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ORIGINAL RESEARCH ARTICLE

Communities of aquatic organisms in the system of ecological monitoring of streams at the Vostochny Cosmodrome (Russia)

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ABSTRACT

The current data on the ecological state of streams at the launch site of the Vostochny Cosmodrome with the use of biological indicators are presented. Recommendations on the surface water biomonitoring of the cosmodrome and the booster rocket drop zones are given. It is shown that the system of biological monitoring of the cosmodrome, as a part of the Roscosmos environmental monitoring, should be coordinated with the Roshydromet monitoring.

Keywords: Bioindication; Biomonitoring; Vostochny Cosmodrome; Zeya River BasinO

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1. Introduction

The Vostochny Cosmodrome is a new Russian spaceport in the Amur Oblast, in the Russian Far East. Its construction began in 2011, and in April 2016 it was put into operation[1]. The launch site of the cosmodrome is located in the Zeya river basin.

1.2 Object of research

The river network of the launch site is represented mainly by small rivers. The site partly includes the watersheds of the Zeya first- and second-order tributaries (Bolshaya Pera, Ora and Dzhatva rivers). Besides, there are watersheds of other first-order right tributaries of the Zeya (Galchikha, Kamenushka, Iur rivers, and Iversky stream), and the first-order tributaries of Bolshaya Pera river (Zolotoy, Serebryany, Medny streams) and Ora river (Okhotnichy and Nikolaevsky streams).

The hydrological regime of rivers is distinguished by multiple rain floods, water level fluctuation with significant amplitudes throughout the ice-free period, the absence of winter water runoff in small streams as a result of through freezing. These features of water ecosystems are mainly determined by a monsoon climate. The available data are evidence of low water mineralization, minor content of biogenic substances, and low organic pollution[2,3].

The construction of the cosmodrome on particular areas of watersheds resulted in the change of surface runoff and water regime of small streams, up to the formation of drainless sites. The construction of roads led to the disturbance of some parts of the floodplain and coast line, and the construction of linear infrastructure facilities caused a delay of groundwater migration[4].

1.2 Biological monitoring of freshwater ecosystems

The environmental monitoring implies the long-term observations, the assessment and forecast of the environment state and its pollution. The methods of physical and chemical analysis currently used cannot provide a full assessment of the human impact on the environment. Firstly, these methods reflect the current situation during the sampling, while the biological method allows to reveal impact on water body in the previous analysis time. Secondly, it is impossible to determine all known and unknown types of water pollutants; biological objects respond to all types of pollution regardless of their nature and provide an integral indicator of water quality as a habitat. The biological analysis can use different groups of hydrobionts depending on the research objectives[5,6].

Phytoplankton can serve as an indicator of the water body trophicity since there is a direct relationship between the phytoplankton productivity and phosphorus content. Zooplankton is characterized by rapid response to environmental changes that allows us to use it as a sensitive indicator of rapid changes in the environment.

Zoobenthos and zooperiphyton are distinguished by stable localization at certain habitats for a long time and hence they are suitable for observing the anthropogenic succession and the processes of self-purification of aquatic ecosystems. The composition of zoobenthos includes the most long-lived (excluding fish) groups of aquatic organisms, namely, molluscs and oligochaetes, which make up a large proportion of zoobenthos biomass in many water bodies and watercourses. Therefore, they are good indicators of chronic pollution and ecosystem stability. Zoobenthos is the basis for biomonitoring of the surface waters in the countries of European Community and the United States. Therefore, most bioindication methods are aimed at the study of its composition and structure.

Macrophytes, as compared to other hydrobionts, are more conservative indicators of water quality; they are more resistant to short-term pollution and are able to integrate pollution fluctuations over time. Besides, many of them are non-specific concentrators of elements. Thus, macrophytes are a good object for long-term monitoring[5-8].

2. Materials and techniques

In the post-flood period, from September 17 to September 25, 2013, the field investigation of watercourses, draining the territory of the cosmodrome, were carried out (**Figure 1**). A total of 12 watercourses were studied. In the period from June 28 to July 2, 2014 (prior to summer-autumn flood), nine watercourses were examined. The standard hydrobiological methods were used for sampling, initial processing and laboratory analysis[9].

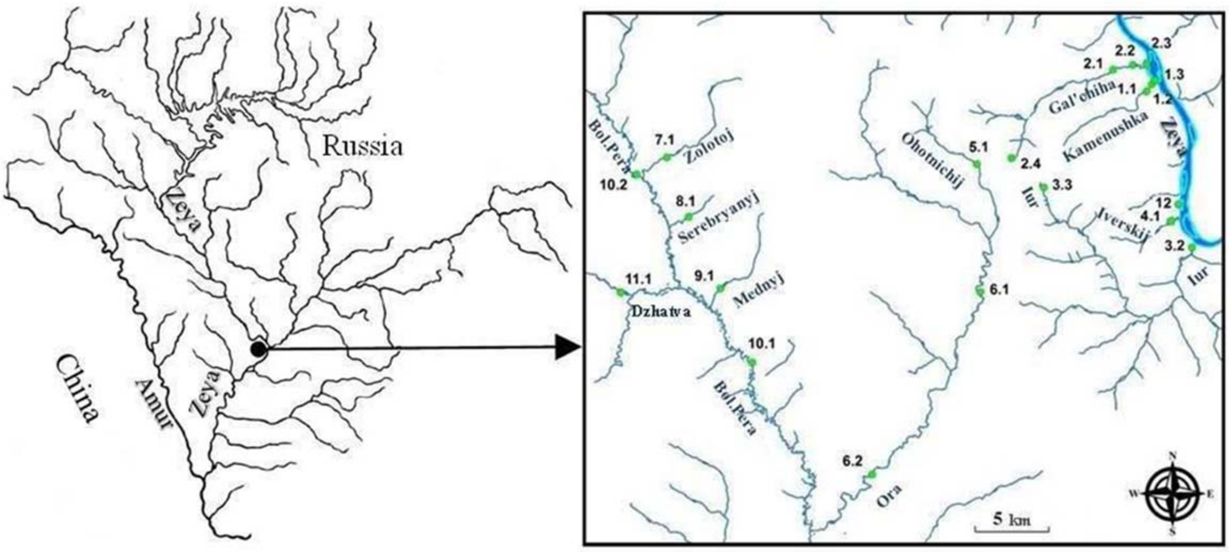

Figure 1. Map of sites where hydrobionts was sampled.

3. Results and discussion

3.1 Structure and composition of aquatic communities

Watercourses at the Vostochny Cosmodrome are characterized by high taxonomic diversity of hydrobionts. In the course of research, 106 species of phytoplankton algae represented by 110 intra-specific taxa were found. In peripheral and benthic algoflora, 153 species of algae from seven groups; 38 species of macrophytes from five groups and 20 families; 60 species of planktonic animals and 108 species of benthic invertebrates from 5 classes were revealed (**Table 1**).

Table 1. Hydrobiological features of streams at launch site of the Vostochny Cosmodrome (28.06–02.07. 2014)

Watercourse	**Phytoplankton**				**Phytoperiphyton**			**Macrophytes**	**Zooplankton**			**Zoobenthos**		
	n	**N, th. cells/dm³**	**B, mg/dm³**	**Chl. a, mg/m³**	**n**	**N, bil. cells/m²**	**B, g/m²**	**n**	**n**	**N, species/m³**	**B, mg/m³**	**n**	**N, th. species/m²**	**B, g/m²**
Galchikha river	13	10.1	22.8	1.21	34	–	395	6	9	1,525	4.18	7	–	–
Iversky stream	8	6.20	2.4	0.20	47	19.3	1.24	5	12	250	9.63	6	0.07	0.19
Okhotnich stream	10	12.7	13.6	0.85	25	12.1	0.51	5	9	210	0.98	6	0.14	0.14
Ora river	28	47.9	102	1.27-2.54	46	33.5	1.23	10	23	470	6.53	20	4.14	6.71
Zolotoy stream	21	51.6	266	1.15	27	–	276	14	13	320	0.95	6	0.43	0.43
Serebryan stream	18	28.4	1040	0.89	21	965	13.3	7	11	480	2.13	10	12.42	16.2
Medny stream	18	21.6	46.6	1.06	17	–	1260	4	6	160	0.42	11	2.50	6.35
Bolshaya Pera river	38	182	358	2.57	26	92,4	3.26	6	13	110	0.25	19	0.35	3.64
Zeya river	38	74.2	57.6	1.83	37	147	2.43	8	18	7,000	4.38	13	0.05	0.18

Note: n–total number of species; N–number (maximum); B–biomass (maximum); Chl. a–Chlorophyll "a" concentration. «–»–no data available.

Diatoms prevailed in phytoplankton and phytoperiphyton. Based on the previous studies (September 2013), the proportion of diatoms in phytoplankton made up 79% in the post-rainfall flood, while during the summer low water (July 2014), only 64%, with an increase of green algae (18%). Phytoplankton of the studied streams of the Zeya basin demonstrates the features of typical river plankton with the dominance of diatoms, and among them—the benthic forms. The taxonomic diversity of macrophytes in the streams under study is around half of the total species given by Ya.V. Bolotova[10] for aquatic flora of the Lower Zeya. The flowering plants dominate in number of species (29 species), among which monocotyledons prevail (55%) which is typical for most hydrophilic flora of the Holarctic, including the aquatic flora of the Amur region[11,12]. The highest aquatic vegetation fully reflects the features of the monsoon climate and hydrological regime of the rivers studied. The monsoon climate and the bogginess of catchments are responsible for the dominance of moss, sedge and cereals in the flora, while the marginal water plants and marsh plants are dominant in the eco-biomorphological structure[13].

The monsoon climate affected the overgrowing of the studied streams, which demonstrate the spotty and semi-aquatic spotty overgrowing despite the shallow water and the occurrence of a large number of quiet pools. The banks are covered with sedge-grass herbs (*Carex rhyn-chophysa* C. A. Mey, *Bolboschoenus sp*., *Agrostis gigantea* Roth), in the channel on stony ground at a depth of 0.1–0.3 m the aquatic moss-like plants (*Marchantia polymorpha* L.,

Leptodictyum riparium (Hedw.) Wamst.), and the knotgrass (*Hippuris vulgaris* L.) dominate; in quiet areas –the buttercup (*Ranunculus gmelinii* DC.). On wet coastal slopes (supralittoral), the mosses (*Rhizomnium punctatum* (Hedw.) T. Kop., *Sphagnum squarrosum* Crome) prevail, among which the violet (*Viola epipsiloides* A. et D. Love) is often found[14].

The zooplankton biocenosis of most streams is multispecies, the evribionts and less phytofilous forms of rotifers, copepods and Cladocera crustaceans (9–23 species) constitute the major portion; a small number of biocenosis species (six species) was found in Medny stream. The watercourses were characterized by significant development of benthic forms feeding on vegetable detritus (harpacticoid and nektobenthonic forms of Cyclopoida) that is apparently typical of such ecosystems in the region[15,16]. The zooplankton composition of all watercourses, except for Zeya, showed the absence of Diaptomidae family. Considering that all of the watercourses had a favorable oxygen regime and neutral pH, it can be assumed that among the factors limiting the development of Diaptomidae were lack of fodder (diatoms and protococcus)[17] and high flow velocity, especially during the flood periods. The number and biomass of zooplankton in streams and small rivers, as a rule, is much lower than in medium-size and large rivers on the territory of the cosmodrome.

In the benthos of many watercourses, the chironomid larvae and the oligochaetes were dominant. Such species composition and structure of zoobenthos in watercourses under study are characteristic of the Zeya basin[18,19]. Almost 100% of the chironomidae species revealed are on the list of chironomidae, previously identified in the Zeya and Amur basins, the same is true for stoneflies, while the share of mayflies makes up 68%[20-22]. The level of development of bottom zoocenoses of the majority of watercourses is extremely low and very low. Low and moderate levels of development are peculiar to Ora River and Serebryany and Medny streams.

3.2 Bioindication evaluation of water quality

In terms of biomass of phytoplankton, zoobenthos and chlorophyll a (CHL a), most of watercourses are oligotrophic water bodies. The relative pigment indices are indicative of the predominance of ChL a over the yellow pigment (carotenoids) at the most sampling points. This suggests favorable conditions for the development of algae in the water, despite the low abundance (by concentration of ChL a). According to the complex ecological classification of land water quality, the concentration of CHL a in all watercourses during the summer-autumn period corresponds to the I class of water quality ("very clean").

In terms of the occurrence of species-indicators of saprobity in phytoplankton, phytoperiphyton, and zooplankton, the organic pollution was evaluated. The saprobity index corresponded to the oligo-beta-mesosaprobic zone, water purity classes were II and III ("clean" and "moderately polluted" water). According to the taxonomic structure and the level of zoobenthos development, the water quality in rivers also corresponded to the II and III quality classes ("pure" and "moderately polluted"), in streams—III and IV ("moderately polluted" and "polluted"). Most likely the biotic indices of small streams are too low, however, this benthos structure provides a background condition.

3.3 Recommendations on the organization of watercourses monitoring at the Vostochny Cosmodrome

The system of ecological monitoring of the launch site should become a component of the Russian Space Agency environmental monitoring. The FSUE "Center for operation of ground-based space infrastructure facilities" is the head enterprise for environmental monitoring of the "Baikonur" launch site and the booster rocket drop zones, i.e., it is responsible for departmental environmental monitoring. In order to achieve this goal, the company has established the Department of environmental safety of ground-based space infrastructure facilities.

Within the framework of particular objects of space infrastructure (e.g., cosmodromes) the systems of operational environmental monitoring (OEM) are formed as the subsystems of departmental environmental monitoring. Monitoring of sources of anthropogenic influence of the Baikonur cosmodrome differs little from the monitoring of industrial facilities[23]. The OEM should be implemented so that it can be included in the system of the state monitoring of the Russian Federation, regional monitoring systems, primarily of the Amur oblast. These monitoring systems should be legally and methodically coordinated, and act in a coordinated fashion.

In the Federal Service for Hydrometeorology and Environmental Monitoring of Russia (Roshydromet) system, water quality control stations are divided into 4 categories. To collect full-scale data on the "Vostochny" launch site, it is advisable to organize structural units similar in function to the station of the III category, which “are located in the cities with a population of up to 0.5 million people, on the closing sections of large and medium-size rivers, in the mouths of polluted tributaries of large rivers and water bodies, in the areas of organized wastewater discharge, resulting in a low level of pollution”[24].

The frequency of hydrobiological observations at the launch sites is as follows: monthly studies are carried out during the vegetation period on the shortened program no.1 (phytoplankton, zooplankton and periphyton) on large water bodies and on the shortened program no.2 (zoobenthos) on small rivers; the complete program is implemented quarterly for phytoplankton, zooplankton, periphyton, zoobenthos, bacterioplankton and macrophytes. In the drop zones, it is worthwhile to conduct the hydrobiological monitoring in accordance with the water quality class: I–II–III classes, annually, VI class—annually or with an interval of 2–3 years for 1–2 indicators, V–VI classes—with an interval of 2–3 years for 1–2 indicators.

4. Conclusion

The analysis of the research results conducted in 2013–2014 shows that the water-ecological situation in the launch site of the Vostochny Cosmodrome is relatively satisfactory. No significant impact of the construction of cosmodrome facilities on the ecosystems of watercourses in the region was revealed.

By hydrobiological characteristics, the watercourses are typical small and medium-sized waterstreams of the Zeya river basin. Significant flow of watercourses due to the monsoon climate, as well as high oxygen content, the absence of pollution with organic substances and heavy metals provides a great potential for physical and chemical self-purification, despite the low level of biocenoses development.

Hydrobiological methods should be used for comprehensive environmental monitoring of water bodies at the cosmodrome. The system of biological monitoring of the cosmodrome, as a part of the departmental environmental monitoring of Roscosmos, should be coordinated with the Roshydromet monitoring.

Conflict of interest

The authors declare that they have no conflict of interest.

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ORIGINAL RESEARCH ARTICLE

Factor decomposition and spatio-temporal difference analysis of China's marine resource consumption intensity

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ABSTRACT

Based on the connotation of the intensity of marine resources consumption, this paper measures the intensity of marine resources consumption in China's coastal provinces from 1996 to 2015, reveals its spatio-temporal evolution characteristics, establishes a factor decomposition model by using the improved logarithmic mean Di exponential decomposition (LMDI), analyzes the factor contribution of changes in the intensity of marine resources consumption in China, and compares the differences. The results show that: (1) from 1996 to 2015, the overall consumption intensity of China's marine resources increased first and then decreased steadily, and the consumption intensity of resources in the primary industry decreased steadily, ranking second. The resource consumption intensity of the tertiary industry is basically synchronized with the change trend of China's marine resource consumption intensity; in the evolution of spatial pattern, the provinces with medium and high intensity of marine resource consumption gradually reduce, while the provinces with low intensity provinces gradually increase, and the regional differences gradually narrow. (2) The contribution rates of technological progress effect, industrial structure effect and regional scale effect to the decline of China's marine resource consumption intensity are 78.224%, 18.334% and 3.442%, respectively; there are significant differences in factor decomposition effects among coastal provinces, among which Fujian is dominated by technological progress effect, Zhejiang, Shandong and Hainan are dominated by technological progress effect and regional scale effect, Tianjin, Hebei and Jiangsu are dominated by technological progress effect and industrial structure effect, while Liaoning, Shanghai, Guangdong and Guangxi are jointly driven by technological progress effect, industrial structure effect and regional scale effect to reduce the intensity of marine resource consumption. (3) From the perspective of the three marine industries, the effect of technological progress is the largest contribution within the secondary industry, accounting for 77.118% in total; the industrial structure effect has the largest contribution within the primary industry, accounting for 314.547% in total. There is no significant difference in regional scale effect among the three industries. Different provinces and regions should pay different attention to the implementation of technologies or measures for the intensive utilization of resources in the three marine industries.

Keywords: Marine Resources; Consumption Intensity; Factor Decomposition; LMDI Model; Effect of Technological Progress; Industrial Structure Effect; Regional Scale Effect; Spatio-temporal Difference; China

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1. Introduction

The ocean is a treasure house of resources for human survival and national development. The rational development and utilization of marine resources has become an important way to solve the problems of lack of land resources, environmental degradation, population expansion and so on. However, with the rapid development of the marine economy in coastal areas and the continuous expansion of the breadth and depth of marine resources development[1], the traditional and extensive development model has led to the decline of offshore biological resources, the high consumption intensity of marine resources, the deterioration of the marine ecological environment and other problems becoming more and more serious[2], which has restricted the sustainable development of China's marine economy. Therefore, reducing the consumption intensity of marine resources and improving the utilization efficiency of marine resources are the key to the sustainable development of marine economy. Due to the differences in regional marine resource endowments and marine industrial structure, there are significant regional and industrial differences in China's marine resource consumption intensity. Therefore, an in-depth study of the contributing factors to the changes in China's marine tertiary industry resource consumption intensity is of great significance for achieving high-quality development of the marine economy and reducing regional marine economic development differences[3].

In recent years, foreign scholars have mostly taken a single sector or industry as the research object, and carried out research from the perspectives of marine economic efficiency, vulnerability of marine resources system, sea area carrying capacity, the relationship between marine resources development and marine economic growth. For example, Pham *et al*. used data envelopment analysis (DEA) to explore the economic performance and capacity efficiency of gill net fisheries in Danang[4]; Chen *et al*. used vulnerability index to analyze the vulnerability of marine fishery system[5]; Ferreira *et al*. introduced the development and application of a comprehensive framework for determining the sustainable carrying capacity of shellfish farming areas[6]; Barange *et al*. took climate change and development activities as influencing factors, established a coupling and coordination model to explore the relationship between marine economic activities and the sustainable utilization of marine fishery resources[7]; Managi *et al*. established the index variable of technological change and studied the impact of technological change on offshore oil and gas exploration[8]. Domestic scholars' research on the development and utilization of marine resources mainly focuses on the following aspects: (1) from the perspective of resource carrying capacity, focusing on the sustainable utilization of marine resources, through quantitative and qualitative analysis, seek the critical point of dynamic balance between resource utilization and the acceptable threshold of ecosystem, and analyze the comprehensive carrying capacity of specific sea areas for human development activities[9,10]; (2) from the perspective of vulnerability, by establishing an index system and using mathematical analysis methods such as data envelopment analysis (DEA) and set pair analysis to evaluate vulnerability, we explore the response and feedback relationship between human activities and marine economy, resources and environmental systems[11,12]; (3) from the perspective of coordinated development of economy and resources, the level of coordinated development of marine resources and environment and marine economy is analyzed by using variable fuzzy identification model[13]; (4) from the perspective of resource constraints and economic growth, based on the corresponding theoretical basis, the "tail effect" model and Tapio decoupling model are used to explore the impact of marine resource consumption on marine economic growth and the decoupling relationship between the two[3,14]; (5) from the perspective of marine economic efficiency, by selecting input-output indicators, we use DEA model, SBM model and Malmquist productivity index model to measure marine economic efficiency, and use regression model to analyze its influencing factors[15,16].

Resource consumption intensity is an important indicator to measure the quality and efficiency of resource utilization in a country or region[17]. At present, relevant research is mainly focused on energy and water resources. For example, Kong *et al*. have made an empirical analysis of China's regional industrial energy consumption intensity and its influencing factors by establishing a Regional Panel Data Model[18]; Cornellie *et al*. decomposed the energy data and determined the main factors affecting the reduction of energy intensity. The results showed that energy prices and the progress of enterprise restructuring were the two most important factors[19]; Zang *et al*. quantitatively analyzed the convergence characteristics of inter provincial water resources intensity in Chinese Mainland by using panel data on the basis of defining the concept and connotation of water resources intensity and water resources relative intensity[20].

Summarizing the existing research findings, foreign scholars' research on marine resources and marine economy tends to be phenomenon analysis and framework guidance. Combined with economic models, they take marine ecological economic system, marine resource value and integrated management as the entry point for basic theoretical and empirical research. Domestic scholars mostly start from the perspective of carrying capacity, vulnerability, coordinated development, etc., by building an evaluation index system to measure the coordinated development degree of human-sea relations or the level of regional sustainable development, or by using "tail effect", decoupling, DEA and other models to quantitatively analyze the relationship between marine resource consumption and marine economic growth. There is relatively little research on the differences in resource consumption of marine tertiary industries and the contributing factors of changes in the relationship between marine resource consumption and economic growth. At present, the application of the concept of resource consumption intensity is relatively mature, but it is mostly used in the field of energy and water resources, and few scholars use it to analyze the relationship between marine resources and economic growth.

From the perspective of the intensity of marine resource consumption, this paper measures the intensity of marine resource consumption in China's coastal provinces from 1996 to 2015, and reveals its temporal and spatial evolution trend; using the improved logarithmic mean Di exponential decomposition method (LMDI), a factor decomposition model is established to analyze the factor contribution of the change in the intensity of resource consumption of China's three marine industries and compare the differences, in order to enrich the relevant theories of sustainable development of marine economy and provide a scientific basis for the rational and efficient development and utilization of marine resources.

2. Research methods and data sources

2.1 Connotation and comprehensive characterization method of marine resource consumption intensity

The economic indicators of resource consumption can be expressed in absolute and relative quantities. Absolute quantity refers to the absolute quantity of resource consumption, such as the total amount of resource consumption; relative quantity refers to the resource consumption per unit output, of which resource consumption intensity is the most commonly used indicator[21]. Resource consumption intensity refers to the total amount of resources consumed per unit of GDP. Considering the close relationship between marine resources and energy and water resources, and there are many commonalities (for example, seabed mineral resources, oil and natural gas also belong to energy, and seawater resources also belong to water resources), the concept and connotation of energy consumption intensity[18] and water consumption intensity[20] are used for reference, the consumption intensity of marine resources is defined as the amount of marine resources consumed per unit of gross marine product (GOP), which reflects the utilization efficiency of marine resources. This index is affected by economic scale, industrial structure, technical level, resource endowment, policy factors and other aspects. The consumption intensity of marine resources is a reverse index. The greater its value, the lower the utilization efficiency of marine resources. Its mathematical expression is as follows:

$$I = \sum_{i}\sum_{j}\frac{E_{ij}}{Q_{ij}} \tag{1}$$

Where: I is the consumption intensity of marine resources (unit: 10,000 t/100 million yuan); E_{ij} is the resource consumption of marine industry j in the i-th province (unit: 10,000 t); Q_{ij} is the gross marine product of the j industry in the i-th province (unit: 100 million yuan).

Previous studies have shown that the quantity of marine resources is the direct cause of affecting the development of marine economy, but simply attributing the constraints of marine economic development to the stock of marine resources cannot effectively reflect the dynamic role of human activities in the development of marine resources, while marine fishing, mariculture and other marine resource development activities closely related to human dynamic role are the root causes of the rise in the consumption of marine resources[3]. Therefore, on the basis of previous studies[3,22,23], starting from the root causes of the rise in marine resource consumption, combined with data continuity and availability, the marine fishing volume and mariculture volume of the primary marine industry, the marine raw salt production, raw oil production, natural gas production of the secondary marine industry The output of coastal placers, marine chemical products and the marine cargo transportation volume of the marine tertiary industry comprehensively reflect the consumption of marine resources.

2.2 Factor decomposition model of marine resource consumption intensity

The treatment methods of factor decomposition in the evaluation of resource consumption intensity mainly include structural decomposition analysis (SDA) and index decomposition analysis (IDA). Because SDA method needs input-output data as support, China generally produces input-output tables every five years, with a large time span[24], and at present, China has not included marine economy into the statistical scope of input-output tables[25], which is not conducive to in-depth research. IDA method uses the total data of departments and industries, which makes it easier to conduct time series analysis and regional comparison[26]. IDA method includes Laspeyres IDA and Divisia IDA. The residual term in Laspeyres IDA method is large, and there is a large result decomposition error; however, the Divisia IDA method meets the requirements of reversible factors and has the main advantages of "no residual value can be generated, and zero is allowed to be included in the data"[27,28], which avoids the problem of affecting the decomposition results due to the existence of residual terms, improves the reliability of the results[29], and is widely used in the decomposition research of factors such as changes in energy consumption[30], changes in water consumption[31], changes in grain production[32], changes in human well-being[33].

Referring to the existing research[34], this paper uses the improved LMDI addition model and adds regional factors on the basis of the original LMDI model to investigate the impact of the change of the proportion of the marine GDP of each province in the National Marine GDP on the change of China's marine resource consumption intensity.

The formula of total marine resource consumption intensity is as follows:

$$I = \sum_i \sum_i \frac{E_{ij}}{Q} = \sum_i \sum_j \frac{E_{ij}}{Q_{ij}} \frac{Q_{ij}}{Q_i} \frac{Q_i}{Q} = \sum_i \sum_i I_{ij} S_{ij} R_i \quad (2)$$

Where: I is the total consumption intensity of marine resources; E_{ij} is the resource consumption of marine industry j in the i-th province; Q_{ij} is the gross domestic product of the marine industry of the i-th province; Q_i is the gross marine product of the i-th province; Q is the gross national marine product; I_{ij} is the resource consumption intensity of marine industry j in the i-th province; S_{ij} is the proportion of the gross domestic product of the marine industry j in the gross domestic product of the i-th province; R_i is the proportion of the marine GDP of the i-th Province in the National Marine GDP.

The formula of the variation of the intensity of marine resource consumption is:

$$\Delta I_{tot} = I_t - I_0 = \Delta I_{tech} + \Delta I_{indu} + \Delta I_{regi} \quad (3)$$

The contribution degree of each decomposition factor is shown as follows:

$$\Delta I_{tech} = \sum_i \sum_i \frac{E_{ij}^T/Q^T - E_{ij}^0/Q^0}{\ln(E_{ij}^T/Q^T) - \ln(E_{ij}^0/Q^0)} \ln \frac{I_{ij}^T}{I_{ij}^0} \quad (4)$$

$$\Delta I_{indu} = \sum_i \sum_i \frac{E_{ij}^T/Q^T - E_{ij}^0/Q^0}{\ln(E_{ij}^T/Q^T) - \ln(E_{ij}^0/Q^0)} \ln \frac{S_{ij}^T}{S_{ij}^0} \quad (5)$$

$$\Delta I_{regi} = \sum_i \sum_i \frac{E_{ij}^T/Q^T - E_{ij}^0/Q^0}{\ln(E_{ij}^T/Q^T) - \ln(E_{ij}^0/Q^0)} \ln \frac{R_{ij}^T}{R_{ij}^0} \quad (6)$$

Where: ΔI_{tot} is the total effect, indicating the change in the intensity of total marine resource consumption; ΔI_{tech} is the effect of technological progress, which indicates the contribution of changes in the efficiency of marine resources utilization caused by technological progress to changes in the overall intensity of marine resources consumption; ΔI_{indu} refers to the effect of industrial structure, which indicates the contribution of marine industrial structure adjustment and optimization to the change of marine resource consumption intensity; ΔI_{regi} refers to the regional scale effect, which indicates the contribution of the change in the status of regional marine economic scale in the country to the change in the intensity of marine resource consumption. The contribution rates of the three decomposition effects to the change of China's marine resource consumption intensity are $\Delta I_{tech}/\Delta I_{tot}$, $\Delta I_{indu}/\Delta I_{tot}$ and $\Delta I_{regi}/\Delta I_{tot}$. When the sign of a decomposition factor effect is consistent with the total effect, it means that the factor plays a positive role in the change of the intensity of marine resource consumption, and vice versa.

2.3 Research area and data source

The geographical units studied in this paper mainly involve 11 coastal provinces and regions of China, including Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi and Hainan. Due to difficulties in obtaining data, Hong Kong, Taiwan and Macao are not included in this study.

The time span is 1996−2015, and the research data are from the China Ocean Statistical Yearbook (1997−2016)[35]. Due to the change of the statistical caliber of the marine GDP indicators in 2006, the marine GDP indicators from 1996 to 2005 are integrated according to the three marine industries for the convenience of research.

3. Results and analysis

3.1 Temporal and spatial evolution of China's marine resource consumption intensity

3.1.1 Time evolution of consumption intensity of marine resources

(1) Time variation of marine economic output value and marine resource consumption. According to the original data, China's marine GDP and marine resource consumption from 1996 to 2015 are calculated, and the change trend is shown in **Figure 1**. From 1996 to 2006, the change trend of Chin's marine GDP and marine resource consumption was basically synchronized. The resource consumption of first, secondary and tertiary industries of marine all increased with the increase of GDP, of which the growth trend was flat from 1996 to 2000, and the growth rate accelerated from 2000 to 2006. From 2006 to 2015, the GDP and resource consumption of the Marine primary and secondary industries showed a slowing trend, and the gross output value and resource consumption of the marine tertiary industry are generally consistent with the change trend of the national level. Among them, the output value of the marine tertiary industry and the national gross output value are gradually increasing, and the resource consumption of the marine tertiary industry and the national marine resource consumption are slowing down and increasing.

