study of water resources carrying capacity. Based on the multi-angle study of the minimum unit, gradually realize the dynamic balance of population size and economic development potential under the water resources carrying capacity of the entire region, in order to rationally allocate resources, adjust industrial structure and production layout, formulate socio-economic development strategies provide decision-making. At the same time, it also provides a scientific basis for actively promoting the monitoring and early warning work on water resources carrying capacity.

Acknowledgments

This research was supported by the Key Research and Development Project of Inner Mongolia autonomous region (2021ZD0015), the National Science Fund Project (52130907, 51879275) and the Five Major Excellent Talent Programs of IWHR (WR0199A012021).

Conflict of Interest

The authors declare no conflict of interest.

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