(2) The intensity of marine resource consumption changes over time. The temporal change of China's marine resource consumption intensity is shown in **Figure 2**. From 1996 to 2015, the consumption intensity of China's marine resources generally showed a trend of first rising and then declining steadily, rising from 8.058 ten thousand t/100 million yuan in 1996 to 13.877 ten thousand t/100 million yuan in 1999, and then gradually declining, reaching 3.958 ten thousand t/100 million yuan in 2015. The resource consumption intensity of the primary marine industry showed a steady downward trend. The resource consumption intensity of Marine secondary and tertiary industries is basically synchronized with the change trend of China's marine resource consumption intensity, which generally shows an upward trend and then downward trend.

From 1996 to 1998, China's marine economy grew slowly, most of the marine resources have not been developed and utilized, and the consumption of marine resources is small. At the beginning of the 21st century, China began to vigorously develop the marine economy, but the initial stage was still dominated by the development of traditional marine resources and the production of primary products. The development of the marine economy was heavily dependent on the input of resource factors, and the intensity of marine resource consumption increased slightly.

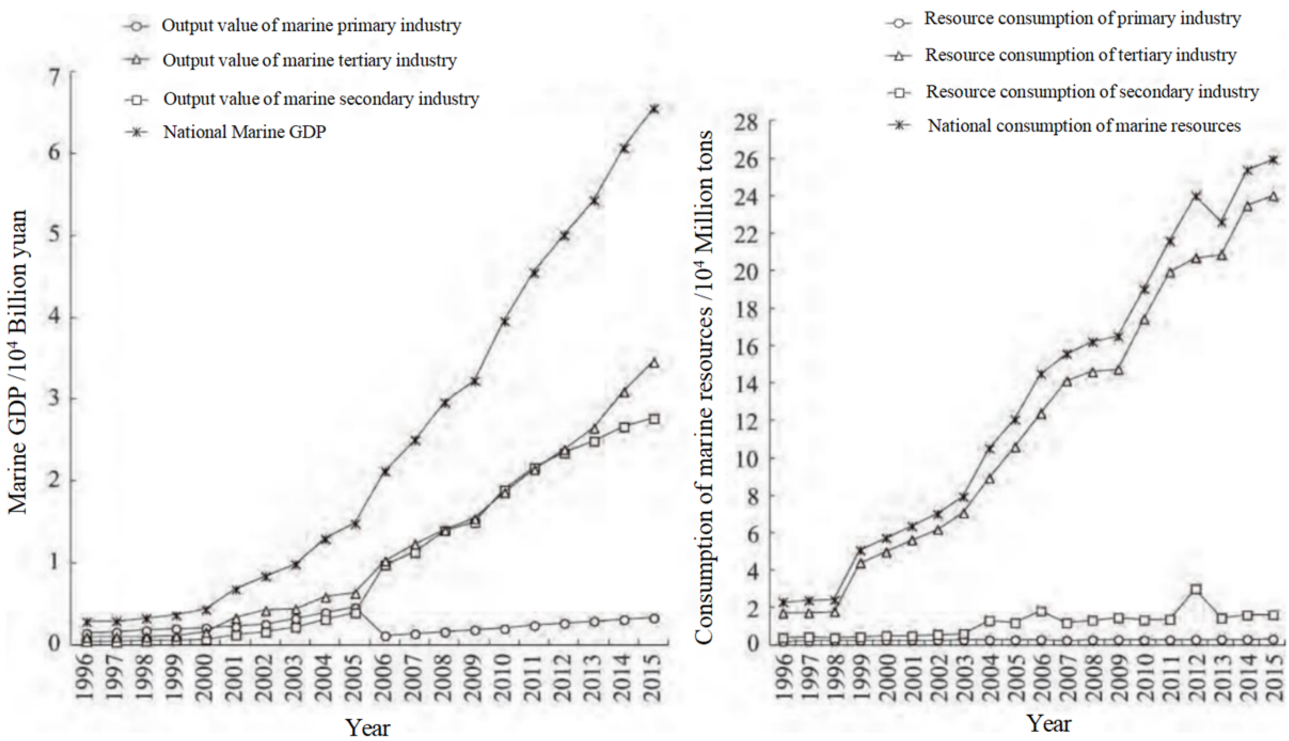

Figure 1. The trends of gross output values of marine economy and the number of marine resources consumed in China from 1996 to 2015.

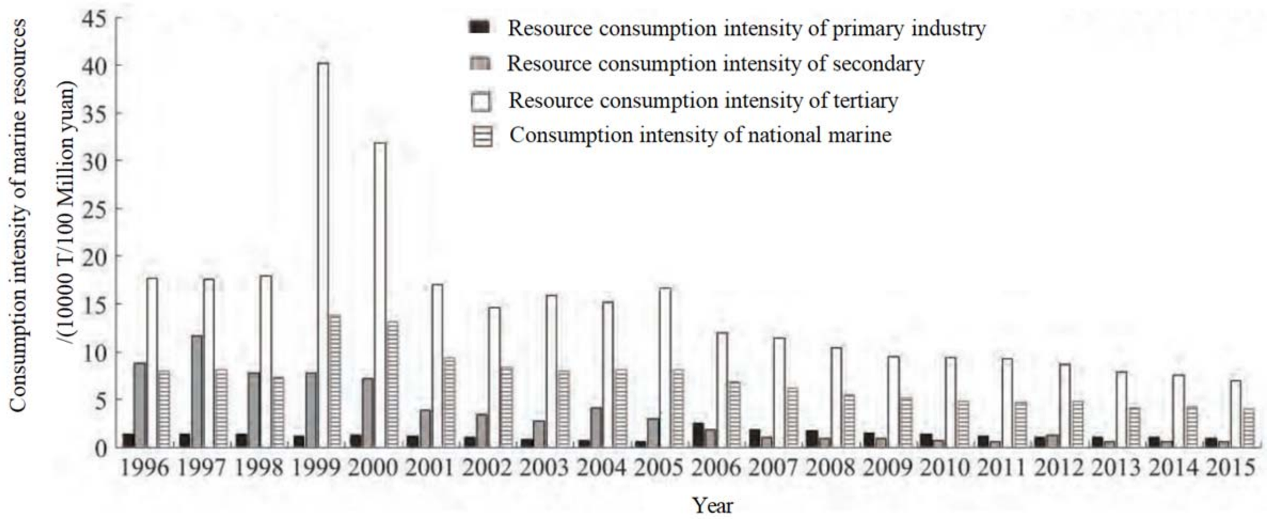

Figure 2. The trends of China's marine resources consumption intensity and the three industries resources consumption intensity from 1996 to 2015.

Since then, the marine economy has developed rapidly, the development mode of marine resource intensive industries has gradually changed from extensive to intensive efficiency, the marine strategic emerging industries with high scientific and technological content and low environmental pollution have gradually risen, the marine industrial structure has been continuously optimized, and the intensity of marine resource consumption has gradually decreased. From 2010 to 2015, the marine economy maintained steady growth, and the marine industry gradually changed to the marine resources deep processing industry and service industry. The growth rate of the pressure of marine resources consumption slowed down, and the intensity of marine resources consumption decreased slightly.3.1.2 Spatial evolution of consumption intensity of marine resources

(1) Evolution characteristics of regional differences. Combined with the calculation formula of

standard deviation and coefficient of variation, the standard deviation and coefficient of variation of marine resource consumption intensity in 11 coastal provinces are obtained, as shown in **Figure 3**.

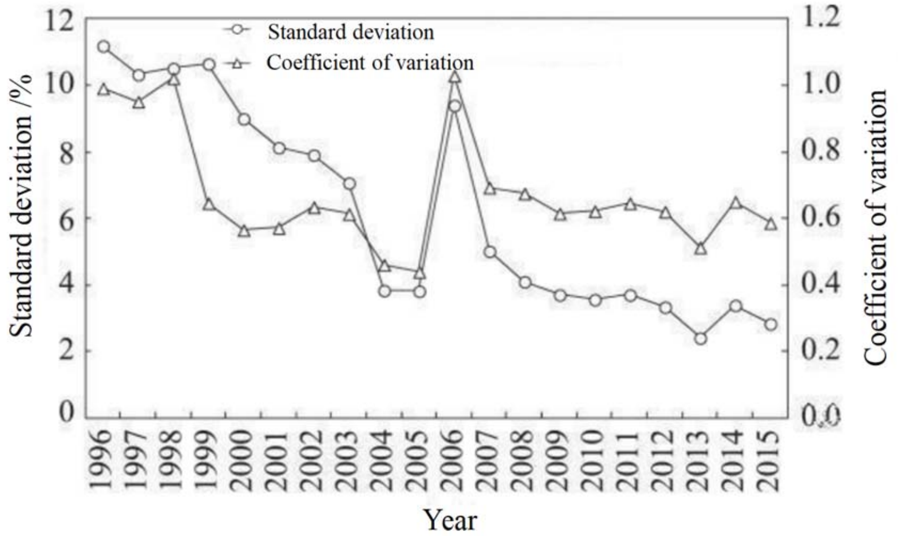

Figure 3. The standard deviation and coefficient of variation line graph of marine resources consumption intensity in China from 1996 to 2015.

The value of standard deviation reflects the change of regional absolute difference. By analyzing the standard deviation of marine resource consumption intensity from 1996 to 2015, it can be seen that the standard deviation has been decreasing from 1996 to 2005 and from 2006 to 2015, of which the maximum standard deviation in 1996 was 11.190 and the minimum value in 2015 was 2.845. The regional absolute difference of marine resource consumption intensity shows a trend of fluctuation and reduction on the whole. The coefficient of variation reflects the change of regional relative difference. Through analysis, it can be seen that the change trend of coefficient of variation is similar to the fluctuation characteristics of standard deviation, and the regional relative difference of marine resource consumption intensity also shows a trend of fluctuation and reduction. Based on the changes of regional relative differences and absolute differences, it shows that the gap of marine resource consumption intensity among coastal provinces shows the characteristics of fluctuation and narrowing during the study period.

(2) Spatial variation and type division of marine resource consumption intensity. Combined with the intensity value of China's marine resources consumption from 1996 to 2015, the ratio f between the intensity of marine resources consumption in each province and the intensity of national marine resources consumption is taken as the division standard[36]. When $F > 1$, it is high intensity, $F < 1$ is low intensity, and $F = 1$ or its value is medium intensity. The calculation results are shown in **Table 1**. From 1996 to 2015, the spatial difference in the intensity of marine resources consumption in 11 coastal provinces and regions in China gradually narrowed, and the number of high-intensity provinces and regions basically remained unchanged, from Hebei, Hainan, Zhejiang and Fujian in 1996 to Hainan, Zhejiang, Shanghai and Guangxi in 2015; the number of medium intensity provinces and regions decreased, from Tianjin and Guangdong in 1996 to Liaoning in 2015, and the proportion of provinces and regions was small; the number of low-intensity provinces and regions has increased, with great regional changes. In 1996, it was mainly distributed in Jiangsu, Shandong, Liaoning, Guangxi and Shanghai, and in 2015, distributed in Fujian, Jiangsu, Guangdong, Tianjin, Hebei and Shandong.

Specifically, the change trend of marine resource consumption intensity in various provinces and regions of China can be divided into the following two types. (1) The consumption intensity of marine resources is gradually decreasing, including Tianjin, Hebei, Fujian, Shandong, Guangdong and Hainan. With the development of marine economy, such provinces and regions accelerate the transformation of marine economic development mode,

Table 1. The ratio of the marine resource consumption intensity in coastal provinces to the national marine resource consumption intensity in China from 1996 to 2015

Year	Tianjin	Hebei	Liaoning	Shanghai	Jiangsu	Zhejiang	Fujian	Shandong	Guangdong	Guangxi	Hainan
1996	0.957	1.922	0.632	0.070	0.823	1.702	1.364	0.663	1.143	0.629	5.494
1997	1.210	1.701	0.600	0.073	0.605	1.728	1.383	0.683	1.042	0.593	5.029
1998	1.456	1.786	0.485	0.051	0.474	1.680	1.396	0.535	1.315	0.607	5.549
1999	3.119	1.210	0.801	1.862	0.943	0.986	0.697	0.452	0.942	0.261	1.774
2000	2.646	1.188	0.843	1.806	0.995	1.151	0.721	0.579	0.902	0.267	2.160
2001	3.082	1.359	0.967	3.029	1.154	1.834	0.910	0.802	0.913	0.403	2.252
2002	3.187	1.562	0.944	3.305	1.108	1.403	0.676	0.757	0.941	0.355	2.159
2003	2.620	1.331	0.938	3.464	0.950	1.556	0.541	0.569	0.827	0.946	2.026
2004	1.813	1.025	0.672	1.714	1.032	1.554	0.490	0.504	0.668	0.550	1.301
2005	1.667	1.237	0.747	1.682	0.911	1.382	0.686	0.521	0.583	0.562	1.786
2006	1.629	0.478	0.775	1.245	0.842	2.181	0.758	0.473	0.576	0.392	5.364
2007	1.761	0.389	0.848	1.439	0.733	2.092	0.742	0.463	0.618	0.636	3.109
2008	0.565	0.193	0.879	1.567	1.005	2.676	0.905	0.385	0.643	1.057	2.363
2009	1.236	0.390	0.889	1.682	0.870	2.037	0.780	0.475	0.557	1.168	2.908
2010	1.056	0.523	0.872	1.740	0.786	2.114	0.838	0.461	0.574	1.193	2.968
2011	0.957	0.494	0.769	1.763	0.816	2.182	0.865	0.432	0.603	1.365	3.068
2012	0.716	0.434	0.813	1.674	0.798	2.072	0.901	0.335	0.613	1.358	2.650
2013	0.624	0.510	0.898	1.433	1.161	2.392	1.019	0.347	0.749	1.572	1.747
2014	0.630	0.577	0.886	1.696	1.036	2.397	0.933	0.323	0.756	1.368	3.127
2015	0.700	0.622	1.013	1.769	0.936	2.408	0.942	0.305	0.716	1.404	2.640

focus on organizing and promoting the high value-added utilization of marine resources, deep processing and the production of low consumption high-tech products, technological progress, industrial structure adjustment and optimization, and regional economic development promote the decline of marine resource consumption intensity, and the pressure on marine resources slows down. (2) The consumption intensity of marine resources is increasing, including Liaoning, Shanghai, Jiangsu, Zhejiang and Guangxi. Such resource consuming industries as marine fisheries and marine mining industries in provinces and regions are still in the development mode of high energy consumption, the proportion of marine emerging industries is still low, the overall level of marine science and technology development in some provinces and regions such as Liaoning and Guangxi is low, the degree of marine intensive production is not high, and the comprehensive advantages and potential of marine resources have not been effectively transformed into economic advantages.

3.2 Analysis on the difference of decomposition effect of changing factors of China's marine resource consumption intensity

3.2.1 Time difference of decomposition factor effect

According to formula (3) to formula (6), the decomposition factor effect and contribution rate of changes in China's marine resource consumption intensity from 1996 to 2015 are calculated (**Table 2**). During the study period, the resource consumption of 100 million yuan of marine GDP decreased by 358,520 tons, of which the effects of technological progress, industrial structure and regional scale reached -280,450 tons, -65,730 tons and -12,340 tons, with the contribution rates of 78.224%, 18.334% and 3.442% respectively, which fully shows that all decomposition factors have a driving effect on the decline of marine resource consumption intensity, and the contribution of technological progress effect is the most significant.

From 1996 to 2015, the effect changes of each decomposition factor have obvious stage characteristics. Before 2006, there were positive and negative alternations. The reason is that China's marine economic development started late. The economic development policy of "emphasizing the land and ignoring the sea" and the industrial structure with too high proportion of traditional industries have a negative effect on the decline of resource consumption intensity, making the utilization efficiency of marine resources relatively low during this period. After 2006, the effect of each decomposition factor tends to be stable, in which the effect of technological progress and the total effect are always negative, and the effect of technological progress contributes the most to the decline of the intensity of marine re-

Table 2. Factor decomposition of marine resources consumption intensity in China from 1996 to 2015 (10,000 t/100 Million yuan)

Time interval	Effect of technological progress $\Delta Itech$		Industrial structure effect $\Delta Iindu$		Regional scale effect $\Delta Iregi$		Total effect $\Delta Itot$
	Effect value	Contribution rate/%	Effect value	Contribution rate/%	Effect value	Contribution rate/%	
1996–1997	0.884	-82.123	-2.878	267.448	0.918	-85.325	-1.076
1997–1998	-1.448	107.715	1.028	-76.470	-0.924	68.756	-1.344
1998–1999	6.491	75.427	2.219	25.789	-0.105	-1.216	8.605
1999–2000	0.820	-39.636	-1.975	95.497	-0.913	44.139	-2.068
2000–2001	-7.618	56.132	3.130	-23.062	-9.083	66.930	-13.571
2001–2002	-5.497	140.694	0.919	-23.515	0.671	-17.179	-3.907
2002–2003	-2.040	112.337	-1.240	68.304	1.464	-80.641	-1.816
2003–2004	-3.524	-114.915	-1.061	-34.613	7.652	249.528	3.066
2004–2005	-3.506	171.268	0.951	-46.454	0.508	-24.814	-2.047
2005–2006	2.577	-52.295	-6.761	137.187	-0.745	15.109	-4.929
2006–2007	-5.044	101.953	0.183	-3.706	-0.087	1.753	-4.947
2007–2008	-1.503	82.678	-0.149	8.181	-0.166	9.142	-1.818
2008–2009	-1.477	95.465	-0.186	12.036	0.116	-7.502	-1.547
2009–2010	-4.537	87.127	-0.588	11.288	-0.083	1.585	-5.207
2010–2011	-0.774	83.070	-0.102	10.939	-0.056	5.991	-0.932
2011–2012	-0.288	72.052	-0.023	5.679	-0.089	22.269	-0.400
2012–2013	-0.638	75.580	-0.173	20.560	-0.033	3.861	-0.844
2013–2014	-0.178	43.086	0.099	-23.934	-0.333	80.848	-0.412
2014–2015	-0.747	113.274	0.035	-5.280	0.053	-7.994	-0.659
1996–2015	-28.045	78.224	-6.573	18.334	-1.234	3.442	-35.852

source consumption; the industrial structure effect and regional scale effect gradually stabilized at negative values in fluctuations, and the industrial structure adjustment is a secondary contributing factor to the decline in the intensity of marine resource consumption. In 2005, the state proposed to build a resource-saving society.

The marine economic development of coastal provinces and regions gradually transformed, and increased investment in energy conservation and consumption reduction, scientific and technological innovation. The efficiency of resource utilization slowly increased with technological progress. However, due to the problems of "path dependence" in industrial development and significant differences in regional marine economic development, China's modern marine industrial system is still not mature. The influence of industrial structure effect and regional scale effect on the decline of marine resource consumption intensity is relatively limited.

3.2.2 Regional differences of decomposition factor effects

(1) Comparison of regional total effects. As shown in **Table 3**, from 1996 to 2015, the consumption intensity of marine resources in 11 coastal provinces and regions decreased to varying degrees, and the standard deviation of the total effect of each province and region was 3.255 ten thousand t/100 million yuan. Among them, the provinces and regions with the largest and smallest decline in the consumption intensity of marine resources were Shanghai and Guangxi, reaching -9.878 ten thousand t/100 million yuan and -0.112 ten thousand t/100 million yuan respectively, with significant regional differences.

(2) Comparison of decomposition effects of regional factors. As shown in **Table 3**, the effect of technological progress in 11 coastal provinces and regions is negative, indicating that the efficiency of marine resources utilization in coastal areas is generally improved, and the effect of technological progress is the main driving factor for the decline in the intensity of marine resources consumption.

The standard deviation of the effect of technological progress is 1.691 ten thousand t/100 million yuan, and the maximum absolute value (Guangdong, -6.048 ten thousand t/100 million yuan) is 205 times that of the minimum value (Guangxi, -0.030 ten thousand t/100 million yuan), indicating that there are great differences in the contribution of the improvement of the utilization efficiency of marine resources in various provinces to the decline of the intensity of marine resources consumption.

The industrial structure effects of Liaoning,

Table 3. Disposition factor effect of marine resources consumption intensity of each coastal province from 1996 to 2015 (10,000 t/100 million yuan)

Province	Technological progress effect ΔI_{tech}	Industrial structure	Regional scale effect ΔI_{regi}	Total effect ΔI_{tot}
Tianjin	-1.669	-2.669	2.085	-2.253
Hebei	-0.986	-0.302	0.440	-0.848
Liaoning	-1.577	-0.056	-0.557	-2.190
Shanghai	-2.229	-6.642	-1.008	-9.878
Jiangsu	-2.445	-0.036	0.613	-1.868
Zhejiang	-4.593	2.853	-0.541	-2.282
Fujian	-2.791	0.136	0.172	-2.483
Shandong	-3.651	1.011	-0.656	-3.296
Guangdong	-6.048	-1.602	-1.687	-9.337
Guangxi	-0.030	-0.003	-0.080	-0.112
Hainan	-2.026	0.737	-0.015	-1.305

Hebei, Tianjin, Jiangsu, Shanghai, Guangdong and Guangxi are all negative, indicating that each province has the first place in the high consumption of marine resources. The secondary industry has shifted to the marine tertiary industry, which mainly focuses on technical services. The marine strategic emerging industries have begun to develop rapidly, and the modern marine industrial system has been gradually established, which has a significant positive effect on the decline in the intensity of marine resource consumption. Except Tianjin and Shanghai, the absolute value of the industrial structure effect of the other five provinces and regions is less than the effect of technological progress, indicating that technological progress plays a greater role in promoting the reduction of the intensity of marine resource consumption than the adjustment and optimization of marine industrial structure. The industrial structure effect of Zhejiang, Fujian, Shandong and Hainan is positive, indicating that in the process of improving the efficiency of marine resources utilization, the industrial structure that has not yet reached rationalization and upgrading is its constraint and limiting factor. The standard deviation of industrial structure effect is 2.443 ten thousand t/hundred million yuan, and the maximum absolute value (Shanghai, -6.642 ten thousand t/hundred million yuan) is 2.367 times that of the minimum value (Guangxi, -0.003 ten thousand t/hundred million yuan), indicating that there are also significant differences in the contribution of industrial structure adjustment in various provinces to the decline of marine resource consumption intensity.

Regional scale effect is the driving factor for the decline of marine resource consumption intensity in Liaoning, Shandong, Shanghai, Zhejiang, Guangdong, Guangxi and Hainan, and the restrictive factor for the decline of marine resource consumption intensity in Tianjin, Hebei, Jiangsu and Fujian. The standard deviation of regional scale effect is 0.985 ten thousand t/100 million yuan, and the maximum absolute value (Tianjin, 2.085 ten thousand t/100 million yuan) is 139 times the minimum value (Hainan, -0.015 ten thousand t/100 million yuan), indicating that there are great differences in the impact of marine economic growth in various provinces and regions on the decline of resource consumption intensity, and the change of the status of regional marine economic scale in the country affects the change of marine resource consumption intensity.

3.2.3 Industrial differences that decompose factor effects

(1) Comparison of decomposition effects of internal factors in the three marine industries. As shown in **Table 4**, from 1996 to 2015, there were significant differences in the effects of technological progress and industrial structure among the three marine industries, and there was no significant change in the regional scale effect.

The cumulative effect of technological progress in the three marine industries is -1,878 thousand t/hundred million yuan, -21,628 thousand t/hundred million yuan and -4,539 thousand t/hundred million yuan, respectively, accounting for 6.696%, 77.118% and 16.186% of the effect of technological progress respectively. It can be seen that the technological progress effect of the marine secondary industry has the greatest contribution to the decline in the intensity of marine re-

Table 4. Industrial difference of decomposition factor effect of marine resources consumption intensity in China from 1996 to 2015 (10,000 t/100 million yuan)

Time interval	Effect of technological progress ΔI_{tech}			Industrial structure effect ΔI_{indu}			Regional scale effect ΔI_{regi}		
	Primary industry	**The secondary industry**	**The service sector; the tertiary industry**	**Primary industry**	**The secondary industry**	**The service sector; the tertiary industry**	**Primary industry**	**The secondary industry**	**The service sector; the tertiary industry**
1996–1997	0.189	1.158	-0.463	-0.090	-2.804	0.016	0.306	0.306	0.306
1997–1998	-0.319	-1.041	-0.088	0.381	0.893	-0.246	-0.308	-0.308	-0.308
1998–1999	-0.668	-2.622	9.781	0.159	3.657	-1.596	-0.035	-0.035	-0.035
1999–2000	-0.481	2.499	-1.198	-1.203	-1.656	0.883	-0.304	-0.304	-0.304
2000–2001	-1.366	-6.472	0.220	-0.836	4.816	-0.851	-3.028	-3.028	-3.028
2001–2002	0.050	-2.882	-2.665	-1.518	1.041	1.395	0.224	0.224	0.224
2002–2003	-0.843	-0.722	-0.474	-0.688	-0.228	-0.325	0.488	0.488	0.488
2003–2004	-1.647	3.545	-5.422	-2.963	-0.707	2.609	2.551	2.551	2.551
2004–2005	-1.628	-2.277	0.399	0.703	0.500	-0.253	0.169	0.169	0.169
2005–2006	12.041	-7.571	-1.893	-13.875	6.409	0.705	-0.248	-0.248	-0.248
2006–2007	-2.291	-2.415	-0.338	0.254	-0.211	0.141	-0.029	-0.029	-0.029
2007–2008	-0.084	-0.760	-0.660	-0.170	0.218	-0.197	-0.055	-0.055	-0.055
2008–2009	-0.472	-0.581	-0.425	-0.156	-0.113	0.082	0.039	0.039	0.039
2009–2010	-2.859	-1.577	-0.101	-0.604	0.066	-0.050	-0.028	-0.028	-0.028
2010–2011	-0.421	-0.322	-0.031	-0.076	-0.044	0.018	-0.019	-0.019	-0.019
2011–2012	-0.312	0.383	-0.359	-0.004	-0.106	0.087	-0.030	-0.030	-0.030
2012–2013	0.056	-0.289	-0.405	-0.164	-0.100	0.091	-0.011	-0.011	-0.011
2013–2014	-0.419	0.310	-0.069	0.125	-0.231	0.205	-0.111	-0.111	-0.111
2014–2015	-0.404	0.006	-0.349	0.048	-0.125	0.111	0.018	0.018	0.018
1996–2015	-1.878	-21.628	-4.539	-20.676	11.274	2.829	-0.411	-0.411	-0.411

source consumption, followed by the marine tertiary industry and the marine primary industry. Vigorously promoting the technological innovation of the marine secondary industry and improving the scientific and technological level of the marine tertiary industry play a vital role in continuously reducing the intensity of marine resource consumption.

The cumulative effect of industrial structure within the three marine industries is -20.676 ten thousand t/hundred million yuan, 11.274 ten thousand t/hundred million yuan and 2.829 ten thousand t/hundred million yuan, accounting for 314.547%, 171.511% and -43.036% respectively, indicating that the driving effect of industrial structure adjustment on the reduction of marine resource consumption intensity mainly comes from the primary marine industry and the second marine industry The change of tertiary industry structure restricts the decline of marine resource consumption intensity, but the impact is still limited, and the effect of technological progress still plays a major role. We will accelerate the adjustment and optimization of the tertiary industry structure and the construction of a perfect modern marine industry system have a very important positive impact on reducing the intensity of marine resource consumption.

(2) Comparison of factor decomposition effects among the three marine industries in provinces and regions. As shown in **Table 5**, the effects of technological progress and industrial structure are significantly different among the three marine industries in each province, and the regional scale effect has no significant change.

The effect of technological progress in most provinces and regions is negative within the three marine industries, indicating that technological progress in most provinces and regions plays a positive role in reducing the intensity of marine resource consumption, and the resource utilization efficiency of the three marine industries has been improved. However, there are still great differences in the contribution of the technological progress effect among the three marine industries in various provinces and regions to the decline in the intensity of marine resource consumption. Among them, the technological progress effect of Tianjin is positive in the primary and tertiary marine industries, Hebei is positive in the primary marine industry, and Shanghai and Guangxi are positive in the tertiary marine industry, indicating that due to the differences in resource endowment and emphasis on

Table 5. industrial difference of decomposition factor effect of marine resources consumption intensity of each coastal province from 1996 to 2015 (10,000 t/100 million yuan)

Province	Effect of technological progress ΔI_{tech}			Industrial structure effect ΔI_{indu}			Regional scale effect ΔI_{regi}		
	Primary industry	**The secondary industry**	**The service sector; the tertiary industry**	**Primary industry**	**The secondary industry**	**The service sector; the tertiary industry**	**Primary industry**	**The secondary industry**	**The service sector; the tertiary industry**
Tianjin	0.191	-1.984	0.123	-2.701	0.467	-0.435	0.695	0.695	0.695
Hebei	0.109	-0.758	-0.337	-0.580	0.225	0.054	0.147	0.147	0.147
Liaoning	-0.320	-1.032	-0.224	-0.622	0.037	0.530	-0.186	-0.186	-0.186
Shanghai	-0.239	-3.466	1.476	-7.033	0.770	-0.378	-0.336	-0.336	-0.336
Jiangsu	-0.367	-1.940	-0.138	-0.707	0.447	0.224	0.204	0.204	0.204
Zhejiang	0.029	-2.715	-1.907	-3.235	4.480	1.608	-0.180	-0.180	-0.180
Fujian	-0.210	-1.367	-1.214	-1.148	0.715	0.569	0.057	0.057	0.057
Shandong	-0.113	-2.155	-1.384	-1.617	1.468	1.160	-0.219	-0.219	-0.219
Guangdong	-0.651	-4.654	-0.743	-2.718	1.318	-0.202	-0.562	-0.562	-0.562
Guangxi	-0.107	-0.041	0.118	-0.044	0.171	-0.130	-0.027	-0.027	-0.027
Hainan	-0.201	-1.515	-0.310	-0.270	1.177	-0.170	-0.005	-0.005	-0.005

economic development. The effect of technological progress limits the reduction of marine resource consumption in individual industries in these provinces.

The effect of industrial structure is negative within the primary marine industry and positive within the secondary marine industry in all provinces and regions; the industrial structure effect within the marine tertiary industry in Tianjin, Shanghai, Guangdong, Guangxi and Hainan is negative, and the other provinces are positive. It shows that the adjustment and optimization of the marine primary industry structure has significantly greater contribution to the decline in the intensity of marine resources than the marine second industry The decline in the proportion of tertiary industry and marine primary industry has a significant positive effect on the decline in the intensity of marine resource consumption, and marine second The optimization and upgrading of the structure of the tertiary industry is the focus of the future adjustment of the marine industrial structure.

4 Conclusions and suggestions

4.1 Conclusion

Based on the connotation of the intensity of marine resources consumption, this paper measures the intensity of marine resources consumption in China's coastal provinces from 1996 to 2015, and reveals its temporal and spatial evolution trend; using the improved logarithmic mean Di exponential decomposition (LMDI) method, this paper decomposes the factor contributions of the changes in the resource consumption intensity of the three marine industries, and explores the temporal, regional and industrial differences. The main conclusions are as follows: (1) China's marine resource consumption intensity changed from 8.058 ten thousand t/hundred million yuan in 1996 to 3.958 ten thousand t/hundred million yuan in 2015, showing a steady decline after rising on the whole; the resource consumption intensity of the primary marine industry showed a steady downward trend, and the marine industry ranked second The resource consumption intensity of the tertiary industry is basically synchronized with the change trend of China's marine resource consumption intensity. In terms of spatial pattern evolution, the medium and high intensity provinces are gradually decreasing, the low intensity provinces are gradually increasing, and the regional differences are gradually narrowing. Among them, Tianjin, Hebei, Fujian, Shandong, Guangdong and Hainan belong to the gradually decreasing type of marine resource consumption intensity, while Liaoning, Shanghai, Jiangsu, Zhejiang and Guangxi belong to the gradually increasing type of marine resource consumption intensity.

(2) The time difference comparison of factor decomposition effect shows that technological progress effect is the most important factor to promote the decline of marine resource consumption intensity, with a cumulative contribution rate of 78.224%; the industrial structure effect is the secondary influencing factor of the decline in the intensity of

marine resource consumption, with a contribution rate of 18.334%; regional scale effect plays a weak role, with a contribution rate of 3.442%.

(3) The comparison of regional differences in factor decomposition effects shows that there are significant differences in technological progress effects, industrial structure effects and regional scale effects in coastal provinces. Fujian is dominated by technological progress effects, Zhejiang, Shandong and Hainan are dominated by technological progress effects and regional scale effects, Tianjin, Hebei and Jiangsu are dominated by technological Progress Effects and industrial structure effects, and Liaoning, Shanghai, Guangdong and Guangxi are dominated by technological progress effects Industrial structure effect and regional scale effect jointly promote the decline of marine resource consumption intensity.

(4) The comparison of industrial differences of factor decomposition effect shows that the effect of technological progress makes the largest contribution within the marine secondary industry, accounting for 77.118% in total; the industrial structure effect has the largest contribution within the marine primary industry, accounting for 314.547% in total; there is no significant difference in regional scale effect among the three marine industries. The effects of technological progress and industrial structure of each province and region are significantly different within the three marine industries. In the future, the implementation of technologies or measures for the intensive utilization of resources in the three industries should be different and focused.

The calculation of China's marine resource consumption intensity and the analysis of the contributing factors affecting its change have explored the temporal and spatial evolution characteristics of marine resource consumption intensity and the differences in time, region and industry to a certain extent. However, there are many types of marine industries, which are limited to the issue of statistical caliber. This paper studies the intensity of marine resource consumption from the perspective of three industries. The contributing factors to the change of resource consumption intensity of specific marine industries still need to be further analyzed to make the research more targeted.

4.2 Suggestions

Continuously reducing the consumption intensity of marine resources is the key to the sustainable development of marine economy. Based on the above analysis, the following suggestions are obtained: (1) promote the technological innovation of marine economic development. The primary stage of marine economic growth mainly depends on the input of marine resources. However, when the economic growth exceeds a certain critical value, the dependence of marine economic development on resources gradually decreases, and the advantages of the connotation expansion reproduction mode led by technological progress are prominent. Technology has become the most important factor in reducing the intensity of marine resource consumption and improving the efficiency of marine resource utilization. Therefore, we should rely on scientific and technological innovation to realize the optimal allocation of marine resources, Strengthen the R & D and promotion of resource saving technologies, reduce the intensity of marine resource consumption and alleviate the pressure of marine resources through the improvement of technical efficiency.

(2) Accelerate the adjustment and optimization of the marine industrial structure, and implement the development strategy of differentiated industries. With the transformation of marine economic growth mode, the effect of industrial structure plays an important and positive role in reducing the intensity of marine resource consumption. Provinces and regions such as Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan, which have reduced the intensity of marine resource consumption, should focus on marine biological resources, oil and gas resources, mineral resources, port resources, etc., rely on talents Technology, location and other advantages, accelerate the transformation of industrial structure to the marine secondary industry and tertiary industry, and support the development of marine emerging strategic industries; Guangxi, where the consumption intensity of marine resources is on the rise, should speed up the transformation and upgrading of traditional marine industries to achieve green industrial transformation and upgrading.

(3) Adopt unbalanced development strategies to promote cross regional exchanges and cooperation in marine economy and technology. Regional scale effect has a positive impact on reducing the intensity of marine resource consumption. The government should reasonably regulate the growth rate and development scale of marine economy, encourage the first developing areas of marine economy to radiate and drive the second developing areas, promote the transfer of production factors in coastal provinces through technology spillover effect and industrial relevance spillover effect, promote the overall improvement of the level of marine economic development, and reduce the differences in the intensity of marine resource consumption between regions.

Conflict of interest

The authors declared that they have no conflict of interest.

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REVIEW ARTICLE

Dilemmas in water use: How is the water resource distributed in the Colombian Amazon basin?

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ABSTRACT

This paper contextualizes the economic environment of the productive sectors that depend on the intensive use of water resources in the Colombian Amazon basin (it is composed of the departments of Amazonas, Caquetá, Guainía, Guaviare, Putumayo, Vaupes, La Bota Caucana and southern Nariño) through the collection and organization of information from official entities and consultations in the region carried out by the Amazon Scientific Research Institute (ASRI). Macroeconomic indicators of the Amazonian departments in each of the different sectors were analyzed considering the added value exposed in the annual average of the Gross Domestic Product (2000–2012 in constant values) and contrasted with the sectoral demand for water and the growth projection, both of the human population and the growth trends of the economic activities. As a relevant result, it was found that the departments with a mining-energy tradition base their economic growth on the intensive use of water (greater pressure on the resource in m3/year). An average annual value of $374.42 million dollars is reported in water use (economic cost for the department of Putumayo alone) for oil extraction, which will increase in the future. This value has not been offset by the department, let alone taken into account in the economic growth indicators. It is concluded that the policy guidelines for water resource management in Colombia should be differentiated by sectors and by departments, considering the economic dynamics in the demand for water use and the heterogeneity of the populations.

Keywords: Water Resources; Economic Sectors; Colombian Amazon Basin; Water Use

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1. Introduction

The water resources of the Colombian Amazon basin (comprising the departments of Amazonas, Caquetá, Guainía, Guaviare, Putumayo and Vaupes) are indispensable for the development of the different economic sectors, as well as for any productive activity and territory in the country. The levels of productive organization are differentiated into sub-sectors that contribute to the country's economic growth through the levels of added value presented by the National Administrative Department of Statistics[1] and expressed through the Gross Domestic Product (GDP) growth index. This quantification generates an approximation that expresses the monetary value of the production of goods and services of final demand during a given period of time, based on the direct or indirect use of available resources. This paper analyzes the particular case of the water resources of the Colombian Amazon basin.

There are great differences in the use of production factors in different sectors of the Amazon basin in Colombia. However, water is part of the backbone of the production systems, whether from the perspective of sectoral demand or from the large supply of this macro region. The productive sectors analyzed that directly and indirectly use water resources are:

- Crude oil and natural gas extraction.
- Cultivation of agricultural products.
- Livestock production, including veterinary activities.
- Fishing, fish production in hatcheries and fish farms.
- Forestry, logging and related activities.
- Service activities related to fishing.
- Extraction of non-metallic minerals.
- Water transportation.
- Water collection, treatment and distribution.
- Extraction of metalliferous minerals.
- Waste and sewage disposal, sanitation and similar activities.
- Tourist activities.
- Coffee cultivation.

The main objective of the analysis of these overlapping sectors in a heterogeneous region is to expose to decision makers in the field of water resource management the differences in the territories and uses of the resource, which highlight the need to propose policy guidelines based on the real economic cost in the use of the resource and the differentiation of sectors and regions, particularly in the case of water, which has a differentiable economic cost in the use, regional and sectoral growth trends. The document is developed according to the following structure: first, the economic contribution of each sector in the Amazonian departments is presented based on the analysis of GDP in a time series of 12 years at constant values (allowing the comparison of variables); the second part analyzes the demand for water resources in each sector for each department; the third section projects the dynamics of demand in the use of water resources up to 2020 based on water supply and sectoral growth rates, showing the trend in the water balance; finally, a series of arguments are postulated to discuss the final considerations in the analysis of this scientific review and synthesis.

2. Methodology

According to the zoning of the Colombian Amazonian macro-basin, the Amazon Scientific Research Institute (ASRI) developed the delimitation of the southeastern territory of the country, which is affected by the Andes Amazon River, Piedmont river and plain, covering an area of about 483,000 km^2[2,3]. This biogeographic vision covers the departments of Amazonas, Caquetá, Guainía, Guaviare, Putumayo and Vaupés, as well as areas in the southeast of Meta, south of Vichada, La Bota Caucana and the hills of Narino (see **Figure 1**).

The other data included in this work arise from the process of analysis of secondary information from surveys and national studies conducted by state entities such as DANE, the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IHMESC) and the Office of the Auditor General of the Republic (AGR), which were complemented with primary data recorded by ASRI in 2013 from six regional perception workshops on aquatic ecosystems conducted in the Amazonian departments (one in each capital city). In addition, it is necessary to point out that the following results are underestimated due to the uncomputed demand, which is very important for a comprehensive analysis. It is said to be underestimated since the calculations do not include the demand for water resource used in activities such as illegal mining, illicit crops, among others. For this reason, it can be stated that this calculation of water demand of these activities is almost impossible to perform.

3. Results

The different productive sectors analyzed base their economies on the direct and indirect use of water resources, which makes this resource an essential element for economic growth. This contribution to the real growth of national accounts in the different sectors was based on the survey of household and production sectors developed in 2005 by DANE, which was updated in 2012 for the departments of Amazonas, Caquetá, Guaviare, Guainía, Putumayo, Vaupés and Vichada. Similarly, the DANE has provided the database of macroeconom-

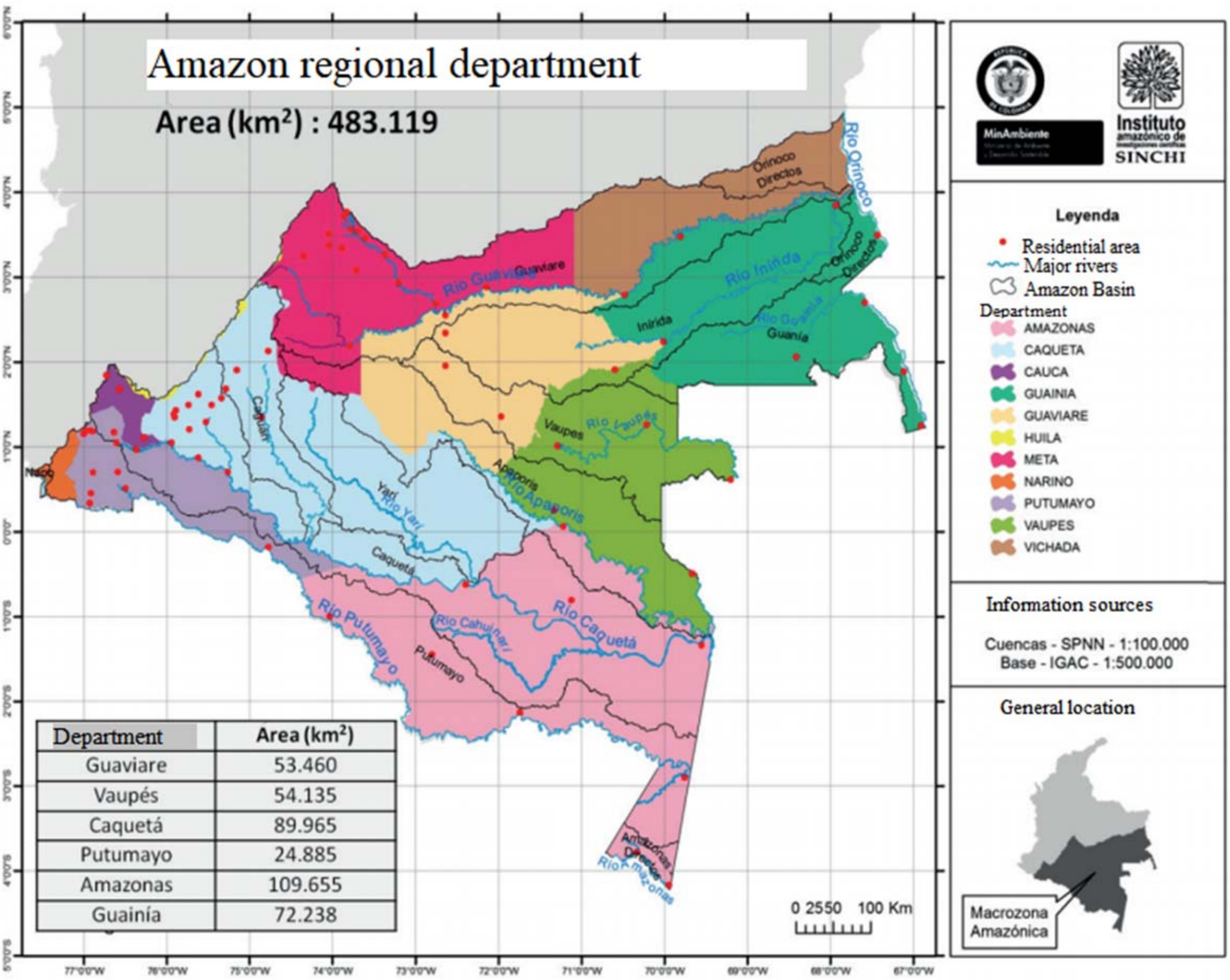

Figure 1. Coverage and departments of the Colombian Amazon.
Source: it is based on Gutiérrez *et al.*[2] and Murcia *et al.*[3].

Table 1. Economic participation in sectoral water use activities

	Gross domestic product (GDP)—Millions of dollars—The average annual price remained unchanged from 2000 to 2012						
Production sectors	**Amazon**	**Caquetá**	**Guainía**	**Guaviare**	**Putumayo**	**Vaupés**	**Vichada**
Crude oil and natural gas extraction					$317.65		$3.52
Agricultural product cultivation	$1.11	$44.66	$1.71	$10.38	$30.75	$1.67	$3.29
Livestock production, including veterinary activities	$0.46	$104.71	$0.42		$13.01		
Fishing, fish production in hatcheries and fish farms	$15.39	$3.45	$1.48	$3.71	$1.39		$2.83
Forestry, timber harvesting and related activities	$3.80	$9.95	$0.60	$1.07	$8.34	$0.37	$2.22
Fishing-related services							$0.32
Extraction of non-metallic minerals		$2.00	$0.04	$1.21	$0.83	$0.18	$0.32
Water transportation	$0.23	$2.67	$0.04	$0.18	$1.39		$0.09
Water collection, treatment and distribution	$0.56	$3.50		$0.04	$0.72		$0.04
Extraction of metalliferous minerals			$0.37		$0.33		
Waste and sewage disposal, sanitation and similar activities	$0.51	$2.95		$0.04			$0.04
Tourist activities	$0.04						
Coffee cultivation		$4.73					
GDP water use	$22.11	$178.84	$4.68	$16.59	$374.42	$2.22	$12.69
Total departmental GDP	$152.74	$918.13	$71.09	$195.01	$814.63	$56.26	$145.27

Source: DANE[1] and Banco de la Republica[6-8].

ic indicators from 2000 to 2012, which measures the growth and contribution of the different sectors and sub-sectors of the economy, considering the average contribution of each of the activities in the use of water resources in the Colombian Amazon basin.

Below is a summary for each department, taking into account the GDP contribution[1] to each activity based on the use of environmental goods and services offered by water resources (see **Table 1**). The GDP contribution of the Colombian Amazon region ilent to 1.1% of the national total amount (GDP for Colombia: USD 211,279.3 million or $37 USD 2,353 million considering the average from 2000 to 2012 (in the past ten years, the average time series is USD 42.3147 billion pesos), which is equiva 9,928.8 billion constant pesos in the base year of 2012).

From the above it can be seen that the department with the largest contribution to the national economy is Putumayo, and in turn this contribution is largely based on the use of available water resources (parallel to the development of the electric energy sector and specialized work in the mining sector), playing a major leverage role in the crude oil and natural gas extraction sectors (USD $317.65 million) and the agricultural crop development sector (USD $30.75 million).

4. Sectoral demand for water in Amazonia

The Amazon region is one of the areas of the country with the highest water supply per year. According to the *National Water Resources Study*[4], the surface water supply of the Amazon region is 893,389 mm^3 and 576,442 mm^3 in average annual and dry years respectively, while other regions such as the Pacific or the Caribbean, the modal year data does not exceed 297,088 mm^3 (in dry years they do not reach 187,804 mm^3, according to the same IHMESC study). On the other hand, the potential demand for water resources in the country is close to 35,877 mm^3 per year, and the Colombian Amazon region covers approximately 336.3 mm^3, which is close to 1% of the total demand.

Although the livestock and agricultural sectors are among those that add the least significant value in water use in terms of their contribution to economic growth, these two sectors are among the activities with the highest demand, as shown in **Figure 2**.

On the other hand, the relevance of the the domestic sector's demand for water resources can be seen, which reaches 71.9 mm^3 per year, benefiting about 1.1 million people with a consumption of about 180 liters per inhabitant per day (see **Table 2**). Family demand (rural and urban) ranks second, but from a social and human perspective, family demand is the most important sector.

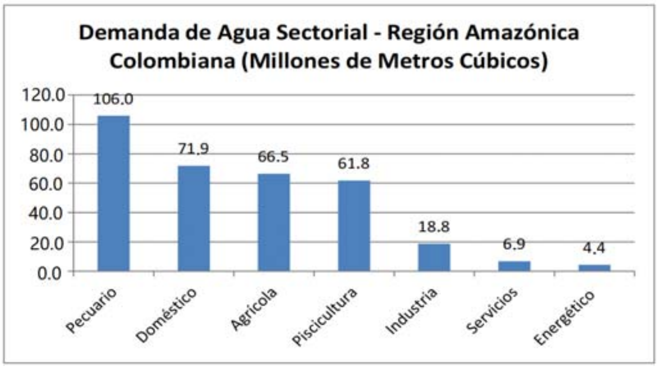

Figure 2. Sectoral demand in the Amazon region in millions of cubic meters.

Source: the National Water Resources Study[4].

Table 2. Departmental population in the Colombian Amazon Basin

Department	Total population—Number of inhabitants		
	2005	2010	2012
Amazon	39.266	47.241	48.150
Caquetá	337.932	447.767	459.515
Guainía	15.676	18,906	192,82
Guaviare	56.758	103.307	106.386
Putumayo	237.197	326.093	333.247
Vaupés	18.636	34.347	34.968
Vichada	44.592	63.670	66.917
Total	750.057	1,041.331	1,068.465

Source: prepared based on DANE[9].

5. Forecast of water demand growth in Amazon region

It is clear that population growth generates an increase in household water demand, but this is closely related to increased use of other sectors. For example, if there is a greater consumption of foodstuffs such as meat (caused by a larger population), water demand in the productive sectors increases. According to the records of water consumption demand presented by Turner *et al.*[5], it can be said that the average domestic consumption requires a maximum of 300 liters of water per day for a family in contrast to the daily demand of water use for food production, which implies an approximate of

[1] Thousands notation (.) and decimal notation (,). The base year is 2012.

3,000 liters per person. This is only a contextualization of the difference in water use for different activities. In Colombia, domestic consumption is considered high when it reaches 122 liters per person per day[4]. The report also points out that the calculation is based on 2012 and expressed in constant values, so as to make consistent comparisons between sectors and between departments.

According to DANE, the population growth rate between 2005 and 2010 in Caquetá was 1.26; in Putumayo it was 1.00; and in the rest of Amazon (Amazonas, Guainía, Guaviare, Vaupés and Vichada), it was 1.65 (see **Table 3**). On the other hand, the national growth rate for the same period was 1.19, which shows that only Putumayo was below the national average.

Regarding the forecast for 2010−2015 and 2015−2020, Caquetá and the other Amazonian departments are expected to reduce their population growth rates, although they will continue to be higher than the national average. In the case of Putumayo, which between 2005 and 2010 was the only department in the region with a lower average, accelerated growth is expected, surpassing the Colombian average between 2015 and 2020. This indicates that there will be a significant increase in the demand for water by households, which must be considered in order to guarantee the supply and efficient use of the resource.

Apart from the demand for water by households, it is clear that certain sectors of the economy have an impact on the resource, either in terms of quantity (water balance) or quality (negative externalities in the production process). The growth of these sectors may be generated by an increase in demand or for other reasons linked to economic growth. Particularly, in the case of sectors such as mining or oil extraction, their expansion is largely due to the incentives provided by the government because they are considered an engine of growth. The following data shows the performance of some productive sectors in the departments of Amazonas, Caquetá, Guainía, Guaviare, Putumayo and Vaupés.

Table 4 summarizes the growth of some sectors related to water resources in the department of Amazonas. It can be seen that the activities that have shown the greatest growth from 2000 to 2011 are livestock production and hunting. On the other hand, fishing and agriculture have lost added value as a measure of macroeconomic approximation that constitutes the GDP. Despite the above, the inhabitants of the department of Amazonas consider that one of the threats related to the hydrobiological resource is indiscriminate fishing.

Table 3. Projected rate of exponential population growth

Department	2005–2010	2010–2015	2015–2020
National	1.19	1.15	1.09
Caquetá	1.26	1.29	1.25
Putumayo	1.00	1.14	1.35
Amazon group*	1.65	1.54	1.52

Note: * Refers to the departments of Amazonas, Guainía, Guaviare, Vaupés and Vichada.

Source: revised calculations from DANE[9].

Table 4. Amazonas—Average growth rates of added value of some economic activities (2000–2011)

Sector	Growth rate (%)
Agricultural	-66.7
Livestock production and hunting	100.0
Fishing and fish farming	-26.9

Source: revised calculations from DANE[1].

With respect to the department of Caquetá, **Table 5** shows the generality of the sectors related to water resources, which have shown significant growth rates in recent years; this is related to the dynamics of the region, whose growth between 2000 and 2011 was close to 40%. The sector that has seen the greatest expansion is water transportation, which generates problems related to the emission of waste through the dumping of oils and lubricants, as well as the use of fuels. On the other hand, the extraction of non-metallic minerals produces a series of negative externalities that affect water resources and ecosystems in this same department.

Table 5. Caquetá—Average growth rates of added value of some economic activities (2000–2011)

Sector	Growth rate (%)*
Agricultural	87.3
Livestock production and hunting	38.0
Fishing and Fish Farming	28.3
Mining	248.3
Water collection, treatment and distribution	14.3
Transport by water	1,323.1
Waste and sewage disposal, sanitation and similar activities	95.0

*Values at constant prices in 2012.

Source: revised calculations from DANE[1].

The agricultural and livestock sectors (the latter is the subsector that contributes the most to the regional GDP) also grew significantly, which should be considered with special care due to the expansion of the agricultural and livestock frontier and the associated problem of deforestation. Livestock production should receive special attention, for that according to FAO[10], it is the main producer of water pollutants worldwide; despite this, due to its great economic power and the enormous demand for meat in households, this sector seems to have an ever-increasing trend.

Table 6 summarizes the DANE data for the department of Guainía. It is striking to note how the extraction of non-metallic minerals (limestone, minerals, salts, among others) has decreased nearly 150% in recent years; on the other hand, activities such as agriculture and fishing have had significantly increased. Fishing has grown by more than 180%, which is a cause for concern due to overexploitation, poor control and non-compliance with minimum size regulations. These problems could jeopardize ecosystems and the sustainability of the resource.

Table 6. Guainía—Average growth rates of added value of some economic activities (2000–2011)

Sector	Growth rate (%)
Agricultural	50.0
Fishing and Fish Farming	183.3
Mining	-150.0
Transport by water	-100.0

Source: revised calculations from DANE[1].

As can be seen in **Table 7**, the value added by the extraction of non-metallic minerals in Guaviare has grown by more than 260%, a very high figure that obliges policy makers to impose restrictions to minimize the negative impacts of this activity on water resources.

Table 7. Guaviare—Average growth rates of value added of some economic activities (2000–2011)

Sector	Growth rate (%)
Agricultural	-256.0
Livestock production and hunting	40.2
Mining	263.3

Source: revised calculations from DANE[1].

In the department of Putumayo, where oil extraction contributes in relative terms the largest amount to the regional GDP, it can be observed that this sector is the one that continues to grow at a higher rate. Similarly, the extraction of non-metallic minerals had a considerable increase of 3.4% for the year 2012, as did the disposal of solid waste and wastewater[11]. Finally, in the department of Vaupés, the agricultural sector has grown by nearly 213% in the last decade, which has generated a deforestation problem associated with the expansion of the agricultural frontier (see **Table 8**).

In addition to population and productive sector growth, water resources are particularly threatened by illegal activities, especially illegal mining, a practice that has experienced unprecedented growth in recent years due to the interest of illegal groups, as this activity is an alternative to coca cultivation.

Table 8. Putumayo—Average growth rates of added value of some economic activities (2000–2011)

Sector	Growth rate (%)
Agricultural	-26.4
Livestock production and hunting	-10.8
Fishing and fish farming	33.3
Crude oil and natural gas extraction	180.0
Mining	50
Water transportation	116.7
Waste and sewage disposal, sanitation and similar activities	100.0

Source: revised calculations from DANE[1].

6. Discussion

Water resources itself is a kind of public goods[12-14].

In very heterogeneous contexts of use, it would behave more like a common-pool resource, where it faces a high degree of competition without excluding access[15]. Similarly, the relationship of water resources in public policy depends on the availability of quantity, not the amount used[16]. As a consequence, the use of water resources is inefficient in economic terms and in several cases affects the quality and inequity of access and availability, as shown in the studies[17,18], which is not different from the context of the Colombian Amazon basin. These differentiated demands have generated rivalry in their consumption and intersectoral competition[19]. Furthermore, these inequalities result in inefficient allocations, increased poverty and social inequity[20], which does not differ from the results previously presented (oil extraction versus human consumption). In addition, it is shown that the people who use water the most are those who enjoy this right at the lowest economic cost.

The characterization of the sectoral demand presented shows the social function of water for the satisfaction of basic consumption and food produc-production needs. However, this differentiated demand proves the inequity in the allocation of the resource. Due to the dynamic use of water by indigenous communities according to their traditional lifestyles, livelihood patterns and local traditional co-management organizations[21], their economic use costs are very low. This can be contrasted with users in the mining-energy sector, who use large quantities of water, which entails a very high economic cost in a scenario of non-existent compensation.

In the case of livestock activities in the Amazon, it can be stated that the sector does not generate high added value (in relative terms of innovation and inclusiveness), but it does promote local development and market positioning from the source; however, there are minimal employment opportunities created[22]. Furthermore, this activity is highly demanding of surface water and its main impact is deforestation, which affects the regulation and supply role of forests on surface water supply, which is the key to maintaining the hydrological and climatic cycle in most parts of the country.

In the case of mining, although it is one of the sectors with the lowest demand for surface water (industry), it is an activity that affects the region's water resources, an aspect that is not considered in the analysis of surface water concessions of the *National Water Resources Study*. If the production of beef consumes 15.4 liters of water per gram, the production of one gram of gold consumes 450 - 1,060 liters[11]. In terms of mining activities, illegal situations can be identified, which overlap with artisanal mining, whose negative effects are of a social, environmental, economic and cultural nature. This is proved in the results of the department of Caquetá and validated by the study of Verschoor and Torres[23].

In addition, the allocation of gold mining rights should also be considered, which is the right most directly granted to international concessionaires and operators. This causes a high risk to public health, for the inputs used in the operation will cause water pollution[11]. These and other factors of extractive activities affect water quality and make water availability a scarce ecosystem service, which undermines its social function, which should take precedence over its use as a production input.

Torras[24] considers that in order to calculate the true GDP of an economy, the depreciation of natural capital should be considered, i.e., it would be necessary to focus not only on how much an economic sector produces, but also on how production associated with the use of a natural resource affects nature. Under this perspective and because of the growing global concern about environmental destruction (and water scarcity), it is essential to find alternatives to approximate the total economic value of the water resource (in terms of function), considering this resource as a high-value input.

Considering the above situation, it is important to focus on the different uses of water in the Colombian Amazon basin, where the vulnerability and limitation of water resources is evident. More importantly, over time, the incremental dynamics used are predicted, which increases the difficulty of formulating and implementing appropriate management policies. Policy guidelines should consider not only the water balance (the quantity of water), but also the associated ecosystems and other water-related ecosystem services, which have not been valued economically in a holistic context in interactions. Policy guidelines should consider the following items:

- Heterogeneity of the territory.
- Identification of sectors, users and forms of use.
- Co-management, governance and local strengthening strategies.
- Environmental stressors.
- Water balance.
- Demand growth trends.

In this order of ideas, the water resource in the Amazon region can be considered abundant, but the dynamism of high impact productive activities directly affects it, both in quantity and quality. Likewise, population growth generates a conflict of use, which reveals the need to balance the effects of economic growth versus human wellbeing, guaranteeing the environmental quality of the resource[25]. On the one hand, we found that the population growth in an area is accelerating, and new demand tends to increase; on the other hand, there are consequences of economic growth that affect the productive base itself by affecting the quantity and quality of water resources: deforesta-deforestation, pollution, extractive activities and degradation of tropical rainforests.

Finally, the dilemma facing the use of water resources in the Amazon region has the following characteristics: (1) it takes 47% of Colombia's territory; (2) it contributes only 1% to the national GDP; (3) various sectors and ethnic populations interact; (4) it is a region of high population growth; (5) it has a low institutional framework and state coverage; (6) it presents a high environmental vulnerability. According to the above situation, it can be said that in this highly complex context, public policies on water resource use are inefficient. It is here where the debate can be opened: to focus regional development policies on sectoral activities that contribute significantly to GDP, or (on the contrary) to centralize public policy on the development of long-term social benefits, under a scenario of sustainability of natural resources.

Conflict of interest

The authors declared no conflict of interest.

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REVIEW ARTICLE

Research progress on the protection and utilization technology of water resources for coal mining in China

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ABSTRACT

Water shortage is a global problem, and China is one of the most water-scarce countries in the world. The reverse distribution of coal resources and water resources has made the protection and utilization of water resources for coal mining in China a major technical problem for the green development of coal. Western China has become the main coal-producing area, but the ecological environment in the region is fragile, the evaporation of water resources is large, and the evaporation loss after mine water discharge is the main reason for the current annual loss of 6 billion tons of mine water in coal mining in China. The technical progress and engineering application characteristics of the protection and utilization of water resources in coal mining are systematically analyzed. After nearly 20 years of technical exploration and engineering practice, Shenhua Group broke through the traditional concept, put forward the technical concept of mine water storage in the goaf for the first time, overcome the technical problems such as water source prediction, reservoir site selection, reservoir capacity calculation, dam construction, safety control and water quality assurance, and built a technical system for underground coal mine reservoirs. This technology has been fully implemented in the Shendong mining area, and will be promoted and applied in other mining areas in the western region, opening up an effective technical way for the protection and utilization of coal mining water resources.

Keywords: Coal Mining; Conservation and Utilization of Water Resources; Mine Water Storage in Goafs; Underground Coal Reservoirs

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1. Raise of questions

China is the world's largest producer and consumer of coal, and respectively accounted for 46.9% and 50.6% of the global coal production and consumption[1]. Coal accounts for 70% of China's primary energy production and consumption for a long time (**Figure 1**), coal will remain dominant in China's main energy for a long time, safety and green has become the theme of current coal mining. At present, China's coal safety situation is getting better, and the coal mortality of one million tons of coal has decreased from 5.77 in 2000 to 0.257 in 2014 (**Figure 2**). China's coal mining efficiency has reached the world's advanced level, and it is leading the world in coal machinery equipment and coal mining technology. More than 95% of the world's 10 million tons of mines are located in China.

Green mining is the core content of coal scientific development, and the protection and utilization of water resources for coal mining is a major problem facing green coal mining. The level of green coal mining in China has been slowly improved, which has seriously affected the

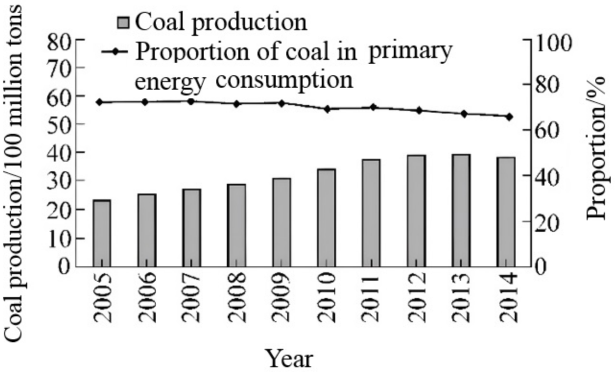

Figure 1. Production of coal and its percentage with primary energy consumption in China.

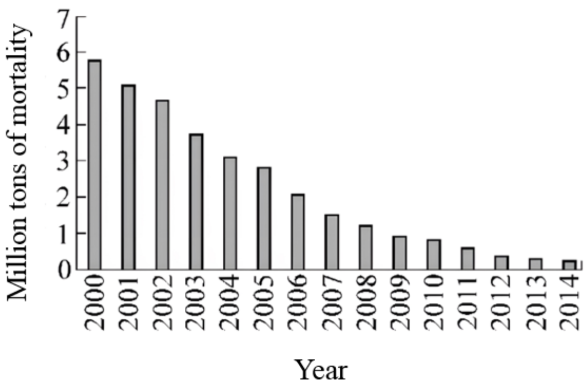

Figure 2. Million tons death rate of coal mine in 2000–2014.

improvement of the overall technical level of coal mining. Therefore, General Secretary Xi Jinping pointed out in his speech on the energy revolution on June 13, 2014 that the damage of coal mining to groundwater resources and surface ecology is the main problem facing coal development.

In view of the global problem of water shortage, the author analyzes the reverse distribution characteristics of coal resources and water resources in China; summarizes the technological progress in the protection and utilization of water resources for coal mining in western China, and points out that the storage and use of water in mines is the main technical direction for the protection and utilization of water resources in coal mining.

2. Water scarcity is a global problem

Water is the source of life, the key to production, and the foundation of ecology. According to statistics, the total reserves of water on earth are about 1.26×10^{18} m^3, sea and other saltwater account for 97.47%, freshwater accounts for only 2.53%. Among them, the total amount of freshwater resources such as river water, freshwater lake water and shallow groundwater that can be truly available to human beings is about 4.15×10^{15} m^3, accounting for only about 0.3%[2,4]. As the world's population increases, the demand for fresh water increases year by year, while the total amount of freshwater available is reduced at the speed of 6.4×10^{10} m^3/a. Currently, about 7,800 million people have limited access to available clean freshwater resources, and more than 2 billion people live in areas with high water supply constraints. By 2050, 67% of the world's population is expected to live in areas where water resources are severely scarce[5,10].

China's water scarcity began in the 1970s; since the 1980s, China's water shortage has gradually spread from local to the whole country, which has had a serious impact on the national economy. China is one of the most water-scarce countries in the world, and in 2014, the per capita water resources were less than 2,000 m^3, and the water resources situation was extremely severe[11]. The distribution of freshwater resources in China is uneven, which is manifested as "more in the south and less in the north, more in the east and less in the west". Yangtze River Basin and the area south of it account for 36.5% of the country, and water resources account for 81% of the country's water resources; Huai River Basin and its north accounts for 63.5% of the national areas, while accounts for only 19% of the country's water resources. The population in the north of China accounts for 2/5 of the total population of the country, but the water resources account for less than 1/5 of the total water resources in the country[12-14]. In terms of water volume, more than 400 of the 561 cities above the prefecture level in the country are short of water. In order to alleviate the shortage of regional water resources, China has successively built a number of large-scale cross-basin water transfer projects, such as the South-to-North Water Diversion Project, Luan River–Tianjin Water division Project, the Water Diversion Project from Yellow River to Qingdao in Shandong, the Shanxi Wanjiazhai Yellow River Diversion Project, and Han-to-Wei River Diversion Project[15], which have partially alleviated the problem of regional water shortage.

3. The protection and utilization of water resources is a major technical problem facing the green development of coal

3.1 Reverse distribution of coal resources and water resources in China

Relevant studies of the Chinese Academy of Engineering have shown that China's coal-bearing basins and coal resources show a "#"-shaped distribution pattern, that is, coal resources are controlled by the east-west spreading Tianshan–Yinshan tectonic belt, the Kunlun–Qinling–Dabie Mountain tectonic belt, and the south–north spreading Daxing'anling–Taihang Mountain–Xuefengshan tectonic belt, and the Helan Mountain–Liupan shan–Longmen Shan tectonic belt. The distribution of coal resources has the characteristics of more in the west and less in the east, more in the north than in the south, and deep in the east and shallow in the west[16]. At present, the mining depth of old mining areas such as Xinwen and Xuzhou in the east has reached about 1,000 m, the resources are increasingly depleted, and the mining complexity is increasing. The western region has become a major coal-producing area with shallow coal burial, thick coal seam and relatively simple mining conditions, accounting for 70% of the country's coal production and the proportion is continuously increasing (**Figure 3**).

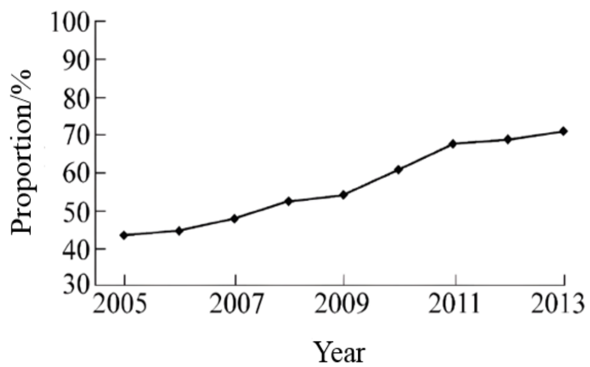

Figure 3. The proportion of coal production in the western region as a proportion of the country.

China's water resources and coal resources show a reverse distribution, and most of the coal-rich areas in the central and western regions are in arid and semi-arid ecologically fragile areas, with water shortages and fragile surface ecology. Water resources of major coal bases are in short supply, and water supply in mining areas mainly depends on the extraction of groundwater resources and comprehensive utilization of mine water. The construction of mining areas is facing difficult problems of water searching, comprehensive utilization of water resources and allocation of water rights[17].

3.2 The protection and utilization of water resources is a major problem facing the development of coal in the western region

The protection and utilization of water resources is a long-term challenge for coal development. According to statistics, China mined 1 tons of coal produces about 2 tons of mine water, but the utilization rate of mine water is only about 25%[18-20]. At present, the annual production of mine water is about 8 billion tons[21], and the annual loss of mine water is 6 billion tons, which is equivalent to 60% of China's annual industrial and civil water shortage (10 billion tons). The main reason for the loss of water resources in coal development is that the mine water discharged on the surface is not effectively utilized, especially in the western mining area.

The climate in the main coal-producing areas in western China is arid, and the annual evaporation is more than 6 times that of precipitation, so in order to ensure safe production, the mine water is discharged from the surface, but due to the large amount of evaporation, it cannot be effectively stored and used. How to achieve mutual coordination between coal development and water resources protection and utilization is a major technical problem facing the green development of coal in the western mining area, and it is also one of the core contents of the construction of ecological civilization in the western mining area.

3.3 The state attaches great importance to the protection and utilization of mine water

The protection and utilization of mine water has become a difficult point and hot issue in the green development of coal, which has attracted the attention of the whole society. General Secretary Xi Jinping pointed out at the sixth meeting of the

Central Leading Group for Finance and Economics: China's coal resources are abundant, and the status of the "coal boss" as the main energy source of our country will not change for a long time. The large-scale mining and use of coal brought about two major problems: first, the destruction of groundwater resources and surface ecology by coal mining; the second is the damage to the environment caused by coal consumption.

In order to solve the above-mentioned difficult problems, the party and the state have promulgated a series of policies and regulations for the protection and utilization of coal development and water resources, and put forward strict requirements. In May 2015, the CPC Central Committee and the State Council pointed out in the *Opinions on Accelerating the Construction of Ecological Civilization* that "actively develop and utilize unconventional water sources such as regenerated water, mine water, aerial cloud water, and seawater, strictly control disorderly water transfer and artificial water feature projects, and improve the safety and security of water resources". In April 2015, the State Council pointed out in the *Action Plan for the Prevention and Control of Water Pollution* (Water Ten Articles) that "to promote the comprehensive utilization of mine water, the supplementary water use of coal mining areas, the production and ecological water of surrounding areas should give priority to the use of mine water, and strengthen the recycling of coal preparation wastewater". In April 2015, the National Energy Administration's *Action Plan for Clean and Efficient Utilization of Coal (2015–2020)* proposed to "increase the utilization of coal gangue, slime, coal mine gas, mine water and other resources", "mining areas with suitable conditionals need to implement water conservation and mining or coal-water co-mining, to achieve the integration of mine water inrush control and water resource protection". In January 2015, the National Energy Administration and others pointed out in the *Opinions on Promoting Safe and Green Development and Clean and Efficient Utilization of Coal* that "coordinate coal resource conditions, mine geological environment, water resource carrying capacity and ecological environment capacity, and determine reasonable scientific production capacity", using water resources as a constraint on coal scientific production capacity. *The Environmental Protection Law of the People's Republic of China*, revised by the National People's Congress in 2015, for the first time enshrined "safeguarding public health" in Article 1 of the General Provisions and explicitly stipulated the principle of "giving priority to protection. In June 2014, the State Council's *Strategic Action Plan for Energy Development (2014–2020)*" stipulated that "according to the characteristics of regional water resource distribution and the carrying capacity of the ecological environment, strict environmental protection and safety access standards for coal mines, and promote green mining technologies such as filling and water conservation". In March 2012, the National Development and Reform Commission also put forward clear indicators and requirements for mine water utilization and surface ecological restoration in the *Twelfth Five-Year Plan for the Development of Coal Industry*. In February 2012, the State Council proposed in the *Opinions of the State Council on the Implementation of the Strictest Water Resources Management System* (State issued [2012] No. 3) to establish a red line for the control of water resources development and utilization, identified specific indicators and requirements, and clearly pointed out that the construction of major projects should be adapted to local water resources conditions[22-29]. The communiqué of the Fifth Plenary Session of the Eighteenth Central Committee of the Communist Party of China put forward the five development concepts of innovation, coordination, greenness, openness, and sharing, once again emphasized the basic national policy of conserving resources and protecting the environment, and raised the "quality of the ecological environment" to a new height.

The above-mentioned policies and regulations have put forward more stringent requirements for the protection and utilization of mine water, especially in the main coal-producing areas in the western region, it is necessary to develop technologies that are corresponding to each other, so as to achieve the coordinated development of coal mining and water resources protection and utilization.

4. Technological progress in the protection and utilization of water resources in coal mining

For a long time, in view of the impact of coal mining on groundwater, a large number of technical research and engineering practices have been carried out at home and abroad. Academician Qian Minggao took the lead in proposing the concept of green coal mining and several areas of research on water conservation and mining technology in western mining areas, pointing out that it is necessary to develop technologies suitable for coal mining and water resources coordination in western mining areas[30,32]. Accordingly, different institutions and scholars have carried out a large number of research work, including basic research on the "three belts" of coal mining and the law of groundwater movement of coal mining[33-40], forming two types of technical approaches: first, water retention mining technology characterized by the "interception method"; the second is the mine water storage and utilization technology characterized by the "diversion method."

4.1 Water-retaining mining technology characterized by the "interception method"

The core of the "interception method" of water retention mining technology is to protect the integrity of the aquifer above the coal seam and avoid the formation of water diversion fractures, thereby blocking the downward seepage of underground water and achieving the purpose of protecting the groundwater of the aquifer. The main technical means used include fill mining, height limit mining, house-pillar mining, and water retention area division[41-47].

Filling mining has been well applied in the eastern and central mining areas of our country, especially in the coal mining "three underground areas" (buildings, railways and water bodies), but to promote its application in the main coal-producing areas in western China, it is necessary to solve the problems of improving the efficiency of filling and reducing the cost of filling. In view of the protection of groundwater for coal mining in western China, relevant scholars have developed technologies such as water retention area division, pillar mining and strip mining based on ecological water level protection[48-50], but their promotion and application still need to solve the problems of improving the extraction rate of coal resources.

4.2 Mine water underground storage technology characterized by "diversion method"

The technology is to use the means of diversion, on the basis of mastering and using the law of groundwater transportation and migration of coal to extract groundwater, transfer mine water to the goaf area for storage, and build corresponding extraction and utilization projects to ensure that mine water does not drain out of the surface, and realize the protection and utilization of mine water resources.

After nearly 20 years of technical research and engineering practice in the Shendong mining area, Shenhua Group has successfully developed the coal mine underground reservoir technology, that is, using the goaf hollow space gap formed by coal mining, connecting artificial dam body to unconnected safety coal pillars to form a reservoir dam body to form a relatively closed water storage space, while constructing mine water injection facilities and water intake facilities, making full use of the goaf area rock mass on the natural purification of mine water, to achieve mine water storage and utilization[51,52], the technology has been successfully fully implemented in Shendong mining area.

4.3 Technological exploration of the protection and utilization of groundwater resources for coal mining

In view of the problem of water drainage losses from coal mining wells in the western mining area, Shenhua Group, together with China University of Mining and Technology (Beijing), China University of Mining and Technology, Tsinghua University, Xi'an Research Institute of China Coal Science and Industry Group, and other universities and scientific research institutions, has carried out a number of scientific and technological innovation projects and engineering practices in the

Shendong mining area, such as *Technology for Protective Mining and Comprehensive Utilization of Water Resources in Shendong Mining Area*, *Research and Application of Protective Coal Mining Technology for Water Resources in Shendong Mining Area*, and *Research on the Law of Modern Coal Mining on Groundwater Resources and Ecological Impact in Shendong Mining Area*. We have mastered the law of transport and movement of coal mining groundwater in the Shendong mining area, and carried out technical explorations for the protection and utilization of mine water: first, we have tried to prevent the generation of mine water, mainly using height limiting and filling mining techniques; the second is to build water storage facilities on the ground; the third is to explore the storage of mine water underground.

Studies have shown that although it is technically feasible to implement filling mining and height limiting of mining in the Shendong mining area, it is difficult to implement it on a large scale for the efficiency of coal mining and the rate of coal resource extraction are significantly reduced. The construction of water storage facilities on the ground is also unable to implement because of technical problems such as difficulties in land acquisition, evaporation and waste of water resources, and serious pollution of water bodies. Accordingly, Shenhua Group broke the traditional concept, carried out the technical exploration of mine water storage in the underground goaf area, experienced the technical development process of goaf water storage facilities, coal mine underground reservoirs and coal mine distributed multi-layer underground reservoirs, and built a relatively complete technical system of coal mine underground reservoirs, including water source prediction, reservoir site selection, reservoir capacity design, dam construction, safety monitoring and water quality control[53,54].

5. Coal mine underground reservoir technology has been successfully applied in western mining areas

Shenhua Group has successfully applied coal mine underground reservoir technology in Shendong mining area, and has built a total of 35 coal mine underground reservoirs with a water storage capacity of about 25 million m^3. In addition, the first coal mine distribution multi-layer underground reservoir was built in the Daliuta Mine of Shendong Mining Area, consisting of 3 underground reservoirs in Coal Seam 2 and 1 underground reservoir in Coal Seam 5, with a storage capacity of 7.1 million m^3, realizing no discharge of water from the mine. In the past three years, the underground reservoir of the coal mine has supplied more than 95% of the water used in the mining area, and in 2014, the water supply of the coal mine underground reservoir reached 65 million m^3, providing water resources for the world's only 200 million ton-class mining area, creating economic benefits for Shendong mining area 27.85 billion yuan in three years, including the savings of domestic and production water purchase 23.29 billion yuan and savings of mine water discharge costs, surface water treatment costs and sewage costs, etc., 4.56 billion yuan.

Shenhua Group has mastered the complete set of independent intellectual property rights of this technology, and has declared more than 70 domestic patents in coal mine underground reservoirs: of which 51 patents have been authorized (29 invention patents). The application of 4 PCT patents has opened up a new path for the protection and utilization of coal mining water resources in the main coal-producing areas in western China, and has realized the coordination between coal mining and water resources protection and utilization. Among them: the invention patent of "a distributed utilization method of underground water in mines" won the 17th China Patent Gold Award, becoming the third Chinese patent gold award won by the coal industry since the establishment of the award in 1989; the achievements of "key technologies for modern groundwater mining groundwater and surface ecological protection of coal in ecologically fragile areas" supported by this technology as the core technology won the second prize of national scientific and technological progress; the achievement of "key technologies and applications of coal mine underground reservoirs" won the first prize of scientific and technological progress in the Inner Mongolian Autonomous Region.

This technology has been successively popularized and applied by the Ministry of Land and Resources and the Ministry of Science and Technology of the State as an advanced technology throughout the country, and the World Coal Association has produced special cases of coal mine underground reservoirs to promote its application in major coal enterprises in the world. Shenhua Group has comprehensively promoted the application of this technology in its coal mining areas, including Baotou Mining Area, Xinjie Mining Area, Yushen Mining Area, Ningdong Mining Area, Dayan Mining Area, Xinjiang Mining Area, etc.. In September 2015, the Ministry of Science and Technology of the People's Republic of China approved the "state key laboratory of water resources protection and utilization of coal mining" built by Shenhua Group with coal mine underground reservoirs as the core technology, and Shenhua Group will committed to the research and development and engineering implementation of water resources protection and utilization technology in mining areas under different geological characteristics and coal mining conditions in western China, providing scientific and technological support for the protection and utilization of coal mining water resources in western China.

6. The technical development direction of underground reservoirs in coal mines

Coal mine underground reservoir technology involves mining engineering, engineering geology, hydrogeology, water conservancy engineering and environmental engineering and other disciplines, which is a complex system engineering, facing many technical problems, such as water source prediction, reservoir site selection and planning, water storage coefficient calculation, dam construction process, dam body parameter design, inter-reservoir passage construction, safety assurance technology, purification law of rock mass to mine water, water quality control, high mineral water treatment and other basic theory and application technical problems. Relying on the State Key Laboratory of "coal mining water resources protection and utilization", and uniting national and foreign scientific research institutes to form a technical system for the protection and utilization of water resources applicable to the main coal-producing areas in western China. The following research work will be carried out in the future:

(1) Evaluation of the impact of coal mining on groundwater system and theoretical study of dynamic balance of regional water resources which includes: the evolution law and control mechanism of cracks in coal mining rock masses, the influence of coal mining on groundwater system, the changes in stress field caused by coal mining and the impact of groundwater level, and the theory and technology of regional water resource dynamic balance.

(2) Research on the basic theory of underground reservoirs in coal mines which includes the "three fields" relationship and evolution mechanism of the mining stress field, the fissure field and the seepage field of coal mining; self-purification mechanism of mine water by rock mass in goaf area; the impact of water storage in underground reservoirs on groundwater circulation systems and surface vegetation growth in coal mines; coal mine underground reservoir dam body safety and water body optimization scheduling theory, etc.

(3) Research and development of key technologies for underground reservoirs in coal mines which includes the study on the construction process and parameter optimization of dam bodies in underground reservoirs in coal mines, the technology for ensuring the safety of coal mine underground reservoirs, the technology for coordinating the operation of coal mine underground reservoirs, the technology for ensuring the water quality of coal mines, the technology for grading and processing water quality in coal mines, and the technology for efficient recycling of mine water.

(4) Theories and techniques of ecological construction of mining areas based on water resources protection which includes the relationship

and mechanism of groundwater system changes and ecological environment systems, the laws of the impact of coal mining on the surface ecological environment system, the law of the impact of efficient coal development on the surface ecology, and the evaluation of the ability of coal mining to restore the ecological restoration capacity of the surface.

(5) Increase the popularization and application of coal mine underground water reservoir technology, formulate technical standards for enterprises and industries, and accelerate the promotion of this technology in the western water-scarce mining areas; It will be gradually promoted in other areas of western China where conditions are suitable, including in the open pit coal mines.

7. Conclusion

(1) Water shortage is a global problem, especially in the western mining areas of China's main coal-producing areas, due to special geographical and climatic conditions, drought and little rainfall, the contradiction between water supply and demand is very prominent, which seriously restricts the green development of coal in the region.

(2) Water retention mining technology characterized by the concept of "interception method" must further solve technical problems such as improving mining efficiency and coal resource extraction rate.

(3) Coal mine underground reservoir technology, as a representative technology of the concept of "diversion method", has realized the coordinated exploitation of coal resources and water resources, and opened up an effective technical way for the protection and utilization of groundwater for coal mining in the west.

(4) The technically complex system engineering of coal mine underground reservoirs involves mining, water conservancy, geology and environment, and other disciplines, and it is also necessary to further carry out relevant basic theoretical research and technical research, so as to form a theoretical and technical system suitable for different geological and mining conditions, and provide scientific and technological support for the protection and utilization of 6 billion t of mine water lost by coal mining in China each year.

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Conflict of interest

The authors declared no conflict of interest.

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ORIGINAL RESEARCH ARTICLE

Present situation analysis and key technology research prospect of water resources protection in Yangtze River Basin

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ABSTRACT

On the basis of analyzing the present situation and main problems of water resources protection and management in river basins, according to the main responsibilities of river basin organizations in water resources protection and management, and based on the principle of unified protection of water quantity, water quality and water ecology, the content framework of water resources protection in river basins is proposed. According to the demand of water resources protection for science and technology, ten key technologies and main research contents of water resources protection in the Yangtze River Basin are put forward to provide support for the implementation of the idea of "maintaining healthy Yangtze River and building harmony between people and water".

Keywords: Yangtze River Basin; Water Resources Protection; Framework System; Key Technology

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1. Introduction

Water is the source of life, the key of production and the foundation of ecology. The Yangtze River Basin is ranked first among the seven major river basins in China for its relatively abundant water resources. There are 5,276 tributaries with a catchment area greater than 100 km^2 and 142 lakes with a water surface area greater than 10 km^2[1]. The annual average surface water resources in the Yangtze River Basin are 9.855×10^{11} m^3, and the total water resources are 9.955×10^{11} m^3. In 2016, the total amount of surface water resources was $1.179\,6 \times 10^{12}$ m^3, equivalent to annual runoff depth of 661.7 mm, and the natural endowment of water resources was good. In 2016, the total water supply of the whole basin was 2.039×10^{11} m^3, of which the surface water supply was 1.958×10^{11} m^3, accounting for 96.0% of the total water supply. More than 44,000 reservoirs have been built in the whole basin, and the utilization rate of water resources is 18.7%, and it shoulders the heavy responsibility of water source diversion in China's South-to-North Water Diversion Project. With the social and economic development inside and outside the Yangtze River Basin, the importance of water resources security is self-evident. At the same time, due to the overexploitation of water resources, the water quality has deteriorated year by year, and the water ecosystem has been destroyed, which has seriously threatened the water resources security in the basin. In January 2016, General Secretary Xi demanded that "at present and for a long time to come, the restoration of the ecological environment of the Yangtze River should be placed in an overwhelming position, and great protection should be paid attention to, and no great development should be carried out". Therefore, the protection of water resources in the Yangtze River Basin has become a top priority. Throughout the experience of water resources protection in developed countries, water resources protection should be a multi-objective comprehensive protection of water quantity, water quality and water ecology. Water quantity is the foundation, water quality is the key, and water ecology is the focus, so we can't neglect one of them. In the process of water resources protection and management, relying on scientific and technological progress, using advanced and mature key technologies and implementing scientific management of water resources protection are the only way to realize "maintaining healthy Yangtze River and building harmony between people and water".

2. Overview of water resources protection in river basin

Water resources protection in the Yangtze River Basin started in the late 1970s and has been implemented for more than 40 years. At present, the protection of water resources in the Yangtze River Basin presents the basic pattern of "one center, two emphases, three links, four constructions", that is, "taking the management of water functional areas as the center, sewage outlets into rivers and drinking water sources as the key objects, planning, examination and approval and supervision as the key links, and focusing on the construction of talent team, monitoring station network, information platform and law enforcement capacity". Specifically, the general situation of water resources protection in the Yangtze River Basin is as follows.

2.1 The legal system of river basin water resources protection is gradually constructed

According to the *Water Law of the People's Republic of China*, *Law of the People's Republic of China on Water Pollution Prevention and Control*, *Administrative License Law of the People's Republic of China*, *Regulations of the People's Republic of China on River Management*, *Measures for the Supervision and Administration of Water Function Zones*, *Measures for the Supervision and Administration of Sewage Outlets Entering Rivers* and other superior laws, the Yangtze River Basin has successively completed the drafting of normative documents such as the *Detailed Rules for the Implementation of the Supervision and Management of the Sewage Outlet into the River by the Yangtze River Water Resources Commission*, *Measures for the Setting and Acceptance of the Sewage Outlet into the River by the Yangtze River Water Resources Commission*, and the *Plan for the Functional Classification Management of the Yangtze River Basin and the Southwest Rivers*, among which the first two items have been approved and implemented by the Yangtze River Water Resources Commission, and the other one is under review. And the legislative demonstration of the *Yangtze River Protection Law* is also actively promoted.

2.2 The planning system of water resources protection in the basin has basically taken shape

Since 1986, the Yangtze River Basin has completed the *Water Protection Plan for the Main stream of the Yangtze River*, which was included in the *Brief Report on the Comprehensive Utilization Plan of the Yangtze River Basin (1990)* approved by the State Council. In recent years, nearly 20 water resources protection planning tasks represented by the revision of comprehensive planning of the Yangtze River Basin and comprehensive planning of water resources of the Yangtze River (slice) have been implemented in the basin[3]. Especially, through the compilation of the *Three Gorges Water Resources Protection Plan*, the technical system of water resources protection engineering was explored and formed, which directly promoted the promulgation of *China's Regulations for the Compilation of Water Resources Protection Plan*. Basically, a planning engineering measure system of water resources protection , which focuses on the layout and regulation of sewage outlets into rivers, water source protection, water ecological protection and restoration, non-point source control and endogenous pollution control; and a non-engineering technical system which concentrates on laws and regulations, institutional mechanism construction, monitoring capacity construction and scientific research capacity construction are formed[4]. In 2016, the Ministry of Water Resources issued the *Layout Plan of Sewage Outlets and Emergency Water Sources at the Water Intake along the Yangtze River Economic Belt*, which defined the prohibited areas, general restricted areas and strictly restricted areas for sewage outlets entering the river.

2.3 Information investigation of sewage outfall and water source into the river is carried out in an orderly manner

According to the requirements of the Ministry of Water Resources *Measures for the Supervision and Administration of Sewage Outlets into Rivers* for the investigation and registration of sewage outlets into rivers, in 2006, the Yangtze River Basin completed the first investigation and registration of sewage outlets into rivers, with a total of more than 9,000 sewage outlets into rivers[5]. According to the national list of important drinking water sources issued by the Ministry of Water Resources, since 2011, the basic information of 56 important drinking water sources in the Yangtze River Basin has been investigated, and the scope of water sources, water intake settings, water supply conditions, water quality conditions, water ecological conditions and water source pipes have been mastered. In 2017, relying on the key work of the Yangtze River Economic Belt, the special verification work of sewage outlets into the river was carried out, and a total of 8,051 sewage outlets above designated size were verified.

2.4 The approval and management of sewage outfall into the river are carried out step by step

On the basis of the investigation and registration of the information of the sewage outfall into the river, we further organized and implemented the demarcation and monument work of the water function area, verified the water pollution-bearing capacity of the water function area, and put forward the control scheme of limiting the total amount of sewage discharge. According to the Measures for Supervision and Management of Sewage Outfall into the River of the Ministry of Water Resources, combined with the most stringent water resources management system currently implemented in China, further standardize the approval procedures for setting sewage outlets into rivers. At the same time, the statistical system of the annual report of sewage outlets directly under the control of river basin institutions has been established[6], and the local water administrative departments have been jointly engaged to carry out law enforcement supervision and inspection of important sewage outlets into the river, thus steadily promoting the normalization of supervision and management of sewage outlets into the river.

2.5 The network of water environment monitoring stations is becoming more and more perfect

The Yangtze River Basin Water Environment Monitoring Station Network was established in 1977. By 1992, the number of monitoring stations in the whole basin had increased from 156 at the initial stage to 551[7], with nearly 700 monitoring sections. At present, there are about 2,500 monitoring sections in the main and tributaries of the Yangtze River. Since 1998, the river basin has carried out 35 provincial boundary buffer section water quality monitoring work, reaching 60 in 2006, 111 in 2010, and 164 in 2016, basically achieving full coverage of provincial boundary water body monitoring in the river basin, with about 30 routine monitoring indicators[8]. More than 400 issues of the *Bulletin of Water Resources Quality of the Yangtze River* and the *Water Quality Bulletin of the Yangtze River Basin and Southwest Rivers* were released on time.

2.6 The informatization level of water resources protection management has been significantly improved

The informatization construction of water resources protection in the Yangtze River Basin has implemented the informatization platform construction step by step according to the principle of "planning first, perfecting the network, highlighting key points and ensuring favorable conditions". The information management system of drainage outlets in river basins based on GIS is established, and the water resources protection management information system of water quality, drainage outlets and water sources based on Web GIS is constructed, which realizes the automatic collection of monitoring data and the intelligence of data statistics and analysis. In recent two years, Google Earth and SQL database have been jointly developed in the Yangtze River Basin, and a monitoring system for water resources protection in the Yangtze River Basin has been built, which can quickly query and search related information such as water function areas, sewage outlets into rivers and water sources[9].

3. Problems faced by water resources protection in river basins

The practical problems of water resources protection in the Yangtze River Basin are more prominent, including water shortage, serious water pollution and ecosystem fragmentation, which are mainly reflected in the following six aspects.

3.1 The low overall water quality compliance rate of the river basin

In 2011, the State Council issued the *National Water Function Zoning of Important Rivers and Lakes (2011–2030)*, and the Yangtze River Basin comprised a total of 1,181 first-level water function zones (including 416 development and utilization areas) included in the water function zoning of important rivers and lakes in the country, and 978 second-level water function zones were demarcated in the development and utilization areas. A total of 1,506 water functional zones in the first or second zone were identified as class III or better than the water quality targets, accounting for 86.4% of the total. According to the *Bulletin on Water Resources of the Yangtze River Basin and Southwest Rivers*, from 2010 to 2016, although the water quality compliance rate of the water function area (**Table 1**) has improved significantly, the compliance rate of the full index evaluation method (referring to 24 conventional monitoring projects) has increased from 64.6% to 73.8%, but the compliance rate is still low. The compliance rate of the two-index evaluation method (COD and ammonia nitrogen monitoring projects) increased from 78.9% to 91.2%.

Table 1. Standard-reaching rates of water quality in important water functional zones of Yangtze River

Year	Number of functional zones evaluated	Full index method		Double index method	
		Number	Percentage/%	Number	Percentage/%
2010	192	124	64.6	0	0
2011	255	146	57.3	0	0
2012	925	593	64.1	730	78.9
2013	934	621	66.5	779	83.4
2014	1,150	788	68.5	1,008	87.7
2015	971	688	70.9	868	89.4
2016	1,195	882	73.8	1,090	91.2

3.2 The prominent contradiction between sewage discharge and water environment capacity

According to the *Yangtze River Water Quality Bulletin* and historical statistics, the sewage discharge in the Yangtze River Basin increased to 15 billion tons in the early 1990s, exceeded 20 billion tons by the end of the 1990s, and exceeded 30 billion tons for the first time in 2007, reaching 33.3 billion tons in 2010 and has now exceeded 35 billion tons, as shown in **Figure 1**.The amount of sewage discharged into the river basin has reached more than 40% of the national total amount, equivalent to the total water volume of a Yellow River. The trend of sewage discharge in the Yangtze River Basin is shown in **Figure 2**. At the same time, the sewage discharge space is concentrated in the urban river section, and the sewage discharge of some sections of the river exceeds the capacity of the water area to absorb pollution, and a continuous pollution belt exceeding the standard has been formed.

3.3 The prominent contradiction between the operation of water conservancy projects and ecological water demand

According to statistics, there are currently more than 2,400 hydropower projects constructed or under construction in the Yangtze River Basin, with an installed capacity of 12 × 108 kW,

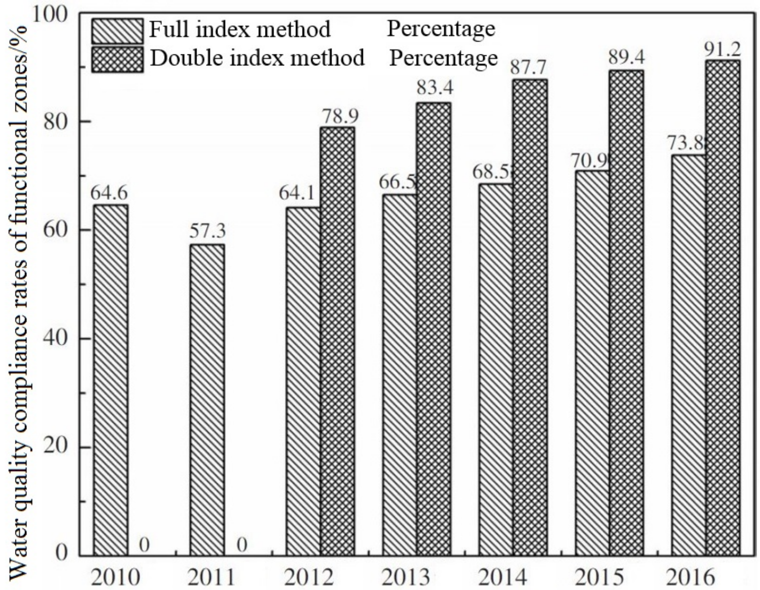

Figure 1. Annual change trend of water quality standard-reaching rates in important water functional zones of Yangtze River.

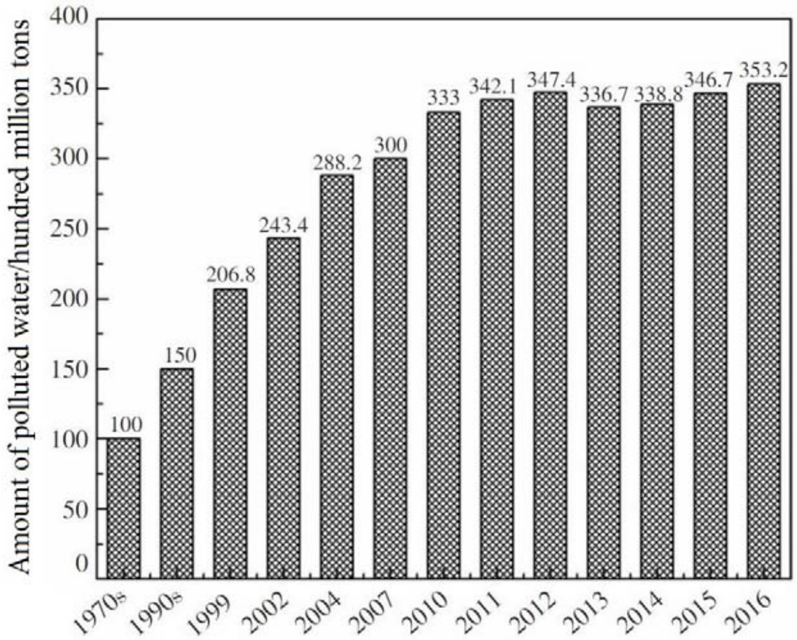

Figure 2. Annual change trend of sewage discharge in the Yangtze River basin.

accounting for 42% of the developable hydropower technology in the whole basin. The total water consumption of the whole basin is 1.984×10^{11} m^3, the total water resources are 1.115×10^{12} m^3, and the development and utilization rate of water resources is 18.7%, which has entered the list of rivers with medium development degree. The upper reaches of the Minjiang River and some tributaries of the Han River are cut off many times, and the ecological water demand process of the upper reaches of the Min Jiang, Dadu River, Jialing River, Wu River and Han River where hydropower development is concentrated is not met.

3.4 The obvious trend of ecological fragility in some waters

Under the dual interference of human activities and climatic variation, the water ecology problems in the Yangtze River Basin are very prominent, mainly manifested in the reduction of habitat area, the singleness of aquatic biomes, and the frequent occurrence of algal blooms. Taking the scale of spawning farm of “the four major Chinese carps ” (black carp, grass carp, silver carp, bighead carp) as an example, the survey results in the 1960s showed that there were 36 spawning farms in the main stream of the Yangtze River from Ba County in

Sichuan (now Banan District, Chongqing) to Pengze in Jiangxi, which was reduced to 30 in 1986, of which 11 were located in the upper section of the Yichang River, and after the Three Gorges Reservoir was stored, the hydrological conditions changed, and 11 spawning grounds in the upper reaches faced the disappearance[10]. In addition, Dianchi Lake, Chao Lake, Hongze Lake, Taihu Lake, Dongting Lake, Three Gorges Reservoir, Land Water Reservoir, and the middle and lower reaches of the Han River have all experienced algal blooms many times, including Taihu Lake, Chao Lake and Dianchi Lake has been identified as a key target for prevention and control since the beginning of the Ninth Five-Year Plan due to the serious problem of algal blooms.

3.5 The low degree of safety and security of drinking water sources

From 2010 to 2016, the water quality of some of the centralized drinking water sources in the Yangtze River Basin participated in the annual standard is shown in **Table 2**, and the water quality qualification rate of the water source is not optimistic. In addition, according to the survey on the safety and security of 56 national important drinking water sources in the Yangtze River Basin conducted since 2012, the water supply guarantee rate of some water sources is less than the target of 95%, and 22 drinking water sources have not built backup water sources; 23 water sources have failed to implement closed management in the first-level protection areas, 8 drinking water sources still have sewage outlets, some water sources have potential pollution sources such as docks, oil depots, and farms; vegetation coverage is less than 80% in 10 primary water sources protection areas; and 17 water sources without automatic monitoring system[11], etc. Other centralized drinking water sources at or above the county level have a lower degree of safety and security.

Table 2. Water quality standard-reaching rates in drinking water sources of Yangtze River

Year	Number of functional zones evaluated	Full index method	
		Number	Percentage/%
2010	346	222	64.2
2011	309	210	68.0
2012	356	202	56.7
2013	340	196	57.6
2014	329	193	58.7
2015	335	220	65.7
2016	481	338	70.3

3.6 The imperfect technical methods of river and lake health assessment

In 2006, the Changjiang Water Resources Commission put forward a new idea of “maintaining a healthy Yangtze River and building harmony between people and water”. What is a healthy river and what is a healthy Yangtze River? Current research and understanding are still incomplete. In 2007, the Changjiang Water Resources Commission organized the “index research of healthy Yangtze River”, the index system of healthy Yangtze River was established from seven aspects: the research on the development and utilization rate of water resources, the water quality standard-reaching rate of the water function area, the degree of ecological water demand satisfaction, fish biodiversity, the excellent river conservation rate of the river, the wetland retention rate, and the soil erosion rate, and the evaluation criteria and evaluation methods of the index were preliminarily discussed[12]. However, there are still problems such as incomplete indicators, weak operability, and difficulty in quantification.

4. Multi-objective integrated protection framework system for water resources

According to the overall requirements of water resources protection of unified protection in accordance with the “water quantity, water quality and water ecology” in the new era, combined with the responsibilities entrusted by China to river basin institutions in “ecological water demand protection, water quality management in water functional areas, protection of drinking water sources, water ecological protection and restoration, supervision and management of sewage outlets into rivers, and protection of groundwater resources”, water resources protection should start from engineering measures and non-engineering measures to establish multi-objective integrated protection framework system in Yangtze River Basin, as is shown in **Figure 3**.

The water resources protection system consists of an engineering system and a non-engineering system. In the engineering system, water quantity protection is reflected in the construction project of water conservation forest and the ecological dispatch project of water conservancy project; water quality protection is reflected in the two aspects of point source pollution control and non-point source pollution control in which point source pollution control mainly implements the standardized rectification of sewage outlets, the transformation of sewage outlets and the in-depth treatment of sewage outlets, and the non-point source pollution control is mainly aimed at agricultural non-point source pollution classification and control of pollution, rural domestic pollution and solid waste; water ecological protection is mainly reflected in shore slope restoration, algal bloom control, water quality purification and comprehensive management of small watersheds[13]. Non-engineering systems mainly include water resources protection monitoring and water resources protection management. Among them, water resources protection monitoring mainly implements water function area monitoring, sewage outlet monitoring, drinking water source monitoring, water ecology monitoring and emergency monitoring; and water resources protection management is reflected in the construction of laws and regulations, the construction of management mechanisms, scientific research and technology promotion, management capacity building, etc.[14].

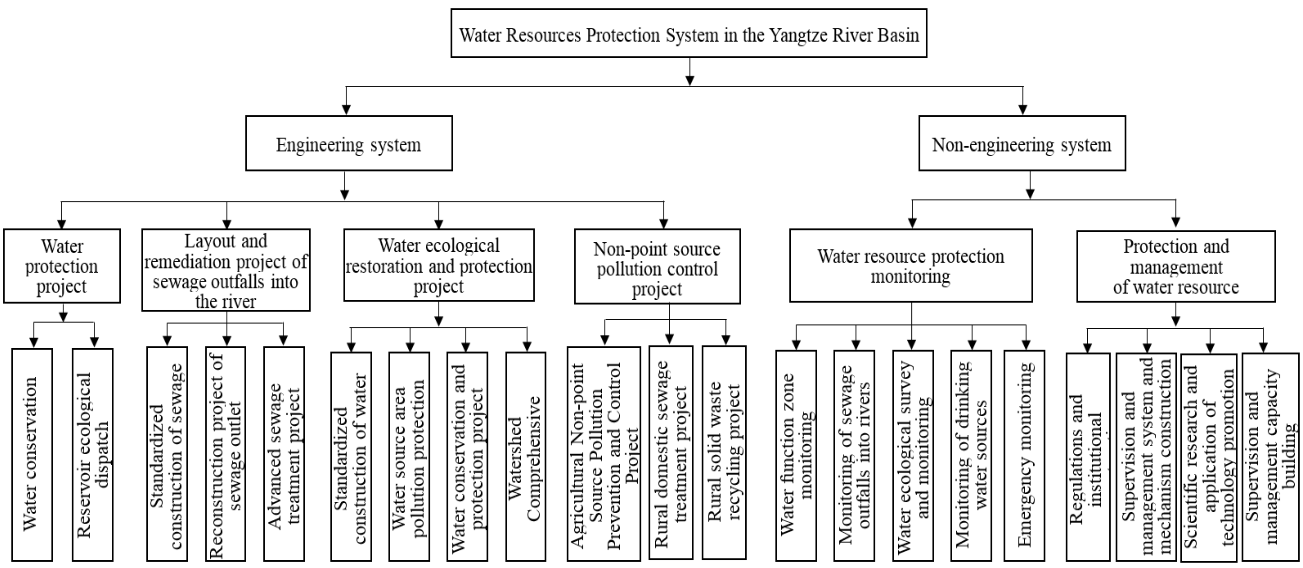

Figure 3. Frame system of water resources protection system in the Yangtze River basin.

5. Technical system of multi-objective comprehensive protection for water resources

According to the framework system of multi-objective comprehensive protection of water resources, scientific research should be aimed at "ensuring the appropriate ecological flow process, the water quality of the water function area and the total amount of sewage discharge, the water quality of drinking water sources, the integrity and function of the water ecosystem, the management and reasonable layout of the sewage outlet, and the standard-reaching quality of the groundwater", focus on ten aspects of technical research and development in view of the current problems in water resources protection, and initially form a multi-objective comprehensive protection technology system for water resources in the Yangtze River Basin.

5.1 Suitable ecological water demand process and key technologies guarantee in the Yangtze River Basin

Focusing on the cumulative impact of storage, introduction, lifting and adjustment projects on the runoff process of rivers, establishing a calculation method for the ecological needs of different characteristic sections of the Yangtze River Basin, constructing a target scheme for the control of ecological water demand in key sections of the Yangtze River Basin, and proposing a guarantee scheme for the suitable ecological water demand process of rivers under strong human interference.

5.2 Key technologies for river and lake health assessment and protection

Focusing on establishing an indicator system for the health of rivers and lakes, establishing quantitative calculation methods for various indicators in terms of water quantity, water quality, water ecology, physical structure, social environment, etc., establishing the standard threshold of indicators for the health of key rivers and lakes in the Yangtze River Basin, and carrying out health diagnosis and restoration of typical rivers and lakes[15].

5.3 Key technologies for the verification and distribution of pollution absorption capacity in dynamic waters

Focusing on the law of pollutant diffusion and self-purification under different water flow conditions, establishing a calculation method for the pollution capacity of dynamic waters in urban river sections, establishing a distribution plan for the capacity of pollutants in dynamic waters, and establishing a control scheme for the total amount of pollutants entering the river under extremely dry water conditions.

5.4 Key technologies for the setting and management of sewage outlets into the river

Constructing a supervision and management model, law and system for the discharge of sewage into the river basin; exploring the application of the pollution trading mechanism in the management of the sewage outlet of the river; improving the demonstration of the setting of sewage outlets into rivers and the establishment of demonstration guidelines for planning inlets; building information systems for sewage outlets into rivers and optimizing layout methods; implementing the investigation of accident risk sources and the preparation of emergency plans for sudden water pollution accidents.

5.5 Key technologies for water ecological protection and restoration in disturbed waters

To explore the vulnerability indicators of river and lake water ecosystems and their causes, guided by river and lake health standards; researching and developing key technologies for the restoration of water ecological structure and function in important sensitive water areas to explore environmental effect assessment and water quality regulation schemes for the connection of rivers and lakes.

5.6 Control technology on the impact of reservoir groups operation of main stream and tributary on lakes and wetlands

Implementing the ecological survey and evaluation of the “Two Lakes” wetland, and carrying out the analysis of the historical evolution trend of the “Two Lakes” wetland, to study the cumulative effect of the operation of the main stream and tributary reservoir group on the hydrological process of the “Two Lakes” and the response relationship of the “Two Lakes” wetland to the variation of the hydrological process. The optimal scheduling scheme of the main stream and tributary reservoir group for the protection of the “Two Lakes” wetland is discussed, and the habitat and biodiversity conservation scheme of the “Two Lakes” wetland are proposed.

5.7 Causes of algal blooms in large reservoirs in the Yangtze River Basin and their prevention and control technologies

Investigate and evaluate the current status of eutrophication in large reservoirs in the Yangtze River Basin, study the production and perishing process and influencing factors of water algae blooms in reservoirs in different spatial and temporal patterns, identify the driving factors of typical algae blooms and their limiting thresholds, develop ecological risk assessment and early warning technology of algae blooms in typical reservoirs, and propose prevention and control technologies and regulation countermeasures for algae blooms of large reservoirs in the Yangtze River Basin.

5.8 Research on key technologies for water quality protection in water sources in the Yangtze River Basin

Carry out investigation and analysis of the current situation of water quality in large drinking water sources, design ecological compensation mechanisms for typical drinking water sources, and develop key technologies for ecological block control of large drinking water sources and water quality early warning technologies for large water sources based on multi-source indication organisms.

5.9 Key technologies for automatic monitoring of water environment in the Yangtze River Basin

Explore the optimization layout scheme of water quality monitoring sections in key water areas, study multi-source water quality testing and adaptive networking technology in large water source areas, improve the monitoring and evaluation standards of toxic organic compounds, and develop multi-index online monitoring technology research and equipment.

5.10 Key technologies for the protection of groundwater resources in the Yangtze River Basin

Carry out functional zoning of groundwater and establish water quality management goals, study the simulation technology of pollutant transport in the groundwater system, develop microbial technology for groundwater pollution control, and establish a groundwater quality monitoring and information release system.

The ideas of the key technical framework system for water resources protection in the Yangtze River Basin are shown in **Figure 4**.

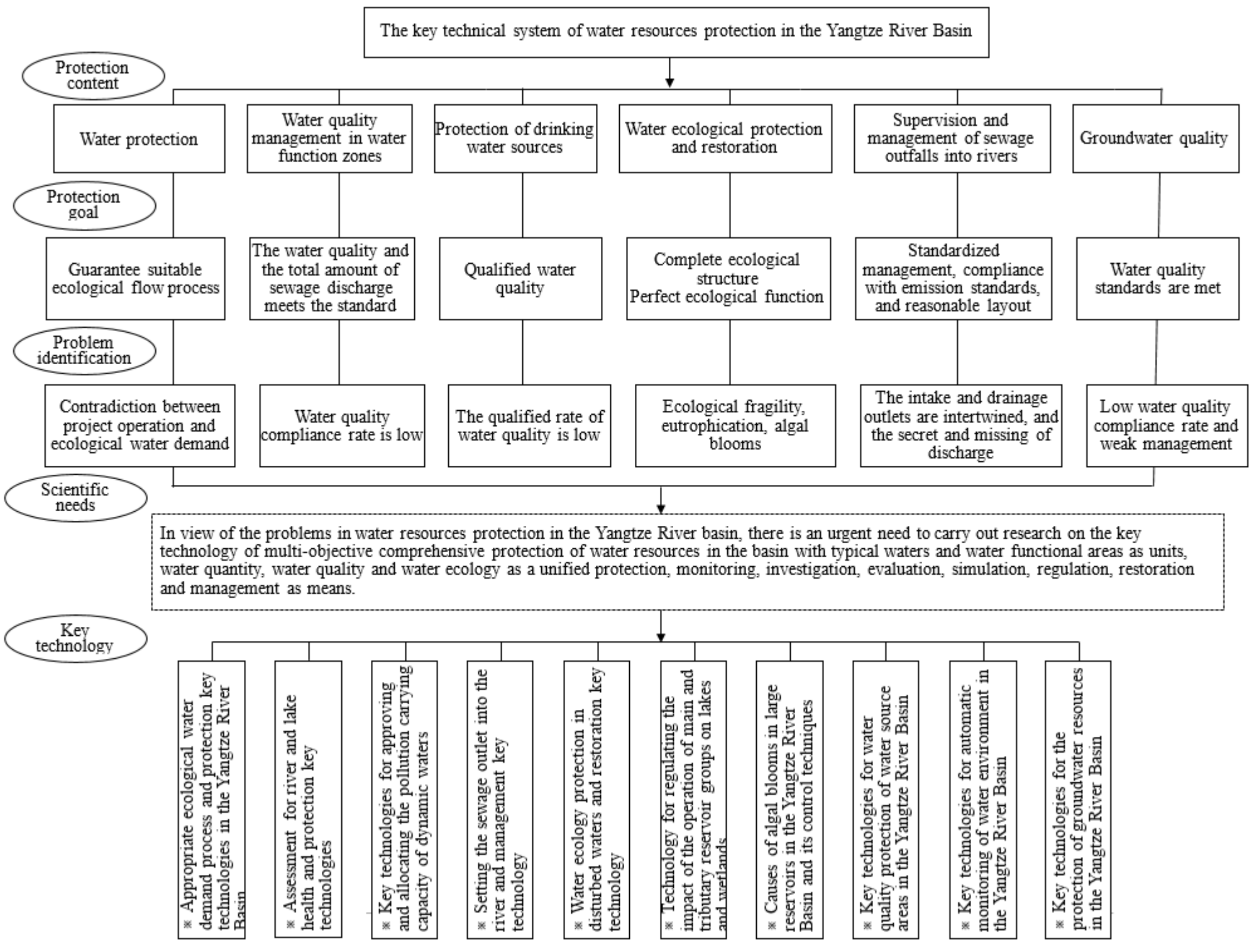

Figure 4. System of water resources protection key technologies in the Yangtze River Basin.

6. Conclusion

The Yangtze River is the third largest river in the world and the largest in China. Its watershed area accounts for 1/5 of the country's land area, supports 1/3 of China's population, contributes 1/3 of China's GDP, and its important position is self-evident. Under the background of the dual interference of climate change and human activities, the protection of water resources in river basins is facing unprecedented pressure. Although after more than 40 years of unremitting efforts, the Yangtze River Basin has initially established a legal system for water resources protection, the status of water resources protection planning has been continuously improved, the thinking of water resources protection planning has been continuously improved, and the management, scientific research and monitoring capabilities of water resources protection have been continuously enhanced. However, it is still faced with problems such as excessive squeezing of ecological water demand, low water quality compliance rate, fragility of local water ecology, difficulty in ensuring drinking water safety, and more sewage in some water functional areas than the capacity to absorb pollution. In the face of river basin management responsibilities and objective problems, the current water resources protection of the Yangtze River Basin must unswervingly practice the idea of unified protection of "water quantity, water quality and water ecology", taking into account the ecological water needs of rivers, water quality standards, and river entry limits Multi-objective comprehensive protection such as total discharge control, water ecosystem integrity, drinking water source safety, and groundwater quality safety. However, in order to truly achieve the ultimate goal of "healthy Yangtze River", we must also fully rely on the progress of science and technology and establish a technical framework system for the whole process of monitoring, investigation, evaluation, simulation, regulation, restoration and management, so as to promote the protection of water resources in the basin in the direction of rapid, accurate and efficient development.

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Conflict of interest

The authors declared no conflict of interest.

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ORIGINAL RESEARCH ARTICLE

Utilization of water resources in Pingtian Lake wetland and its protection countermeasures

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ABSTRACT

In order to better protect and utilize the water resources of the wetlands along the river in Anhui, through a comprehensive analysis of the current situation of water resources development and utilization in Pingtian Lake National Wetland Park in Chizhou, Anhui Province, the key factors affecting the ecological function of the water resources of the Pingtian Lake Wetland were explored, and specific wetland water resources protection measures were proposed: first, to restore the topography of the wetland habitat and improve the ecological function of the lake itself; second, to promote modern ecological agricultural technology and reduce non-point source pollution in rural agriculture; and third, to take the opportunity of "sponge city" construction and centralized environmental management to strictly control the discharge of urban sewage and corporate pollutants; fourth, to innovate the wetland ecological compensation system and increase the protection of wetland water resources; fifth, to strictly abide by the red line of ecological protection and implement wetland water resources management in accordance with laws and regulations.

Keywords: Pingtian Lake Wetland Park; Water Resources Conservation; Biodiversity

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1. Introduction

Wetlands are natural or man-made, permanent or temporary stagnant or flowing water, freshwater, brackish or brackish marshlands, peatlands, or waters, including areas of seawater with a water depth of not more than 6 m at low tide[1]. Wetlands are one of the most important ecological environments for human beings[2]. Wetland ecosystems are the natural ecosystems that carry the most ecological functions on the earth, have high biological productivity, and have significant ecological benefits[3]. However, wetland ecosystems are also the most degraded and loss-free ecosystems in the world today[4]. Compared with rivers, lake wetlands are greatly affected by human activities and have poor water fluidity, more lake facies deposition, and slow water quality renewal. It is prone to eutrophication and other characteristics, and its ecological system is the most fragile. With the development of the economy and society, the utilization of wetland water resources in China faces many threats, and the improper utilization and protection of wetland water resources will inevitably lead to the weakening of wetland flood regulation and storage functions and the degradation of wetland habitats. At the same time, wetland biodiversity conservation, ecological security, and ecosystem stability are also constrained. Wetlands play a huge role in water transmission, storage, and supply. Hydrology is a key factor in determining the characteristics and types of wetlands[5], and the integrity and quality of wetland water resources are of great significance for wetland conservation. Taking Pingtian Lake National Wetland Park in Chizhou City, Anhui Province as an example, the purpose is to analyze the current situation of water resource utilization of urban lakes and wetlands in the middle and lower reaches of the Yangtze River and to explore the water resources protection strategy of urban lakes and wetlands.

2. Overview of Pingtian Lake wetlands

Pingtian Lake, formerly known as Baisha Lake, is located in Guichi District, Chizhou City, Anhui Province (longitude 117°29'28" to 117°34'20" E, 30°37'31" to 30°41'59" N)[6], with Chizhou City. The urban area is closely connected and is one of the important ecological function areas in the overall planning of Chizhou City. The total area of Pingtian Lake wetland is 4,290 hm^2, of which the water area is 1,100 hm^2, which is one of the important components of the lake wetland group in the middle and lower reaches of the Yangtze River. The catchment of Pingtian Lake is mainly three small rivers in the southeast direction and the disorderly runoff of the surrounding surface, and the effluent enters the old road of Qiupu River from the north-facing flood ditch, which is a typical small shallow water Lake[7].

Chizhou is the first state-level ecological and economic demonstration zone in China, and there are three major river systems in the territory, namely the Yangtze River system (Yaodu River, Huangxiang River, Qiupu River, Baiyang River, Datong River, Jiuhua River), Qingyi River system (Qingxi River, Lingyang River, Laba River) and Poyang Lake water system (Longquan River). Chizhou belongs to the northern subtropical humid monsoon climate zone[8]. The Yangtze River flows through Chizhou City for about 145 km, and its shoreline is about 162 km long. Chizhou is rich in surface water resources, which are 4 times and 2 times the average of Anhui Province and the whole country, respectively[9].

Pingtian Lake is located on the northern edge of the subtropical region and has a warm and humid subtropical monsoon climate. According to the wetland classification system of the "National Wetland Resources Survey Technical Regulations (Trial)", statistics are carried out on the basis of the second wetland resource survey in Anhui. It is believed that there are four types of wetlands in Anhui Chizhou Pingtian Lake National Wetland Park, namely lake wetlands, swamp wetlands, constructed wetlands and river wetlands; there are 6 kinds of lakes and wetlands, and there are 1 kind of wetland type of permanent freshwater lakes and 1 kind of wetland type of rivers and wetlands of rivers. There are three types of wetlands: aquaculture farms, artificial water transmission rivers, and reservoirs, and the swamp wetlands are mainly herbaceous swamps[10]. The average annual sunshine hours of Pingtian Lake are 1,730–2,100 h, and the average annual temperature is 16.1 °C. The annual temperature was the lowest in January with a range of 3.1–3.5 °C, and the highest in July with a range of 27.9–28.7 °C. The average frost-free period is 220 d[11].

3. Main functions of the Pingtian Lake wetland

3.1 Flood control

Hydrology is the most important factor in wetland environment[5]. Similarly, wetlands also affect the hydrological situation in the basin. According to research, the distribution rate of wetland in one river in the United States is 4%, and its ability to store flood is 50% higher than that in the case of wetland disappearance, while the distribution rate of wetland in another river basin is 40%, and its ability to store flood is 140% higher than that in the case of wetland disappearance[12]. Compared with the surrounding areas, the wetland of Pingtian Lake is relatively low-lying and has the function of allocating and homogenizing the river runoff in Chizhou City, which is an important part of the hydrological cycle in Chizhou City and the surrounding rural areas. Pingtian Lake wetland is close to the foot of Qishan Mountain. The lake branches with large areas and different sizes are densely distributed, and the beach soil is deep, so it has a strong ability to store water resources. At the same time, Pingtian Lake wetland is rich in plant resources, and the diversity of plant communities is obvious. It can significantly slow down the flood flow rate and reduce the flood peak, which plays an important role in effectively preventing and controlling flood disasters in the surrounding areas, especially in the downstream areas.

3.2 Irrigation of farmland

The low-lying area in the wetland area of Pingtian Lake is mainly the lake areas and the nearby residential agricultural production areas, and the existing cultivated land is 1,400 hm^2, which is planted the main things are rice (*Oryza sativa*, *Oryza glaberrima*), rapeseed (*Brassica napus*), and russet (*Zizania latifolia Stapf*), lotus root (*Nelumbo nucifera Gaertn*), corn (*Zea mays*), soybean (*Glycine max*), sweet potatoes (*Ipomoea batatas*) and so on. Pingtian Lake Wetland has a strong water transmission and water supply capacity, which can be used for farmland within the wetland area and villages around the wetlands seven natural villages, including Xiashan villages, Shunli villages, Bishan villages, Qishan Village, Yang'an Village, Baisha Village and Shishan Village, provide sufficient water for agriculture and domestic use.

3.3 Aquaculture

There are many lakes in the Pingtian Lake area, and the aquaculture industry is relatively developed, mostly based on artificial aquaculture, mainly cultivating freshwater fish, such as bighead carp (*Aristichthys nobilis*), silver carp (*Hypophthalmichthys molitrix*), carp (*Cyprinus carpio*), crucian carp (*Carassius auratus*), bream (parabramis pekinensis), yellow catfish (*Pseudobagrus fulvidraco*), etc.

3.4 Ecological landscape

Pingtian Lake is vast in smoke, the mountains around the lake are raised, the trees are verdant, the grass is full of flowers, the water spirit leaves are lush, and the forest vegetation coverage rate is 95%, which is known as "Chizhou West Lake" and "Venice of the East". The natural environment in the area is beautiful, rich in history and culture, and in history, "Pingtian Spring Rise" is one of the famous Ten Scenic Spots in Chizhou. Successive generations of literati and writers of all dynasties have traveled here to appreciate, and left many popular poems, when Li Bai wrote "Water is like a white silk, and this place is flat. You can ride the bright moon and watch the flowers on the wine boat". The history books record that Yue Fei of the Southern Song Dynasty once stationed troops in Guichi Qishan to cross the river to resist Jin, and trained sailors at Pingtian Lake. Prince Zhaoming of the Southern Dynasty fiefdom was here, and often fished by the Pingtian Lake. Guishan Island in Pingtian Lake, its shape resembles a god turtle, facing south and worshiping, is known as the god turtle worshiping Jiuhua. In 2014, Pingtianhu Wetland Park was named one of the top ten "China's most beautiful moon-viewing places" by CCTV.

The unique topography and rich biodiversity resources of Pingtian Lake Wetland have constructed a typical "landscape in the city" characteristic landscape of Chizhou City. At the same time, it is also an important object of the majority of environmental protection and scientific research workers to carry out wetland resource surveys and urban wetland resource utilization and protection research. In addition, Japanese astronomical experts have considered that it occurred in 2009 through a multi-party investigation, combining factors such as geographical location, resource environment and air quality. During the total solar eclipse on July 22, Chizhou Pingtian Lake Observation Deck is one of the best places to observe.

3.5 Leisure and fitness

With its unique geographical location and natural environment, Pingtian Lake Wetland provides local residents with good leisure and recreation and sports and fitness places, especially with the improvement of transportation facilities in the lake area, becoming a resident walking, cycling and morning running, fishing, moon viewing, entertainment good place. In recent years, the number of projects in Pingtian Lake Wetland Park for leisure and entertainment, homestay catering, sports and fitness has gradually increased, such as Pingtian Peninsula Hotel Floating restaurant, fisherman's delight, farmer's delight (leisure farm, homestay), water sightseeing cruise, tourist resort area (Shuiyunjian Villa), music square, water beach, wetland coffee bar, lake viewing pavilion, lotus terrace, etc. In 2004, the State General Administration of Sport held an international motorboat competition in Pingtian Lake, which is now designated by the State General Administration of Sport as the training base of the Aquatics Center.

4. Environmental impact factors of water resources in Pingtian Lake wetland

4.1 Municipal sewage discharge

Pingtian Lake National Wetland Park is adjacent to Chizhou Municipal Education Park (Chizhou College, Anhui Health Vocational College, Chizhou Vocational Education Center and other schools) in the east, and Chizhou City in the north. The Economic and Technological Development Zone is closely connected to Chizhou High-speed Railway Station and Chizhou Long-distance Bus Station in the south, and Pingtianhu Road and Wanluoshan Road in the main urban area of Chizhou City in the west. In recent years, the wetland waters of Pingtian Lake have passed through Baisha village bridge, Baisha No. 1 bridge, Anhui health vocational college, Chizhou college, and so on. The sewage outlet of Chizhou Transportation School accepts a large number of pollutants discharged by domestic sewage and industrial enterprises, resulting in high total phosphorus and total nitrogen indicators of lake water quality (both exceeding the water quality requirements of Class IV), showing a more serious eutrophication trend.

4.2 Rural non-point source pollution

Rural agricultural population around Pingtian Lake Wetland 1. 20,000 people, large and small livestock 17,950,000 heads, lake aquaculture water surface 732 hm^2. Farmers around the wetlands mainly make their living from crop cultivation, livestock and poultry breeding, and aquaculture. In the process of agricultural production, some farmers lack the awareness of ecological environmental protection and the concept of food safety, rely too much on chemical pesticides to control diseases and insect pests, and blindly increase the amount of pesticides and the number of sprays. The overall application of chemical fertilizers is too large, and the proportion of nitrogen, phosphorus and potassium is out of balance, the phenomenon of nitrogen fertilizer application is more common, and the application period is not reasonable[13]. The low utilization rate of chemical fertilizers and pesticides and the high rate of loss not only lead to soil pollution in farmland but also cause organic pollution to water bodies through surface runoff of farmland Eutrophication pollution and even groundwater pollution and air pollution[14]. In addition, a small number of farmers randomly sprinkle a large amount of manure, lees, etc. into the lake waters where aquatic products are cultivated, the aquaculture density is high, and the excess bait is scattered in the lake water. Some city dwellers and farmers around the lake area like to bathe and wash their clothes in Pingtian Lake, and use soap a lot. All this will accelerate the deterioration of the water resource environment of the Pingtian Lake wetland.

4.3 Project construction

Due to the lack of strict natural ecological environmental protection elements in the early engineering construction planning and design of Pingtian Lake wetland, the wetland agricultural water conservancy project in the lake area, the highway around the lake, the cultural landscape, transportation, and leisure farms. The construction of various types of projects such as homestay services, floating restaurants, and educational parks is frequent, and the contradiction between biodiversity conservation and the maintenance of the vested interests of the local people is becoming increasingly prominent[15]. The construction of various engineering projects has artificially destroyed the topography and landform in the Pingtian Lake basin to varying degrees, changed the surface runoff mode, and is difficult to communicate with the surrounding lakes and rivers, and the frequency of lake water renewal is reduced. The speed of lake water flow slowed down, and the lake sediment remained for a long time, resulting in the decline of the flood regulation and storage function of the wetland ecosystem of Pingtian Lake, and the situation of flood prevention during the flood season was grim. It also artificially destroys the balance of natural ecosystems, which is not conducive to the conservation of wetland biodiversity.

In addition, due to the construction of roads and related engineering projects in the lake area, many lakes in the wetland have been artificially isolated into "orphan ponds" (some of which are only connected by artificially set up culverts), and the runoff mode of the wetland surface has changed, the effective water area of the lake is reduced.

4.4 Tourism project development

The environmental quality of Chizhou is second to none in the central and eastern regions, and it is a national garden city, a national forest city, a national green ecological demonstration urban area and an excellent tourist city in China, and won the "Chinese Environment Award" in 2013. In recent years, the Chizhou Municipal Government has attached great importance to the construction and promotion of Pingtian Lake wetland tourism projects, focusing on the construction of Pingtian Lake Tourist Resort, and planning to build a en boardwalk in Pingtian Lake Square and Lotus Terrace. There are 4 tourist piers in Peach Blossom Island and Pingtian Peninsula, and water sports attractions include water speed boats, water walking balls, and water sports Jet skis, banana boats, water skiing, self-paddling rubber boats, self-rowing wooden boats and self-driving boats. Although the development of wetland tourism projects can help promote local economic and social development and better play the function of wetland resource service, improper management and implementation will also lead to the degradation of the self-purification function of lakes and the flow. The surface runoff mode of the inland area has changed, and the wetland habitat has been artificially destroyed, affecting the stability of the wetland ecosystem and biodiversity. For example, water activities such as water restaurants, water yachts (boats) and other water activities produce a large amount of garbage, oil, wastewater and other pollutants are directly discharged into the lake, if not properly disposed of, it will inevitably aggravate the degree of lake water pollution, and the total phosphorus and nitrogen of the lake's nutrient salts cannot flow out normally, which destroys the balance of nutrients and salts in the lake. Thus enriching in the lake area, the growth rate of algae organisms such as cyanobacteria and green algae accelerates, resulting in an accelerated process of eutrophication of lake water and poor water quality in the lake.

4.5 Artificial control of schistosomiasis

Schistosomiasis is one of the major infectious diseases that seriously endangers the health of the people and affects economic development and social stability[16,17]. Pingtian Lake was once known as the "Schistosomiasis Nest"[18]. In recent years, although schistosomiasis in the administrative villages around the Pingtian Lake wetland has been effectively controlled, some places will occasionally adopt measures such as surface hardening of the wetland and drug snail eradication, to prevents schistosomiasis from rebounding and epidemic. However, surface hardening and drug snail extermination will artificially destroy wetland habitats to varying degrees, change the way of surface runoff, and affect wetland biodiversity.

5. Water resources protection measures for Pingtian Lake wetland

5.1 Restore the topography of wetland habitats and enhance the ecological function of the lake itself

Strengthen the construction of the interconnection project between the lake and the lake within the Pingtian Lake wetland and the construction of the connection project between the surrounding rivers and lakes, restore the surface runoff mode of the wetland, increase the speed of lake water flow, reduce lake phase sedimentation, and improve the self-purification ability of lake water. Further promote and improve the ecological transformation of the Pingtian Lake embankment, the construction of the inner slope view of the embankment, the construction of the low-drainage ditch boardwalk, and the reconstruction of the Pingtian Lake Official Kiln Tsui Flood control gates and other key projects will enhance the ability of wetlands to regulate and store floods. Establish a wetland ecological buffer zone between the wetland of Pingtian Lake and the surrounding low hills (such as Qishan Mountain), pay attention to the protection of wetland habitat diversity, and gradually restore and enrich the overall ecological function of Pingtian Lake wetland. The barge of the lake body should adopt the method of natural barge as much as possible, and advocate the extensive use of aquatic plant barges and grass slopes into the water barge, so as to absorb pollutants and reduce the flow rate of surface runoff[19].

In addition, the Wetland of Pingtian Lake often appears invasive alien plants, such as Canada's "Yellow Flower", etc., and the wetland management department should strengthen the inspection of the natural biodiversity of the wetland. Invasive alien plants should be treated in a timely manner by a combination of artificial removal and chemical control to ensure the ecological safety of wetlands.

5.2 Promote modern ecological agricultural technology and reduce non-point source pollution in rural agriculture

Pingtian Lake wetland surrounding Xiashan village, smooth village, Bishan village, Qishan village, Yang'an village, Baisha village, Shishan village and other rural areas to strengthen wetland protection knowledge propaganda, enhance farmers' awareness of wetland ecological environment protection. Strengthen the modern ecological agriculture technology training service, guide the wetland farmers scientific and safe application of pesticides and fertilizers. In accordance with the relevant requirements of wetland protection, it is necessary to strictly control the scale and methods of poultry, livestock and aquaculture. Put feeds and bait scientifically, properly dispose of animal manure, breeding waste and other pollutants, prohibit unauthorised throwing of manure, distiller's grains, etc. into lake waters, and minimize non-point source pollution in wetland and rural agriculture.

In addition, for a small number of areas prone to schistosomiasis, it is necessary to strengthen the training and business guidance of drug snail control technology, and minimize the artificial hardening of the wetland surface due to the prevention and control of schistosomiasis.

5.3 Take the construction of "sponge city" and the centralized treatment of the environment as an opportunity to strictly control the discharge of urban sewage and corporate pollutants

"Sponge city" means that the city can be like a sponge, in adapting to environmental changes and responding to natural disasters and other aspects of good "elasticity", when it rains, absorb, store, seep, purify water, and "release" and use the stored water when necessary[20]. Chizhou is one of the first batch of national-level "sponge city" construction pilot cities in China, along with the "sponge city". The development of construction, combined with the centralized treatment of the environment, the overall ecological environment of Chizhou City has been significantly improved. The management department of Pingtian Lake Wetland should seize the opportunity of the construction of "sponge city" and centralized environmental governance, consolidate and expand the achievements of sponge city construction and centralized environmental governance, and increase the transformation of urban sewage treatment facilities. Optimize the layout of the regional industrial structure, strictly control the discharge of pollutants by enterprises, curb the pollution of water resources in Pingtian Lake from the source, and make the water quality conditions of the wetlands of Pingtian Lake meet the basic requirements of the water function area. Accelerate the construction of ecological ditches, and use plants in ecological ditches to absorb surplus nutrients in wetland runoff. For algae organisms such as cyanobacteria and green algae that thrive in large quantities in the waters of some lakes, the means of moderately increasing the stocking of algae-eating fish such as bighead carp and silver carp can be adopted. Reduce the distribution of algae organisms in the lake and improve the quality of water resources in the lake.

5.4 Innovate the wetland ecological compensation system and increase the protection of wetland water resources

Ecological compensation is one of the important means to protect wetland biodiversity. Pingtian Lake National Wetland Park should strictly implement the "Interim Measures for Ecological Compensation of Surface Water Sections in Chizhou City"[21], insisting the principle that "who exceeds the standard, who pays, who benefits, who compensates", pay attention to the decisive role of the market in the allocation of resources, and widely introduce society groups and citizens, as well as special funds for wetland biodiversity conservation from various sources outside the region, gradually improve and innovate the ecological compensation mechanism for wetlands in Pingtian Lake. It is necessary to guide residents and enterprises around the wetland to consciously abide by the wetland ecological compensation system, rationally develop and utilize the ecological resources of the wetland, and promote the harmonious development of man and nature[22]. It is necessary to increase the daily inspection of wetland water resources protection and the publicity of the legal system, and prohibit unauthorized reclamation, illegal discharge of pollutants, illegal establishment of enterprises, and unauthorized raising of poultry and livestock in the Pingtian Lake wetland. Illegal drug fishing and other acts of artificial destruction of the ecological environment of wetlands. Strengthen the management of river and lake shorelines and river floodplains, implement the return of fields to lakes and the return of fields to wet, strictly prohibit encroachment on the ecological space of rivers and lakes, and orderly promote the recuperation of rivers and lakes[23].

5.5 Strictly abide by the red line of ecological protection, and implement wetland water resources management in accordance with laws and regulations

Delineating the red line of ecological protection and implementing the strictest ecological control strategy is the need to implement the spirit of the 18th and 19th National Congresses of the Communist Party of China. Scientifically and rationally delineating ecological redlines and strictly controlling ecological redline areas are important contents and inherent requirements for the construction of ecological civilization in China's new era, and are also the most important tough means and arduous tasks for protecting regional ecological environment and biodiversity[24]. On June 27, 2018, the People's Government of Anhui Province officially issued the "Anhui Province Ecological Protection Red Line". The total area of ecological protection redlines in Anhui Province is stipulated to be 21,233.32 km^2, accounting for about 15.15%, including 16 precincts in three categories[25], including Chizhou Pingtianhu National Wetland Park. Pingtianhu National Wetland Park and relevant government departments of Chizhou City should strictly abide by the red line of ecological protection, strengthen communication and coordination between departments, and balance the relationship between the development and utilization of all parties and the protection of interests. To implement the wetland ecological control system according to local conditions, we can establish an incentive and constraint mechanism for the utilization of water resources in combination with the current river chief system, and consolidate the responsibility for the management of wetland water resources. Ensure that the development, utilization and protection of water resources in the Pingtian Lake wetland are carried out in an orderly manner. It is possible to explore the establishment of a unified water resources database for the Pingtian Lake wetland and even the entire Anhui River wetland, and coordinate water conservancy, environmental protection, transportation, and transportation. Hydrology and other government departments and relevant scientific research institutions data, the use of big data technology, the water quantity, quality, and spatial distribution of water resources to carry out timely monitoring and data updates, the establishment of the real-time monitoring system, provide fast and effective services for the utilization and protection of wetland water resources and the protection of the natural ecological environment.

6. Conclusion

The utilization and protection of the water resources of Pingtianhu National Wetland Park are of great significance to the conservation of biodiversity along the river in China and have a positive role in promoting the construction of ecological civilization in Chizhou City and even Anhui Province. The government department where Pingtian Lake is located needs to effectively increase the sense of responsibility, and learn from the experience of wetland water resources utilization and protection in large national nature reserves such as Shengjin Lake and Poyang Lake nearby, and use modern information technology means. Organize special forces to carry out in-depth research on the utilization and protection of wetland water resources, and constantly explore new paths for the utilization and protection of wetland water resources in Pingtian Lake.

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Conflict of interest

The authors declared no conflict of interest.

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ORIGINAL RESEARCH ARTICLE

Research on water resources protection system in Minjiang River basin in the new period

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ABSTRACT

This paper put forward the idea of formulating the water resources protection system of the basin in the new period based on the new situation and new requirements. Taking the Minjiang River basin as the research object, taking its outstanding environmental problems as the guide, and taking the ecological function positioning of the basin as the basis, this paper proposed the water resources protection system of the Minjiang River basin under the new situation of ecological civilization construction.

Keywords: Water Resources Protection; Three Lines and One Single; Ecological Civilization; Spatial Planning; Comprehensive Basin Planning

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1. Introduction

Since the reform and opening up, China's economic and social development has made world-renowned achievements, but also paid a huge environmental price. In the past, we first had to solve the problem of "food and clothing", and some of the development and construction units had poor awareness of environmental protection and a weak concept of the legal system, and the pursuit of economic benefits was their first priority. The 19th Party Congress proposed that socialism with Chinese characteristics has entered a new era. At this stage, China should vigorously promote the construction of ecological civilization, carry out the pilot project of "multi-regulation", unify the planning system, and take the green development road of "ecology first". Under the new situation of ecological civilization in the new era, the direction of water resources development in the river basin is to lead economic and social development by planning, with ecological priority as the premise of planning and "three lines and one list" as the constraint[1-3].

Due to the disorderly development of small hydropower in Minjiang River, unreasonable utilization of water resources and insufficient supervision in the past, many environmental problems have been left in Minjiang River basin[4-6], and the protection of water resources in the process of development and utilization in the basin is more urgent and important[7]. This paper takes the Minjiang River basin as a case study, analyzes the outstanding environmental problems in the Minjiang River basin, combines the requirements of the new situation of ecological civilization, and proposes a water resource protection system for the Minjiang River basin in the new era based on the ecological function positioning of the basin, provides theoretical guidance for comprehensive planning and planning environmental assessment of the basin, and provides technical support for the development, utilization and protection of water resources in the basin. According to the analysis, the Minjiang River basin mainly has outstanding ecological and environmental problems, such as the ecological flow of some sections does not meet the requirements, the quality of water environment in the middle reaches of the river does not meet the standards, and the aquatic biological resources are seriously damaged. In view of the above environmental problems and causes, and based on the new situation of ecological civilization, the Minjiang River basin water resources protection should be led by planning, with ecological priority as the premise, "three lines and a list" as a constraint, coordinate the system management of watershed mountains, forests, fields, lakes and grasses, and strengthen the supervision of water resources development.

2. Minjiang River basin overview and data selection

The Minjiang River is a first-class tributary on the left bank of the upper reaches of the Yangtze River, originating at the southern foot of Minshan Mountain at the junction of Sichuan and Gansu Provinces, and after the Minjiang River, Dadu River and Qingyi River converged at Leshan City, its flow direction turns southeast and finally joins the Yangtze River at Yibin City. The Minjiang River basin covers an area of 135,400 km^2, involving Qinghai and Sichuan provinces, with a total length of 735 km, divided into upper, middle and lower reaches by Dujiangyan and Dadu estuary, with an average annual flow of 3,022 m^3/s at the estuary, and its main tributaries being Dadu River and Qingyi River. The construction of water conservancy and hydropower projects in the basin has changed the natural runoff process of the river[8], and with the intensification of human activities, a series of ecological and environmental problems have been triggered.

The hydrological stations of Zhenjiangguan, Pengshan and Gaochang in the main stream of Minjiang River were selected as representative stations in the upper, middle and lower reaches of the main stream, and the measured hydrological information of the three stations from 1957 to 2016 was selected as the basic data information, combined with the report on the ecological and environmental conditions of Sichuan Province from 2012 to 2017, so as to analyze the main ecological and environmental problems in the Minjiang River basin.

3. Outstanding ecological and environmental problems in the Minjiang River basin

The Minjiang River basin is an important part of China's "two screens and three belts" and an important ecological protective screen in the middle and lower reaches of the Yangtze River; it is also a major area for maintaining forests, grasslands and biodiversity in China; the lower reaches of the Minjiang River are an important channel for fish migration and exchange between the Minjiang River system, the Jinsha River and the Yangtze River system.

3.1 Serious ecological degradation in the upper reaches of the Minjiang River

Due to its special geographical conditions, coupled with the influence of the "foehn effect", the river valley has a dry climate, poor soil, low vegetation cover, fragile ecological environment, and difficult to restore vegetation[9]. Since modern times, unreasonable farming methods, overgrazing and logging, and geological disasters have seriously damaged the regional vegetation, reduced forest cover, destroyed alpine meadows, reduced water-holding capacity, resulting in serious soil erosion.

3.2 Some sections in the upper and middle reaches do not meet the ecological baseflow control objectives

The hydropower station of the upper reaches of the main stream of the Minjiang River are mainly small hydropower plants with high head and low gate dams, and existing hydropower development does not pay enough attention to ecological environmental protection, and the river takes continuous diversion development, which causes unreasonable scheduling when considering the release of ecological flow, resulting in low flow in the downstream river during the dry period in some periods, and even leading to partial disconnection of flow in some sections of the river. This has led to environmental degradation[5]. In recent years, with the improvement of environmental protection requirements, the situation of partial disconnection in the upper reaches of the main stream of Minjiang River has been ameliorated. From the actual annual average flow process of Pengshan hydrological station from 1957 to 2016 (**Figure 1**), the flow at Pengshan station has shown an obvious decreasing trend in the past 60 years, which is related to the gradual decrease of incoming water from the upper reaches and the gradual increase of water consumption in the middle reaches.

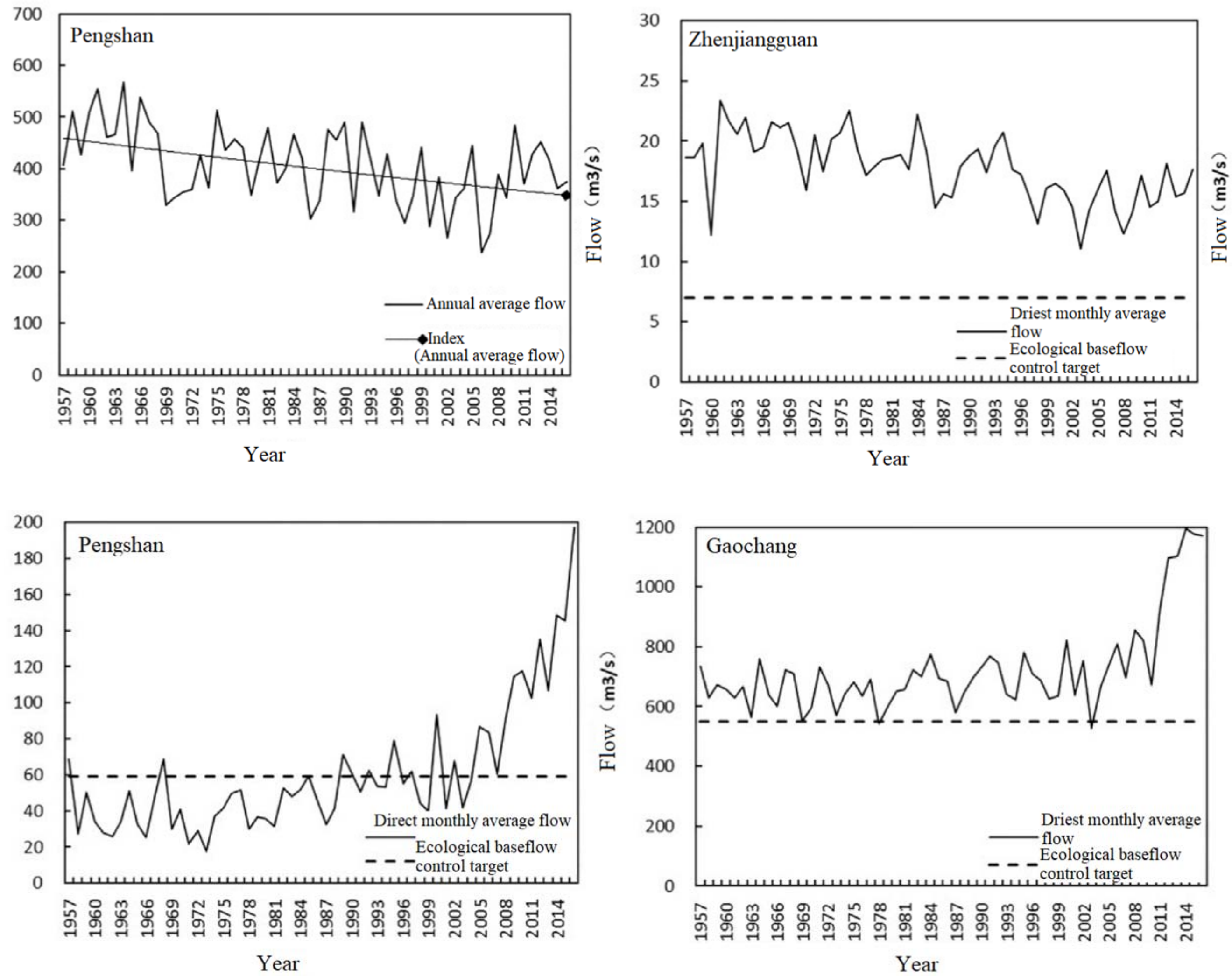

Figure 1. The average flow and the average flow of the driest month from 1957 to 2016 at the main hydrological stations of the Minjing River main stream.

According to the *Comprehensive Plan for Water Resources in the Yangtze River Basin*, the *Comprehensive Plan for the Yangtze River Basin*, and the *Comprehensive Plan for the Minjiang River Basin*, the ecological baseflow control targets for the Minjiang River mainstem cross-sections at Zhenjiangguan, Pengshan, and Gaoba are 7 m^3/s, 59 m^3/s, and 551 m^3/s respectively. The most depleted monthly flow at the upstream Zhenjiangguan and downstream Gaochang cross sections can mostly meet the ecological baseflow requirements, while the most depleted monthly flow at the midstream Pengshan station in most years before 2004 cannot meet the ecological baseflow control target requirements, and the unsatisfied period is mainly concentrated in the dry period from February to April. After Zipingpu Power Station was put into operation in 2006, due to its regulating effect, the discharge flow of Pengshan hydrological station in each month increased significantly compared with previous years, and all of them could meet the ecological baseflow requirements.

On the one hand, because almost all the water from the upper reaches of the Min River enters the Chengdu plain through the Dujiangyan intake during the dry period, causing the flow of Jinma River to reduce or even cut off during the dry period. The construction of Zipingpu has solved the problem of Jinma River cutting off due to the reserved ecological flow. On the other hand, the middle and lower reaches are the economic core area of the basin, and with the economic and social development and the continuous expansion of the population scale, the demand for water resources grows year by year. At the same time, the midstream area is distributed with several large and medium-sized irrigation areas such as Dujiangyan and Tongjiyan, and the continuous expansion of the irrigation area leads to a significant increase in agricultural water consumption. This has all led to a decrease in water resources in the middle reaches of the Minjiang River, and some sections do not meet the ecological base flow control target requirements. In recent years, these phenomena have been ameliorated, but with the accelerated construction of Chengdu Economic Zone and Tianfu New Area, the demand for water resources in the middle and lower reaches will further increase.

3.3 Low compliance rate of water environment quality in the midstream stem and tributaries

According to the bulletin of the state of the environment of Sichuan Province, from 2012 to 2017, the overall water quality of the main streams of the Minjing River was lightly polluted, and the overall water quality of the tributaries was moderately polluted[10]. From 2012 to 2017, the overall water quality of the Minjiang River stem and tributaries showed improvement, with a significant increase in the rate of water quality compliance in the stem and a small increase in the rate of water quality compliance in the tributaries (**Figure 2**).

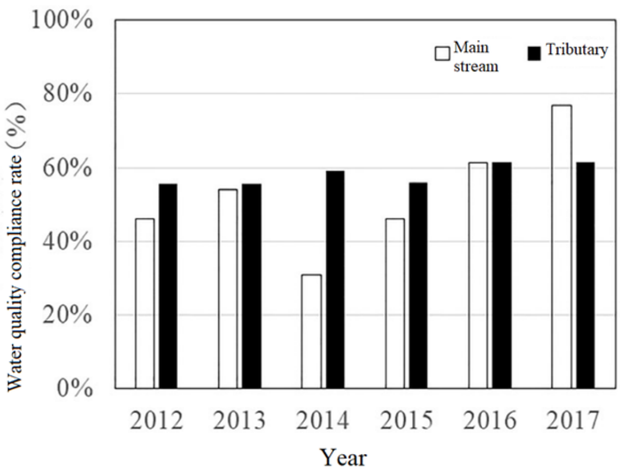

Figure 2. Minjiang River system dry and tributary water quality standards attainment rate in 2012–2017.

The proportion of class III and above of water bodies increased from 55.5% in 2012 to 66.60% in 2017, and the proportion of inferior V ter bodies decreased from 17.50% in 2012 to 10.30% in 2017 (**Figure 3**). Water quality pollution in the mainstem is mainly concentrated in the midstream section of the river from the exit of Chengdu to the entry of Leshan, which is mainly polluted by total phosphorus, and some river sections have chemical oxygen demand and ammonia nitrogen pollution. The tributaries Xinjin South River, Jinniu River, Simeng River and Mangxi River are heavily polluted, and Fu River is moderately polluted, with the main pollution indicators being total phosphorus, ammonia nitrogen and chemical oxygen demand.

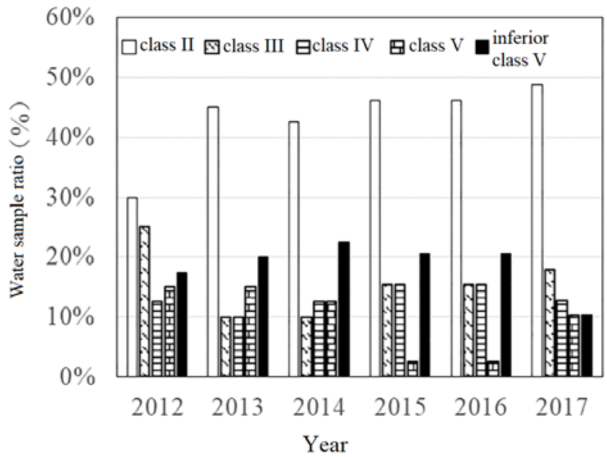

Figure 3. Proportion of water quality categories in the Minjiang River system from 2012 to 2017.

Insufficient water resources and high pollution intensity in the middle reaches of the Minjiang River are the main causes of water environment pollution in the middle reaches. The incoming water of the upstream of Minjiang River decreased year by year. Especially during the dry season, the cross sections such as Pengshan cannot guarantee the ecological base flow control target, and there were breaks of the flow in Fu River and Nan River, leading to the deterioration of water quality. The middle and lower reaches are the core economic areas of the basin, and the large amount of domestic sewage and industrial wastewater discharged from the cities along the river has led to the pollution of the water environment in the middle and lower reaches of the Minjiang River, with domestic pollution dominating in Chengdu and industrial pollution in Meishan and Leshan.

3.4 Serious damage to aquatic biological resources in the basin

The aquatic biological resources in the Minjiang River basin have been severely damaged under the impact of small hydropower development in the upper reaches of the river, water reduction and water pollution problems in the middle reaches, and human disturbance in the lower reaches, and the impact of development of the Dadu and Qingyi rivers. From the whole Minjiang River basin, the national level I protected fish, white sturgeon and Chinese sturgeon have been extinct for many years, except for Dacian sturgeon, which is occasionally caught in the lower reaches of Minjiang River. The second-class protected fish, the Sichuan-Shaanxi Churro salmon, has been extinct in the upper reaches of the Minjiang River and the Qingyi River, and has also retreated to the depopulated zone above kyom-kyo tributary of the Dadu River, and is on the verge of extinction; the coelacanth has also not been caught for many years. Minjiang mainstem long thin loach, golden sand loach and other drifting egg-producing fish spawning grounds may have historically been distributed in the lower reaches of the river below Wenchuan and Mao county. At present, the Minjiang mainstem drifting egg-producing spawning grounds have retreated to the lower reaches of the Dadu River estuary.

4. The development ideas of watershed water resources protection system in the new era

The watershed water resources protection system in the new era should fully absorb the defects in the process of watershed water resources development and utilization in the previous stage, based on the functional positioning of the watershed, take the outstanding environmental problems existing in the watershed as the target, and examine the watershed water resources development and protection with new requirements and views[11–13]. Firstly, a scientific comprehensive basin plan is used as a guide to avoid environmentally sensitive factors from the source; secondly, the system management of mountains, water, forests, fields, lakes and grasses is proposed to coordinate the ecological and environmental problems with the content of the plan; thirdly, the supervision of the implementation of the basin plan and the system management measures is strengthened to ensure that the water resources development and utilization strictly abide by the red line of ecological protection, the bottom line of environmental quality and the upper limit of resource development and utilization in the basin (**Figure 4**).

4.1 Improve water resources protection system with planning as the leader

With national development planning as the leader, spatial planning as the basis, based on the new situation, new tasks and new requirements, we should make scientific preparation of comprehensive basin planning, improve the basin water resources protection system, so as to provide strong support for the development and protection of basin water resources. Basin water resources development should be led by comprehensive basin planning. Clarify the functional positioning of comprehensive basin planning and basin environmental protection and development positioning, take the spatial planning as the basis, comprehensively map the basin's territorial space background conditions, fully consider the basin's ecological function status and resource and environmental constraints. Scientifically delineate the basin's ecological space, develop the "three lines and one list", strictly adhere to the ecological protection red line, environmental quality bottom line and resource development and utilization limit line. Strengthen the control of space and major control lines, promote the comprehensive planning of the basin and planning environmental assessment to the ground, formulate and optimize the development pattern from the planning level, and avoid environmentally sensitive areas.

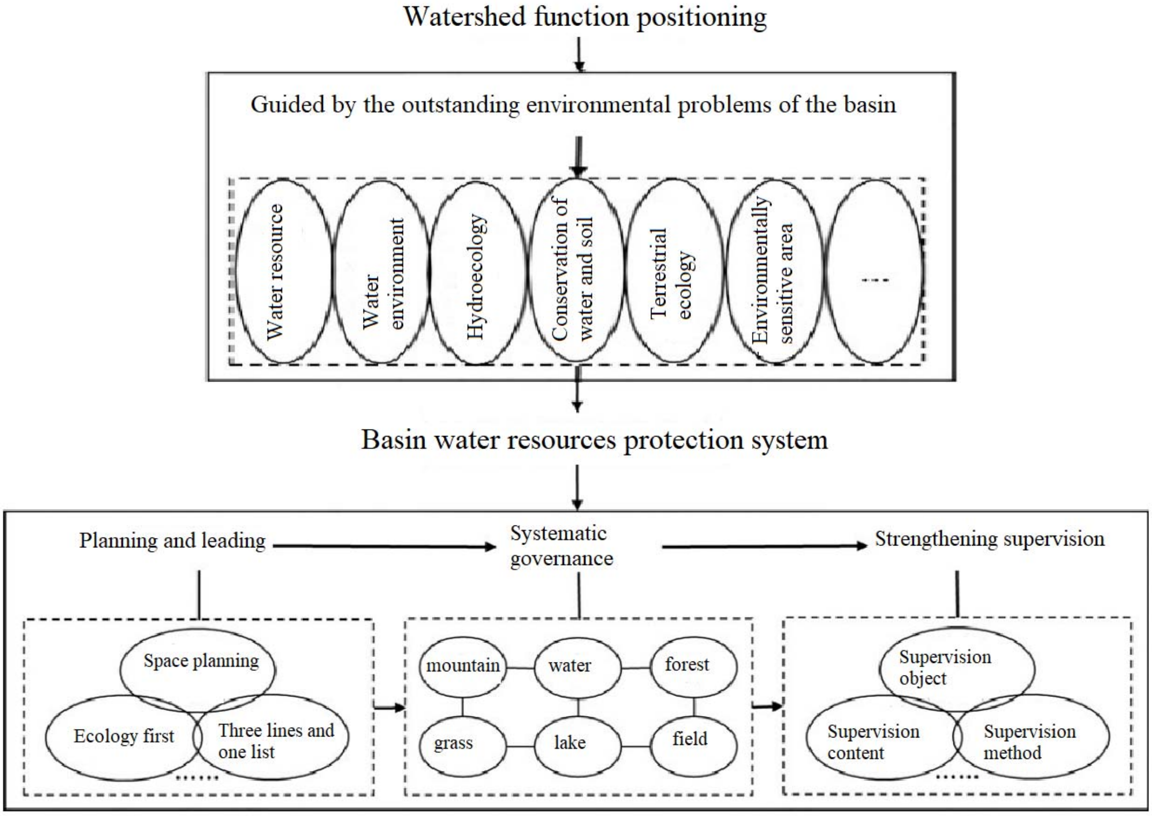

Figure 4. Basin water resources protection system structure chart.

4.2 Systematic governance of mountains, water, forests, fields, lakes and grasses to ensure ecological security

We analyze the outstanding ecological and environmental problems in the watershed in terms of water resources conditions, water environment quality, aquatic ecological environment, soil erosion management, water connotation function and biodiversity maintenance function, and the protection status of ecologically fragile areas and environmentally sensitive areas. Based on the positioning of ecological functions in the watershed and oriented by the outstanding ecological and environmental problems, we will fully consider the integrity of the ecosystem, coordinate the systematic governance of mountains, water, forests, fields, lakes and grasses in the basin, and do a good job of water resources protection planning, water environment management planning, water ecology restoration planning and soil and water conservation planning in the watershed.

4.3 Strengthen the supervision of major environmental protection measures with great efforts

In response to various outstanding ecological and environmental problems caused by historical watershed development, develop and introduce appropriate work methods for supervision of water resources management, clarify the main objects of supervision, supervision content and supervision methods, etc., continuously improve the capacity and level of water resources supervision, so as to ensure that the development and utilization of water resources in the watershed strictly adhere to the ecological protection red line, the bottom line of environmental quality and the limit line of resource development and utilization. Thoroughly implement the environmental access list, strengthen supervision, and guarantee ecological security of the basin, achieving sustainable use of water resources.

5. Minjiang River basin water resources protection system

5.1 Scientific preparation of the Minjiang River basin comprehensive plan, highlighting its leading role

During the preparation of the Minjiang River basin comprehensive plan, the primary goal should be to maintain its function as an important ecological protective screen in the upper reaches of the Yangtze River. Based on the functional and ecological positioning of the Minjiang River basin, the ecological space of the basin should be delineated, and “three lines and one list” should be formulated to improve the water resources protection system of the Minjiang River basin. The ecological space of Minjiang River is divided into four types: priority protection, key protection, treatment and restoration, and guided development[14], in which the priority and key protection waters are mainly distributed in the upstream and downstream of the main stream of Minjiang River, and the water environment treatment and restoration waters are concentrated in the middle reaches of the main stream; the priority and key protection areas are mainly distributed in the upstream area of Minjiang River, and the middle and downstream areas are the key areas for economic and social development and the main agricultural products. In 2030, the attainment rate of the main control index of the water function area in the basin will reach 92% or more, and the ecological base flow control targets of 7.4 m^3/s, 15 m^3/s and 551 m^3/s should be met at Zhenjiangguan, Jinma River outer river control gate and Gaochang cross section respectively.

5.2 Taking highlighting ecological and environmental issues as the guide, put forward the Minjiang River basin water resources protection layout

In view of the prominent environmental problems of ecological fragility in the upper reaches, water shortage and serious water pollution in the middle reaches, and high requirements for water ecological protection in the lower reaches, the layout of water resources protection in the upper, middle and lower reaches of the Minjiang River basin is proposed respectively. Upstream focus on strengthening the construction and conservation of water-containing forests, managing soil erosion, scientific scheduling, ensuring the flow of water discharge, and restoring aquatic habitats. The middle reaches should strengthen industrial structure adjustment and urban sewage treatment plant construction, and strengthen pollution control of the South River, Fu River, Mangxi River and other tributaries; scientifically carry out water dispatching to guarantee the ecological water volume of the rivers; strengthen water conservation, carry out water-saving renovation of irrigation areas, and improve irrigation water utilization coefficient. Downstream focus on strengthening the water ecology protection and restoration to protect the Minjiang River system and the Jinsha River and Yangtze River system of fish migration channel. Strengthen the tributaries Dadu River and Qingyi River water conservancy project scheduling and ecological downstream water monitoring and management; strictly implement the total discharge control program for water function areas into the river.

5.3 Strengthen the ecological water security and water environment management supervision in the Minjiang River basin

During and after the implementation of the Minjiang River comprehensive plan, the main regulatory objects and contents include: ecological water security measures, soil erosion control measures and aquatic habitat restoration measures in the upper reaches; water environment management measures and ecological water security measures in the middle reaches; downstream hydropower development and channel improvement projects on the aquatic habitat disturbance control and restoration measures, etc.

6. Conclusion

The water resources protection system of the basin in the new period should be led by planning, coordinate the system management of mountains, water, forests, fields, lakes and grasses, and strengthen the supervision of major environmental protection measures.

The prominent ecological and environmental problems in the Minjiang River basin are ecological degradation in the upper reaches, short water resources and serious water pollution in the middle reaches, and damage to aquatic habitats in the basin, which are mainly caused by historical disorderly development, neglect of ecological environmental protection, and lack of environmental supervision.

The Minjiang River basin water resources protection system should first be based on the new situation and new requirements. The scientifically prepare the Minjiang River basin comprehensive planning and planning environmental assessment, so as to avoid environmentally sensitive areas from the planning level; on this basis, focus on strengthening the ecological water security measures in the upper and middle reaches, water pollution prevention measures in the middle reaches, aquatic ecological protection measures in the lower reaches and the corresponding environmental supervision.

Conflict of interest

The authors declared no conflict of interest.

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ORIGINAL RESEARCH ARTICLE

Spatial and temporal distribution and utilization of water resources in Guangxi and suggestions for their protection

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ABSTRACT

The spatial distribution characteristics of surface water and underground water resources in Guangxi were discussed. The temporal variation trend of surface water and groundwater resources and the present situation of water resources exploitation and utilization in Guangxi in recent 10 years are analyzed. This paper points out the problems of water pollution in the exploitation and utilization of water resources, and puts forward some suggestions on water resources protection and water pollution control in Guangxi.

Keywords: Water Resources; Development and Utilization; Water Pollution; Water Resources Protection; Guangxi

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1. Introduction

Water is a very important kind of natural resource, an organic part of a country's comprehensive national strength, and one of the most important resources indispensable for human survival and development. China's per capita water resource is only 2,300 m^3, only 1/4 of the world's average level, and China is one of the countries with the most shortage of water resources per capita in the world[1]. Central water conservancy work conference in 2011 put forward to make saving water as the strategic fundamental measures to solve the problem of China's water resources, focus on the strictest water resources management system, speed up to establish three red lines of control and utilization of water resources, controlling efficiency of water use, controlling pollution in water function area. Saving water was carried throughout the economic and social development and the whole process of the masses life and production[2].

Guangxi is located in South China with a land area of 236,700 km^2, including mountains 53.1%, hills 21.7%, plains 22.4% and water 2.8%[3]. The land borders beibu Gulf in the south and faces Southeast Asia. The continental coastline is about 1,595 km. Guangxi has a humid climate and abundant rainfall; the Xijiang River system flows from west to east and the land water network criss-crosses. Guangxi is not only rich in surface water resources, but also abundant in underground water resources; the total and per capita water resources are in a leading position among all provinces in China, and Guangxi is one of the important water sources in the South-to-North Water Diversion Project in China. Therefore, it is of great significance to protect Guangxi water resources.

2. Spatial and temporal distribution of surface water resources in Guangxi

2.1 Spatial distribution characteristics and rules of surface water resources

According to the Water Resources Bulletin of Guangxi Zhuang Autonomous Region in 2016, the total reserve of surface water resources in Guangxi is 217.7 billion m^3[3]. In terms of the amount of surface water resources of the 14 prefecture-level cities in Guangxi District, the total amount of water resources of Guilin is the largest, about 41.9 billion m^3. Hechi City is about 31.5 billion m^3; Liuzhou is about 21 billion m^3; Hezhou is about 16.9 billion m^3; Yulin is about 14.7 billion m^3; Wuzhou is about 13.6 billion m^3; Baise is about 13.1 billion m^3; Nanning is about 12.2 billion m^3; Laibin is about 12.1 billion m^3; Qinzhou is about 11.7 billion m^3; Guigang is about 10.3 billion m^3; Chongzuo is about 8.15 billion m^3; Fangchenggang is about 7.29 billion m^3; Beihai has the smallest total amount of water resources, about 3.4 billion m^3[3].

Guangxi is further divided into Eastern Guangxi according to its geographical location, including Hezhou, Yulin and Wuzhou; Southern Guangxi: Beihai, Fangchenggang, Qinzhou; Western Guangxi: Baise, Chongzuo; Northern Guangxi: Liuzhou, Guilin, Hechi; Central Guangxi: Nanning, Laibin, Guigang. As shown in **Figure 1**, the total water resources in the north of Guangxi reach 94.4 billion m^3, the total water resources in the east of Guangxi reach 45.2 billion m^3, the total water resources in Central Guangxi reach 34.6 billion m^3, the total water resources in Southern Guangxi reach 22.46 billion m^3 and the total water resources in Western Guangxi reach 21.25 billion m^3[3]. It can be seen that the spatial distribution of total surface water resources in Guangxi is uneven, showing a pattern of more in the north and less in the south, more in the east and less in the west[4].

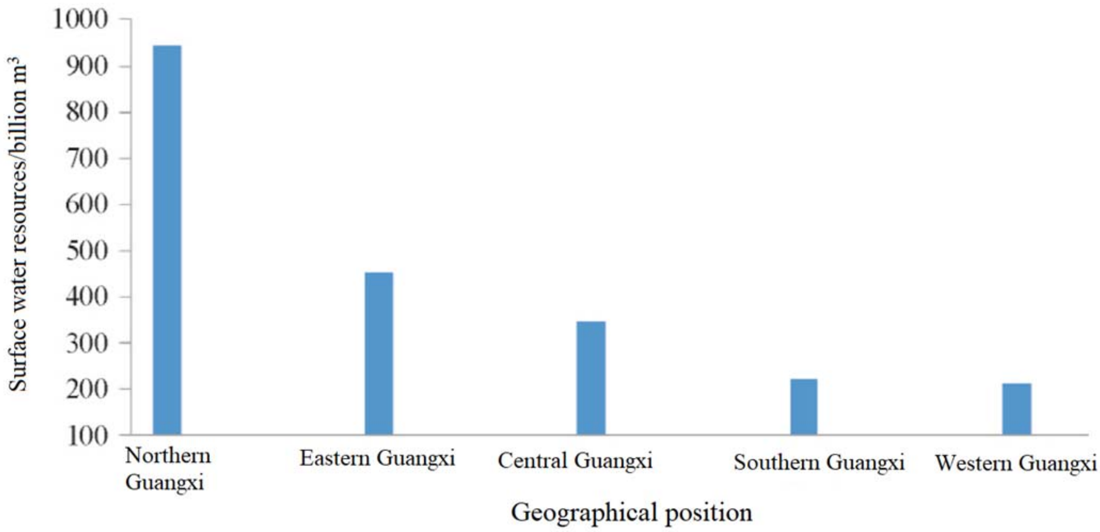

Figure 1. Distribution of surface water resources in Guangxi.

2.2 Temporal distribution characteristics and rules of surface water resources

As can be seen from **Figure 2**, surface water resources in Guangxi have been on the rise in the past 10 years, with an average annual resource amount of 200.58 billion m^3. The total water resources in 2009, 2010, 2011 and 2014 were lower than the average, while the total water resources in other years were higher than the average. The surface water resources of Guangxi was the least in 2011 with 135 billion m^3, and it was the most in 2015 with 243.2 billion m^3[5]. Therefore, the temporal distribution of surface water resources is also uneven.

Another characteristic of the distribution of surface water resources is that the change of surface water resources is basically the same as that of total precipitation, and the surface water resources are relatively abundant in years with abundant precipitation, and vice versa. The correlation analysis between the amount of surface water resources and the rainfall data from 2008 to 2016 was conducted[3–12], and the correlation coefficient between the two was 0.973, greater than the critical value of 0.764 (α = 0.01), indicating a significant correlation between the two.

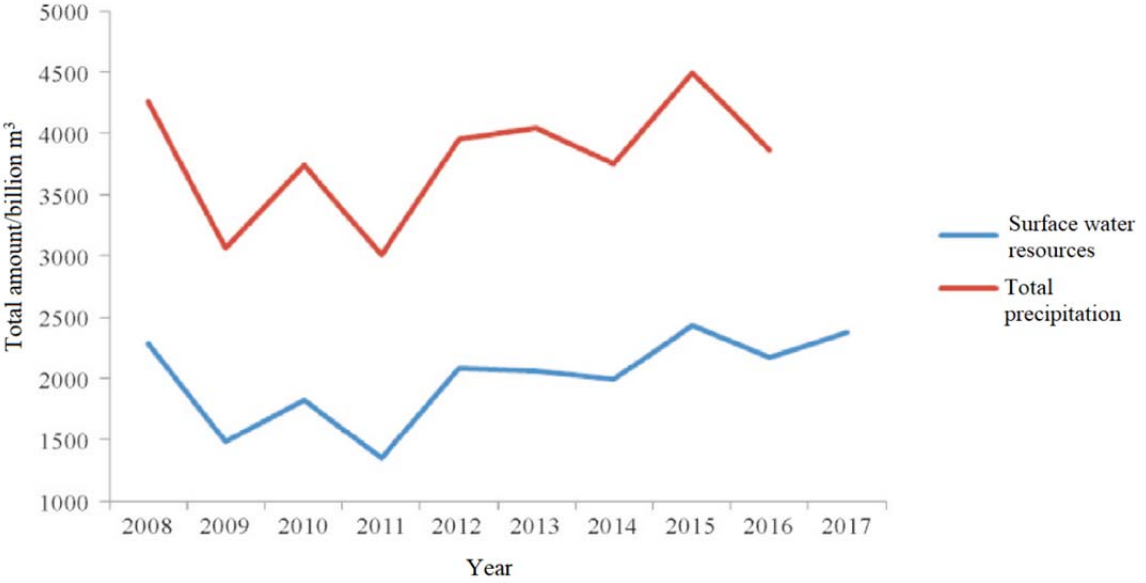

Figure 2. Annual distribution curve of surface water resources and precipitation in Guangxi.

The surface rivers in the area are divided into four river drainage area systems. In the Xijiang river system of Pearl River basin, there are mainly Hongshui River, Qianjiang, Xunjiang, Yujiang, Liujiang and Guijiang River and He River, whose watershed area accounts for 85.8% of the total area of Guangxi; the Dongting Lake system of the Yangtze River basin is mainly composed of the upper reaches of Xiangjiang River and Zishui River, whose basin area accounts for 3.5% of the total area of Guangxi; Baidu River belongs the red River system, which only accounts for 0.7% of the total area of Guangxi. The coastal rivers of South Guangxi and the river sources of Western Guangdong, which belong to the coastal basins of South China, account for about 10% of the total area of Guangxi[1].

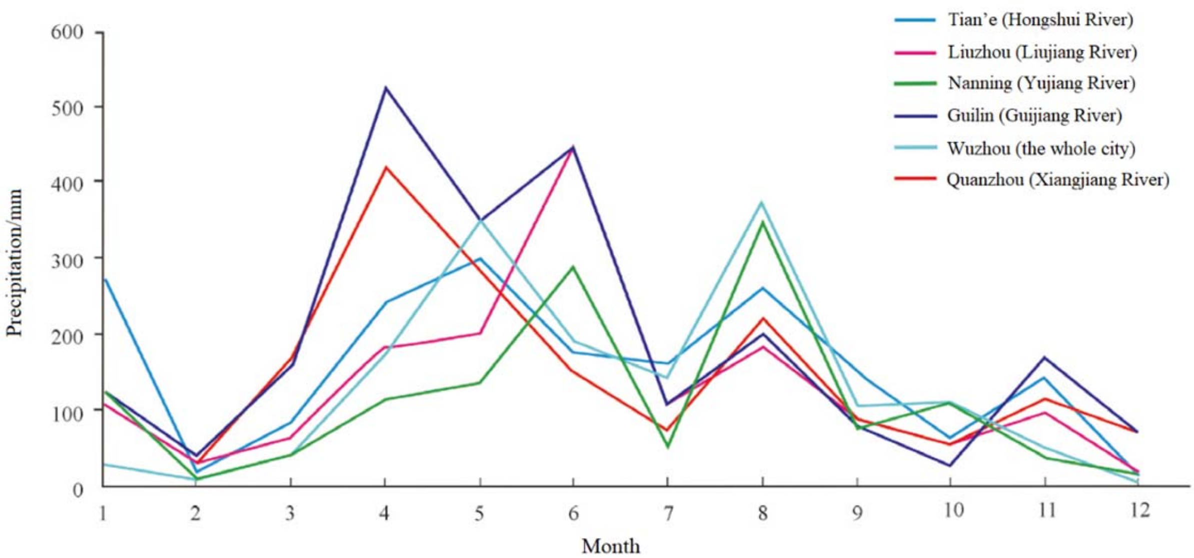

Figure 3. Comparison of monthly precipitation in major rivers in 2016.

Figure 3 shows that the amount of surface water resources in the same year also keeps changing. The water resource reserves are the largest in April and the smallest in October. Therefore, April to June can be divided as the wet season, the surface water resources are relatively sufficient, October to December can be divided as the dry season, and the surface water resources are relatively scarce.

3. Spatial and temporal distribution of groundwater resources in Guangxi

3.1 Spatial distribution characteristics and rules of groundwater resources

According to the water resources bulletin of Guangxi Zhuang Autonomous Region in 2016, the total reserves of groundwater resources in Guangxi are 52.9 billion m^3. According to the statistics of city as units, the total amount of groundwater resources of the 14 prefecty-level cities in Guangxi Zhuang Autonomous Region is ranked as follows. The total value of water resources in Guilin is the largest, about 9.81 billion m^3; Hechi is about 6.39 billion m^3; Liuzhou is about 4.58 billion m^3; Yulin is about 4.55 billion m^3; Baise is about 4.44 billion m^3; Hezhou is about 4.02 billion m^3; Nanning is about 3.59 billion m^3; Qinzhou is about 2.86 billion m^3; Laibin is about 2.57 billion m^3; Wuzhou is about 2.47 billion m^3; Guigang is about 2.34 billion m^3; Chongzuo is about 2.34 billion m^3; Fangchenggang is about 1.89 billion m^3; the North Sea has the smallest total water resources, about 1.09 billion m^3[3].

As shown in **Figure 4**, the total amount of groundwater resources in Northern Guangxi reaches 20.78 billion m^3. The total water resources of Eastern Guangxi are 11.04 billion m^3, Central Guangxi 8.5 billion m^3, Western Guangxi 6.78 billion m^3 and Southern Guangxi 5.84 billion m^3. It can be seen that, consistent with the distribution characteristics of surface water, the spatial distribution of total groundwater resources in Guangxi also presents a pattern of more in the north and less in the south, more in the east and less in the west[4].

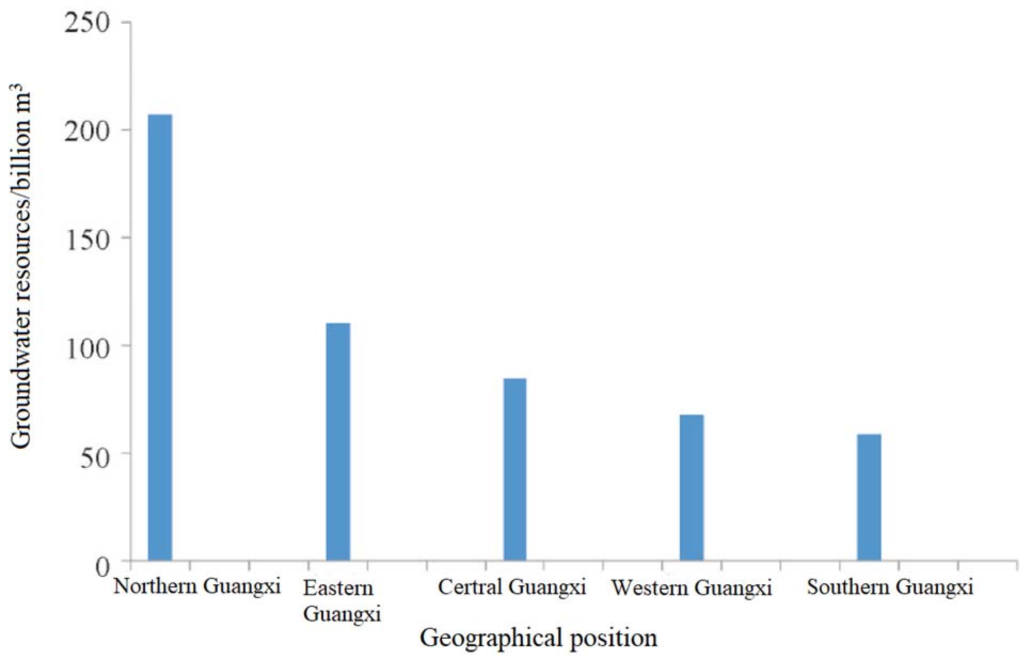

Figure 4. Spatial distribution of groundwater resources in Guangxi.

3.2 Temporal distribution characteristics and rules of groundwater resources

As shown in **Figure 5**, groundwater resources in Guangxi have generally shown an upward trend in the past 10 years, which is attributed on the one hand to the increase of precipitation in recent years, and on the other hand to the government's enhanced protection of water resources. The annual average resource volume of Guangxi is about 42.82 billion m^3. The total groundwater resources in 2009, 2010, 2011 and 2014 were lower than average, and the total groundwater resources in other years were higher than average value. The groundwater resources in Guangxi are at least 25.68 billion m^3 in

2009[7] and at most 58.7 billion m^3 in 2012[9]. Therefore, the temporal distribution of groundwater resources is also uneven.

The data of groundwater resources, rainfall and surface water resources from 2008 to 2016 are used for correlation analysis, and the results are shown in **Table 1**. The correlation coefficient between groundwater resources and surface water resources is 0.846, greater than the critical value of 0.764 (α = 0.01), indicating a significant correlation between the two. The correlation coefficient between groundwater and rainfall is 0.798, greater than the critical value of 0.764 (α = 0.01), indicating a significant correlation between the two. However, it is less than the correlation coefficient of 0.846 between groundwater resources and surface water resources, indicating that groundwater resources are more important to recharge from surface water.

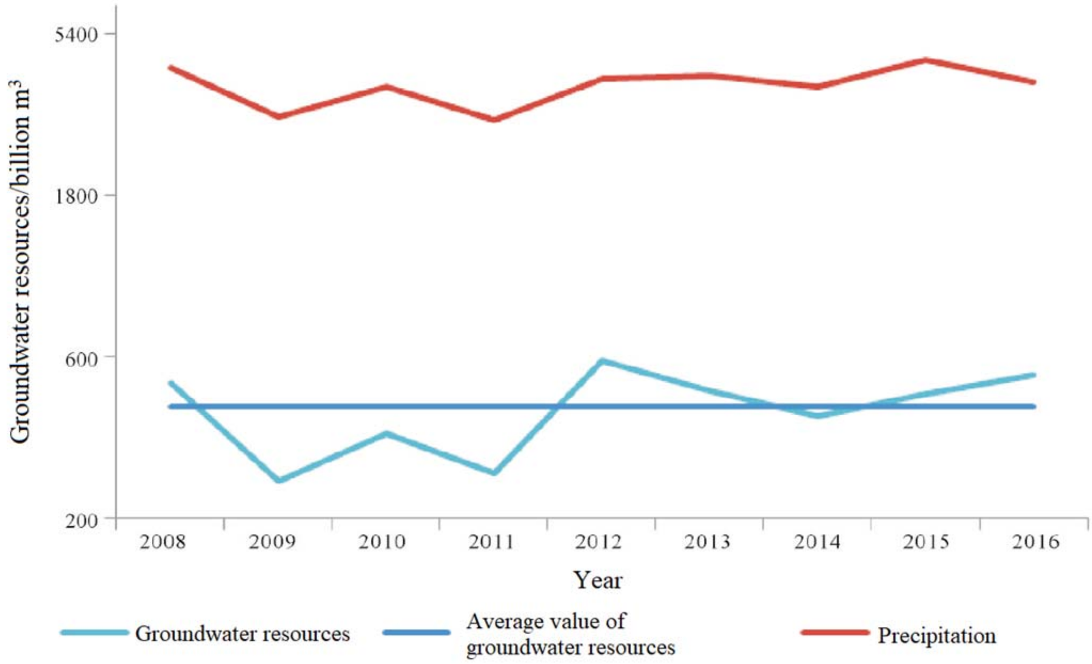

Figure 5. Annual distribution curve of groundwater resources and precipitation in Guangxi.

Table 1. Correlation analysis of groundwater resources with annual precipitation and surface water resources

Item	Precipitation	Surface water resources	Groundwater resources
Precipitation	1		
Surface water resources	0.973	1	
Groundwater resources	0.798	0.846	1

There are four types of groundwater in Guangxi: pore water of loose rock, karst water of carbonate rock, fissure pore water of red clastic rock and fissure water of bedrock. Except Beihai plain area, most areas of Guangxi belong to mountain and hilly area. Karst landform is relatively developed and karst water is distributed in the area most widely. The most widespread, mainly distributed in central, west and northeast Guangxi, north and southeast Guangxi, with an area of about 94,600 km^2. Groundwater recharge source is mainly the infiltration of atmospheric precipitation and mutual recharge with surface water, so the change of groundwater level is also directly related to rainfall. It basically conforms to the division of dry and wet season of surface water, which is divided into wet season from April to June and dry season from October to December.

4. Utilization of water resources in Guangxi

As shown in Figure 6, in the past 10 years, water consumption in Guangxi has generally shown a downward trend, which may be largely due to the improvement of water resource utilization rate and people's awareness of water conservation. The average water consumption over the years is about

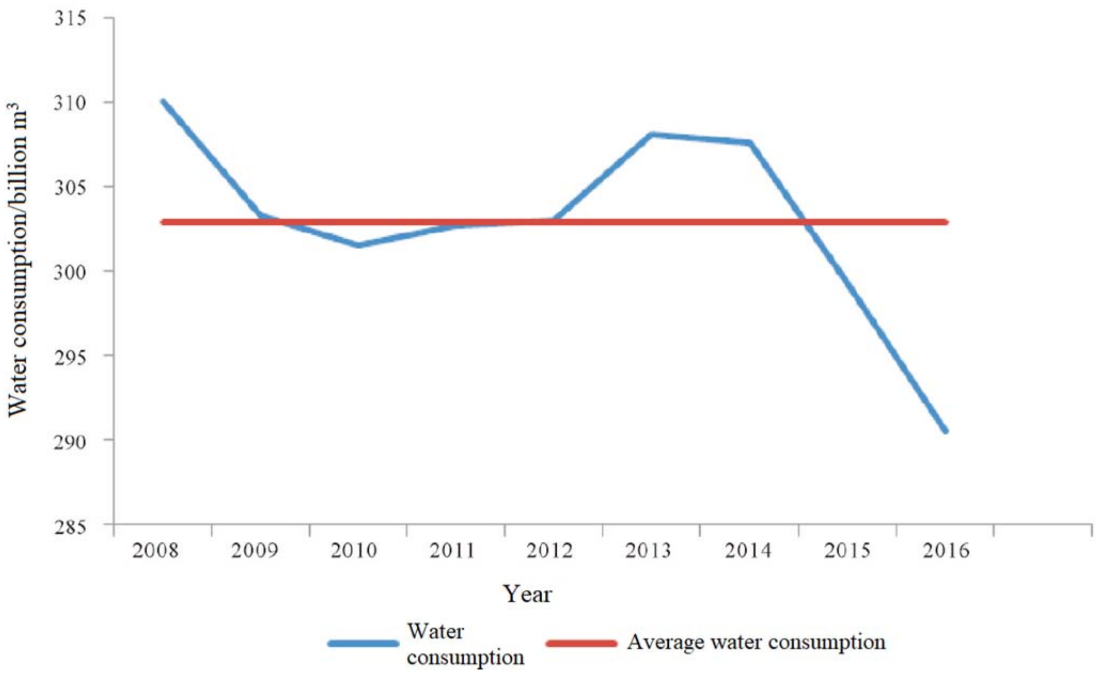

Figure 6. Annual distribution curve of water consumption in Guangxi.

30.29 billion m^3. The water consumption in 2010, 2011, 2015 and 2016 was lower than the average, and the water consumption in other years was higher than the average.

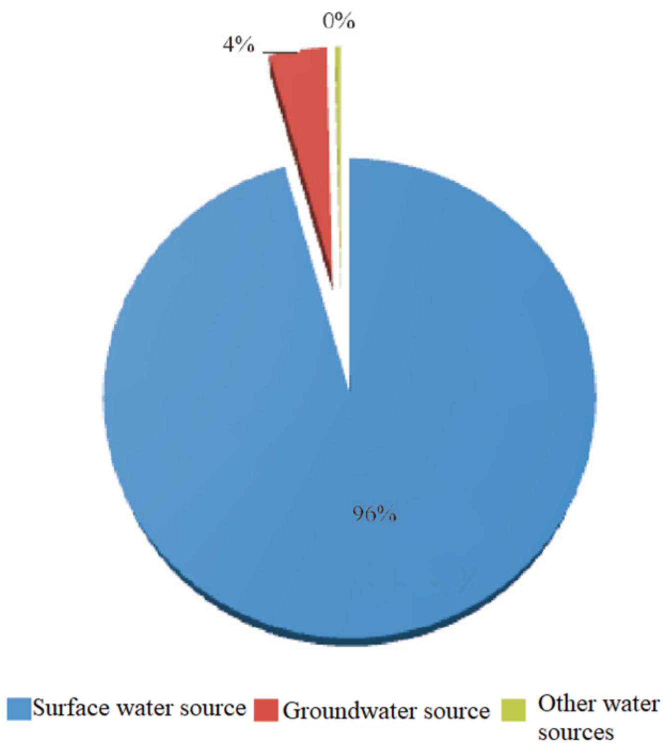

Figure 7. Schematic diagram of water use structure in Guangxi.

As shown in **Figure 7**, water in Guangxi mainly comes from surface water, taking 2016 as an example. In 2016, the total water supply of the region was 29.06 billion m^3, of which 27.80 billion m^3 was supplied by surface water sources, accounting for 95.7% of the total water supply; underground water supply was 1.15 billion m^3, accounting for 3.94% of the total water supply; other water sources supply 110 million m^3, accounting for 0.39% of the total water supply[3].

Water reserves are not fixed, but dynamically cyclical. Water has many uses. According to the *Water Act* of China, water resources can be divided into three types: domestic water, production water and ecological environment water. In this paper, production water is further divided into agricultural and industrial water, so the utilization of water resources is divided into four categories: agriculture, industry, life and ecological use.

As shown in **Figure 8**, agricultural water consumption in Guangxi is the largest, accounting for 68% of the total water consumption. The second is industrial water, accounting for the total water consumption 17%; next comes domestic water, which accounts for 14% of the total; ecological water consumption is the least, accounting for only 1% of total water consumption. The agricultural water consumption in Guangxi is much higher than the national average, while the industrial water consumption is lower than the national average. At the same time, the structure of water consumption in Guangxi is changing constantly, among which the proportion of domestic water consumption increases rapidly.

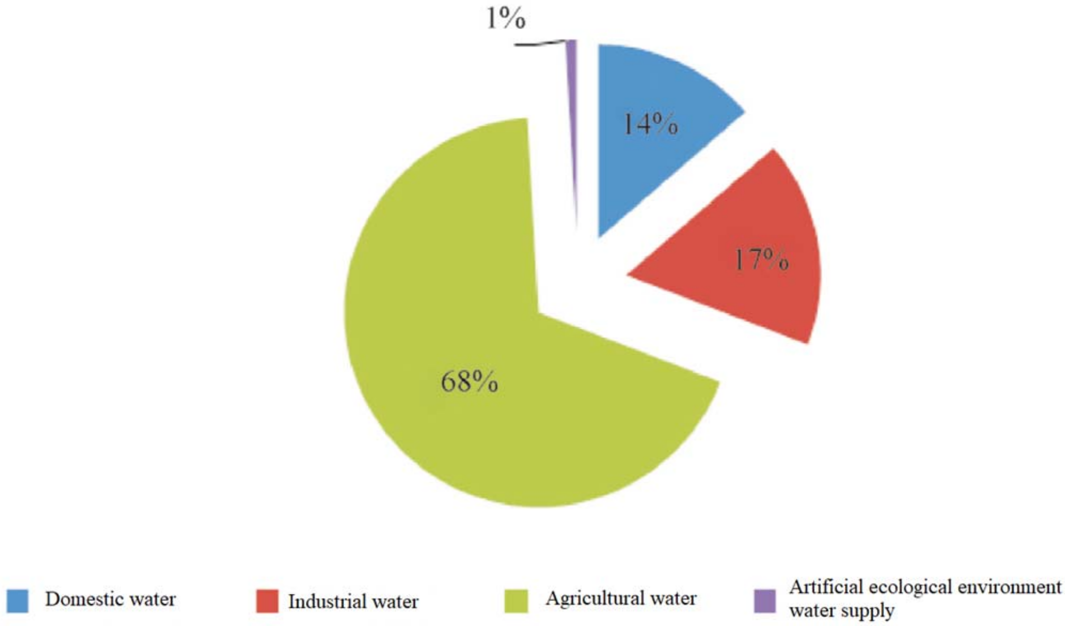

Figure 8. Schematic diagram of Guangxi water supply structure.

5. Water pollution in Guangxi

With the rapid economic development and rapid urbanization and industrialization in Guangxi, the problem of water resources pollution has also came as a result. According to the different pollution sources, Guangxi water resources pollution can be divided into mining pollution, industrial pollution, agricultural pollution and urban pollution.

5.1 Water pollution from mines

Guangxi is rich in mineral resources and known as the hometown of nonferrous metal minerals. Over the years, a large number of tailings and wastewater rich in heavy metals (such as As and Pb) in mining areas have not been well treated and discharged into rivers around the mining area, polluting rivers around the river or farmland[13]. For example, on July 6, 2013, Hejiang River, one of the main tributaries of the Xijiang River, suffered from regional heavy metal pollution, which has seriously affected the drinking water supply of people along the river and caused concern about water consumption in Guangdong Province downstream. The source of the pollution is basically identified as mining enterprises along the Mawei River section of the Hejiang River. In addition, according to data, the mining wastewater discharge in Nandan County is 1,700 t/a, and the amount of harmful substances in the wastewater is 206 t/a lead and 1776 t/a arsenic, which leads to serious pollution of Diaojiang River: the concentration of some heavy metals exceeds the maximum concentration of surface water allowed by nation by 10 times or even 100 times[23]. In addition, a large amount of tailings is deposited on the riverbed, which destroys the aquatic ecosystem of the river and makes fish and shrimp disappear in the middle and upper reaches of the river[14].

5.2 Water pollution from industrial sources

With the development of Western China and the rise of Beibu Gulf Economic Zone as a national development strategy, industrial enterprises and construction projects are gradually increasing, and industrial pollutants are gradually increasing in some areas, causing serious pollution in some river sections. For example, on January 15, 2012, heavy metal cadmium was detected in the Longjiang River section of Yizhou City, Guangxi Province, exceeding the standard of class III of *Surface Water Environmental Quality Standard* by about 80 times, which severely threatened the drinking water safety of residents along the coast and downstream[15]. Some engineering construction, industrial process management and control measures are not in place, but also pose a threat to the water environment. Some established sewage treatment plants have limited scale and low treatment capacity, which cannot meet the needs of local economic development and sewage treatment. As a result, untreated industrial sewage is directly discharged into rivers, causing pollution and damage to water environment and water ecology[16].

5.3 Water pollution from agricultural sources

As a major producer of grain in China, Guangxi agriculture is its pillar industry, so compared with provinces and cities with developed industry, agricultural water pollution in Guangxi is also a very important source of pollution. Agricultural pollution sources are relatively unitary, and the main sources of pollution are pesticides, fertilizers and feed. For example, the pollution of gully and pond system in the upper reaches of Lijiang River in Northern Guangxi is serious. Among the 2,721 gully and pond water bodies interpreted by remote sensing, 720 are suspected to have been polluted and 1,350 are potentially polluted. The pollution sources causing these water bodies are mainly non-point source pollution in rural settlements[17].

5.4 Water pollution from urban sources

With the expansion of city scale and the increase of population, the discharge of municipal wastewater is increasing. The construction of sewage pipe network lags behind the construction of sewage treatment plant, which greatly affects the effect of sewage collection and treatment, so that sewage treatment plant cannot fully play its role. For example, Nanning was rated as one of the five cities with the most serious water pollution in China in 2016. The main reason is that the sewage discharged by urban factories everywhere and the treatment capacity of municipal sewage treatment plant is limited, which leads to the extremely poor water quality of all rivers in the city, accompanied by fetid odor and red tide. In 2010, Qian *et al.* conducted a study on mercury distribution and pollution in Lijiang River system, which showed that there was mercury pollution to a certain extent in Lijiang River system of Guilin City[18].

6. Suggestions on water resources protection and management

At present, there is a certain gap in the demand and utilization of all kinds of water resources in China, and with the continuous acceleration of urbanization, the water resources shortage will be more and more serious. Therefore, the protection of water resources is urgent. The following suggestions are put forward for the protection of water resources.

(1) The government actively carries out the publicity of water resources protection to enhance the public's awareness of environmental protection. For water resources in the region, the government should make unified planning, rational exploitation and effective utilization, and gradually transit from concentration management to total control management[19]. Improve the monitoring and reward and punishment system for water pollution, strengthen the binding force of law, increase the intensity of punishment, so that violations of laws are punished by law. Expand the team in charge of water resources protection and give full play to the role of the river chief system.

(2) To reduce the discharge of industrial wastewater, economic, political and legal means

can be used simultaneously. To administer, punish and supervise the correction of enterprises that discharge pollutants abnormally. For substances discharged during industrial production, a series of detailed and standardized evaluation standards are formulated, and third-party spot checks are often carried out on assessment reports made by enterprises, and penalties for violations are strengthened, so as to deter other enterprises from violating the environmental bottom line. The site selection of large factories and chemical plants with serious discharge pollution shall be strictly examined and kept away from water sources to avoid pollution to water sources and affect the whole water system.

(3) Standardize the distribution of agriculture, animal husbandry and forestry, strictly control the discharge of chemical fertilizers, pesticides, livestock urine, processing sewage and other pollution sources, so as to control the impact on water resources, and strengthen monitoring with a variety of monitoring means. Do not throw rubbish and pesticide waste bottles into rivers, and control the fertilizer applied to crops quantitatively. Farmers are encouraged to use fewer polluting fertilizers and pesticides, and to use more farm manure. In addition, livestock waste can be specially treated as non-toxic fertilizers. And reasonably irrigate the farmland, improve planting efficiency, learn to farm scientifically, plant first crops requiring less fertilizer.

(4) Reduce the direct discharge of household garbage. One is to classify the recycled garbage; second, waste disposal should be timely to avoid waste accumulation causing pollution to the environment. The distribution of water resources, the collection of water charges, the collection of sewage charges and the collection of funds for pollution control in each region can be effectively unified, so as to realize the steps from local to overall governance, so as to solve the water environment problems in our region[20]. Improve the urban sewage treatment system: in order to control the deterioration of water, enterprises must actively control water pollution, especially the discharge of toxic pollutants must be treated separately or pretreatment. With the adjustment of industrial layout and urban layout and the construction and improvement of urban sewer pipe network, centralized treatment of urban sewage can be gradually realized, so that urban sewage treatment and industrial wastewater treatment can be combined[21]. As for individuals, we should protect water resources in production and life, thus cutoff the behavior of waste and pollution from the root.

(5) To establish water resources protection areas, some natural water sources must be strictly protected. Only suppress from the source of containment, actively handle in the middle, and finally repair serious, can we better solve the problem of water pollution. For the rivers in the area, we should focus on the improvement of the surrounding environment of the river, cleaning up the silt in the river, preventing soil erosion, river accumulation and other problems; for the lakes in the area, water quality monitoring should be strengthened to prevent the occurrence of eutrophication such as water bloom, and trees should be planted around the river to enhance the self-purification capacity of the river itself.

Conflict of interest

The authors declared no conflict of interest.

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ORIGINAL RESEARCH ARTICLE

Spatial and temporal characteristics of China's water footprint of energy and its matching relationship with water resources

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ABSTRACT

Energy and water resources are very important for human survival and social development. Energy and water footprint can reflect the real occupation of water resources in the process of energy production. Based on the energy and water footprint evaluation model, this paper calculates the life cycle water footprint of fossil energy and power production in 30 provinces (cities and autonomous regions) in China, studies the temporal and spatial pattern evolution characteristics of China's raw coal, crude oil, natural gas, hydropower and thermal power from 2004 to 2016, and analyzes the spatial matching relationship between China's energy and water footprint and water resources. The results show that: (1): during the study period, the water footprint of fossil energy increases first and then decreases with 2012 as the boundary. The rapid growth of hydropower water footprint promotes the continuous growth of power water footprint. (2): In terms of spatial pattern, the water footprint of fossil energy increases in the West and decreases in the East with the Huhuanyong line as the boundary, and the Inner Mongolia, Shanxi and Shaanxi region as the high-value concentration area; in the power water footprint, there is a significant spatial boundary between hydropower water footprint and thermal power water footprint. The rapid growth of hydropower water footprint has gradually formed a high-value concentration area of power water footprint in the Yangtze River Basin, the Pearl River Basin and the southeast coast. (3): The spatial matching degree of energy and water footprint and water resources fluctuates and declines in the pattern of high in the south and low in the north. The spatial matching degree of fossil energy and water footprint is lower than that of electric power and water resources. The energy water contradiction between raw coal production and thermal power generation is the most prominent. One third of the country has the problem of energy water mismatch. North China with high energy and water footprint has great pressure on energy water matching. The contradiction between energy production and water resources allocation still exists. Truly reflect the matching relationship between energy and water footprint and water resources, help to optimize the comprehensive management of energy and water resources, and provide a quantitative basis for maximizing the energy water synergy.

Keywords: Energy Water Correlation; Energy and Water Footprint; Life Cycle Assessment; Water Resources; Spatial Matching; Green Development

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1. Introduction

Energy and water resources are interdependent and mutually restricted. The continuous promotion of urbanization and industrialization in China not only promotes the sustainable growth of energy consumption, but also increases the consumption and pollution of water resources in energy production, processing and transportation. The contradiction between energy and water resources affects the sustainable development of social economy. As an important indicator of water resource occupation and pollution in the process of energy production and consumption, energy and water footprint can effectively reflect the energy–water relationship.

Most of the relevant studies on energy and water footprint are concentrated after 2010, mainly on the calculation methods of energy and water footprint, and less on its spatial-temporal evolution and influencing factors[1-3]. The measurement of energy and water footprint can be divided into top-down and bottom-up methods. Most of the existing research methods for measuring energy and water footprints are top-down methods. The energy and water footprints of various economic sectors are calculated by energy consumption in monetary units, mainly using input-output methods[4-7]. For example, Okadera *et al*.[4] used the input-output method to analyze the water footprint of energy consumption in Liaoning Province of China from the perspective of energy consumption, and studied its external energy dependence; Zhang *et al*.[5] used MRIO model to analyze China's energy life cycle water use, water consumption and wastewater discharge from the perspective of consumption. The research time of the input-output method is limited by the preparation years of the national input-output table, so it is impossible to obtain the data in recent years. Compared with such methods, the bottom-up method can better reflect the current situation of energy and water footprint because the data in recent years are easier to obtain. The bottom-up method is to calculate the energy and water footprint through the physical quantity of various types of energy in the process of production and processing[8-11]. For example, Okadera *et al*.[8] calculated the energy and water footprint of Thailand from the perspective of energy production and supply; Scherer *et al*.[9] evaluated the water footprint of different types of hydropower departments; Dingning *et al*.[12] established an energy and Water Footprint Evaluation Model Based on ISO standard water footprint method from the perspective of improving water resource efficiency, and calculated the water footprint of China's primary energy and power production life cycle at the national and provincial levels. In this paper, the energy and water footprint evaluation model[12] based on the life cycle of energy production from bottom to top is used to calculate the energy and water footprint, and the water footprint of fossil energy and electric power are compared and analyzed, in which the water footprint of fossil energy refers to the water footprint of primary fossil energy.

The existing energy and water footprint studies are mostly based on the cross-sectional data of a certain year, and lack of research on the time and space dimensions of energy and water footprint; secondly, some scholars analyzed the impact of energy and water footprint on the environment, but neglected the research on the spatial matching relationship between energy production and water resources; in addition, the research on the quantitative correlation between energy and water resources is of great significance to the cross basin energy water security. Based on this, this paper studies the temporal and spatial characteristics of China's energy and water footprint from 2004 to 2016, and analyzes the spatial matching degree between China's energy and water footprint and water resources, in order to provide a new perspective for the study of energy water relationship and a quantitative basis for the regional energy transformation and development of coordinated energy and water resources.

2. Research methods and data sources

2.1 Energy and water footprint evaluation model

The energy and water footprint evaluation model is established based on the ISO standard water footprint method[13]. Starting from the life cycle of energy production, it covers mining, treatment, processing and transformation, use, waste treatment, etc., in the life cycle. The energy and water footprint evaluation model is used to calculate the water footprint in the production life cycle of fossil energy (raw coal, crude oil, natural gas) and electric power (hydropower and thermal power). Hydropower and thermal power are referred to as hydropower and thermal power in this paper. The energy and water footprint includes the direct water footprint in the production life cycle and the indirect water footprint brought by the materials and energy input in the production process. Since it is difficult to obtain the data of water pollution in the life cycle of energy production, the water pollution caused by energy production is represented by the grey water footprint[14,15] in the WFN water footprint method. The energy water footprint is divided into energy blue water footprint and energy grey water footprint. The energy blue water footprint is the surface runoff and groundwater from rivers, lakes and aquifers required in the production process, and the energy grey water footprint is the amount of water required to dilute the polluted water in the production process to the discharge standard. The formula of energy and water footprint evaluation model is:

$$EPWF = PWF_{\text{direct}} + PWF_{\text{indirect}} = PWF_{\text{b,d}} + PWF_{\text{g,d}} + PWF_{\text{b,in}} + PWF_{\text{g,in}} \tag{1}$$

Where: *EPWF* refers to the water footprint of unit energy output; PWF_{direct} refers to the direct unit output water footprint of the energy production process; PWF_{indirect} refers to the indirect unit output water footprint of the energy production process; $PWF_{\text{b,d}}$ refers to the blue water footprint of direct unit output in the energy production process; $PWF_{\text{g,d}}$ refers to the direct unit output grey water footprint of the energy production process; $PWF_{\text{b,in}}$ refers to the blue water footprint of indirect unit output of energy investment; $PWF_{\text{g,in}}$ refers to the grey water footprint of indirect unit output of energy investment. Considering all the processes in the life cycle, the water footprint of the energy system shall be the sum of the water footprints in each life cycle stage, expressed by the following formula:

$$EPWF = \sum_{m=1}^{n}\left(PWF_{m(\text{b,d})} + PWF_{m(\text{g,d})}\right) + \sum_{n=1}^{n}\left(PWF_{n(\text{b,in})} + PWF_{n(\text{g,in})}\right) \tag{2}$$

Where: *m* refers to the *m*-th production process; *n* refers to class *n* energy; the meanings of other variables are the same as above. The calculation formula of grey water footprint of each energy unit output is as follows:

$$PWF_{\text{g,d}} = \frac{L \times V}{C_{\max} - C_{\text{nat}}} = \frac{G}{C_{\max} - C_{\text{nat}}} \tag{3}$$

Where: *L* refers to the unit energy production wastewater discharge (M^3/GJ) *V* refers to the amount of pollutants in the discharged wastewater (mg/m^3) G = LV refers to the unit energy production pollutant discharge (mg/GJ) $C_{\max}$ refers to the acceptable pollutant concentration in water (mg/m^3), C_{nat} refers to the pollutant concentration in natural water(mg/m^3).

The calculation formula of energy and water footprint *EWF* is as follows:

$$EWF = \sum_{n=1}^{n} EWF_n = \sum_{n=1}^{n}\left(EPWF_n \times P_n\right) \tag{4}$$

Where: EWF_n refers to the energy and water footprint of class *n*; $EPWF_n$ refers to the water footprint per unit output of class *n*-th energy; P_n refers to the energy output of category *n*.

2.2 Center of gravity and standard deviation ellipse model

The coincidence area of center of gravity distance and standard deviation ellipse is used to analyze the overall matching degree of energy and water footprint and water resources in space. The coverage area of the standard deviation ellipse reflects the main area of the energy and water footprint and the spatial distribution of water resources. The distance between the centers of gravity of the two reflects the difference and overall matching degree of the energy and water footprint and the spatial distribution of water resources. The greater the distance between the centers of gravity, the smaller the matching degree, and vice versa. The calculation formula is:

$$x = \sum_{i=1}^{n} G_{ij} x_i \Big/ \sum_{i=1}^{n} G_{ij}\ ,\ y = \sum_{i=1}^{n} G_{ij} y_i \Big/ \sum_{i=1}^{n} G_{ij} \tag{5}$$

Where: (*x*, *y*) is the center of gravity coordinate of energy and water footprint and the center of gravity coordinate of available water resources; *n* is the number of areas, *n* = 30; (x_i, y_i) is the barycentric coordinate of the spatial weight of the *i* region; G_{ij} is the spatial weight of the i^{th} region in the j^{th} year.

2.3 Energy and water footprint pressure index

In order to compare and analyze the matching degree of energy and water footprint and water resources in different regions, the energy and water footprint pressure index F is constructed with reference to relevant research[16-18] to represent the pressure of water footprint on water resources in the life cycle of energy production. The larger the energy and water footprint pressure index, the smaller the matching degree between energy and water footprint and available water resources. The specific formula is as follows:

$$F_{ij} = \frac{EWF_{ij}}{Q_{ij}} \quad (6)$$

Table 1. Water footprint value per unit of production in energy production life cycle in China

Energy type	Classification	Energy production and processing process	Classification of water footprint per unit energy output	Water footprint per unit energy output /(m³/GJ)	Ref.
Fossil energy	Coal	Raw coal mining	Direct blue water footprint of raw coal	0.014	[21]
			Direct grey water footprint of raw coal	0.137	[22]
		Coal washing	Coal washing direct blue water footprint	0.007	[21]
			Direct grey water footprint of coal washing	0.027	[22]
	Petroleum	Crude oil exploitation	Direct blue water footprint of crude oil	0.167	[23]
			Direct grey water footprint of crude oil	0.016	[24,25]
		Machining	Direct blue water footprint of crude oil processing	0.057	[26]
			Direct grey water footprint of crude oil processing	-	
	Natural gas	Exploitation	Natural gas direct blue water footprint	0.077	[27]
			Natural gas direct grey water footprint	0.013	[25,28]
		Processing purification	Direct blue water footprint of natural gas processing	0.006	[29]
			Direct grey water footprint of natural gas processing	-	
Power	Hydropower	Evaporation and leakage of reservoir	Hydropower direct blue water footprint	6.750	[30]
		Construction of hydropower plant	Indirect blue water footprint of hydropower	0.002	[12]
	Thermal power	Cooling system	Thermal power direct blue water footprint	0.681	[31]
			Thermal power direct grey water footprint	0.083	[19,28,32]
		Energy input of thermal power	Thermal power indirect blue water footprint	0.063	[19]
			Indirect grey water footprint of thermal power	0.387	[19]

Where: F_{ij} is the energy water footprint pressure index of i region in the year of j, and EWF_{ij} is energy water footprint of i region in the year of j, Q_{ij} refers to available water resources of i region in the year of j.

2.4 Data source

This paper selects the data from 2004 to 2016 to analyze the temporal and spatial characteristics of energy and water footprint and its matching relationship with water resources in 30 provincial administrative regions of China (Tibet, Hong Kong, Macao and Taiwan are not included due to lack of data). The energy production comes from the *China Energy Statistical Yearbook*[19], and the average low calorific value coefficient of each energy comes from the 2017 *China Energy Statistical Yearbook*[19]. The water footprint values and data sources per unit output in the life cycle of various types of energy production are shown in **Table 1**. When calculating the grey water footprint of each energy unit output, COD, the chemical oxygen demand of main pollutant in wastewater discharge, is used as the measurement index for calculating the grey water footprint of energy. Due to the complexity of energy consumption calculation in the process of fossil energy production, only the direct water footprint of fossil energy is calculated. The study shows the current situation of water resources in each region by the available water resources. The available water resources are calculated according to 40% of the total water resources[18], and the total water resources come from the *China Statistical Yearbook*[20].

The COD content of wastewater from raw coal mining and coal washing is 200 g/t and 30 g/t, respectively[21]. The maximum acceptable COD value in wastewater discharge of coal industry is 70 mg/L[21]. The consumption of water resources during crude oil exploitation is defined as 7 m^3/t[23]. Water consumption during oil processing is defined as 2.37 m^3/t[26]. The water quota of drilling mud during natural gas production is 30 m^3/10,000 m^3[27]. During natural gas processing, the unit production water consumption of the purification unit is 2.4 m^3/10,000 m^3[29]. The data of COD emission during the exploitation of crude oil and natural gas comes from the *China Environmental Statistics Yearbook*[25]. The COD emission from crude oil exploitation is 821 mg/GJ and that from natural gas exploitation is 379 mg/GJ. According to the pollutant discharge standard for petroleum refining industry[24], the maximum acceptable COD value in the wastewater discharge of petroleum industry is 50 mg/L. The direct grey water footprint of petroleum processing process is not calculated in this paper due to the lack of data. Since there is no specific pollutant discharge standard for the natural gas industry, the study refers to the environmental quality standard for surface water[28], and 30 m/L is selected as the maximum acceptable COD value in the wastewater discharge of the natural gas industry.

The water consumption during hydropower generation mainly comes from the evaporation and leakage of the reservoir, that is, the direct blue water footprint[30]. The indirect blue water footprint of hydropower refers to the water consumption of dam construction, which is 0.00168 m^3/GJ[12]. In the selection of parameters for direct grey water footprint of thermal power, the production and emission coefficient[32] is used to calculate the amount of COD produced by the unit product of thermal power generation. The proportion of energy and fuel input in the thermal power industry is derived from the national energy balance table in the 2017 *China Energy Statistical Yearbook*. With reference to the environmental quality standard for surface water[28], 30 m/L is selected as the maximum acceptable COD value in the wastewater discharge of thermal power industry. The indirect blue water footprint of thermal power is the blue water footprint of energy input in the process of thermal power, and the indirect grey water footprint of thermal power is the grey water footprint of energy input in the process of thermal power.

3. Results and analysis

3.1 Analysis of space-time characteristics of energy and water footprint

3.1.1 Analysis of time evolution characteristics of energy and water footprint

Based on the energy and water footprint evaluation model, the energy and water footprint values of China's raw coal, crude oil, natural gas, hydropower and thermal power from 2004 to 2016 are calculated according to formulas (1)–(4), and the results are shown in **Figure 1**. During the study period, the water footprint of fossil energy first increased and then decreased in 2012. The rapid growth of market energy demand from 2004 to 2012 led to the continuous growth of fossil energy output at this stage, and the water footprint of fossil energy continued to grow to reach the highest value of 18.573 billion m^3 in 2012; 2012–2016 is in the "12th Five Year Plan" strategic period of energy. The energy structure has been continuously optimized and upgraded, the total output of fossil energy has decreased, and the water footprint of fossil energy has decreased. From the perspective of energy and water footprint structure, the original coal water footprint of fossil energy water footprint accounts for about 84% and has been stable for a long time. The proportion of crude oil water footprint is 11%–18%, showing a continuous decreasing trend. The proportion of natural gas water footprint is the smallest, but showing a continuous increasing trend. From the perspective of fossil energy grey water footprint, the proportion of fossil energy grey water footprint in the fossil energy water footprint is as high as 70%. The temporal evolution characteristics of fossil energy grey water footprint are basically consistent with that of fossil energy water footprint, reaching the highest value of 14.457 billion m^3 in 2012.

The power and water footprint showed a sustained and rapid growth trend from 2004 to 2016. The electric power water footprint in 2016 was 48.279 billion m^3, three times that of 2004. This is due to the continuous growth of electric power production in the power industry due to the influence of national policies and other factors during this period. From the perspective of power water footprint structure, the proportion of hydropower water footprint increased from 52% in 2004 to 60% in 2016, and the proportion of thermal power water footprint gradually decreased. From the perspective of power grey water footprint, the time series evolution characteristics of power grey water footprint are basically the same as that of power water footprint, reaching a maximum of 7.507 billion m^3 by 2016. The proportion of power grey water footprint in power water footprint is less than 20% and is decreasing.

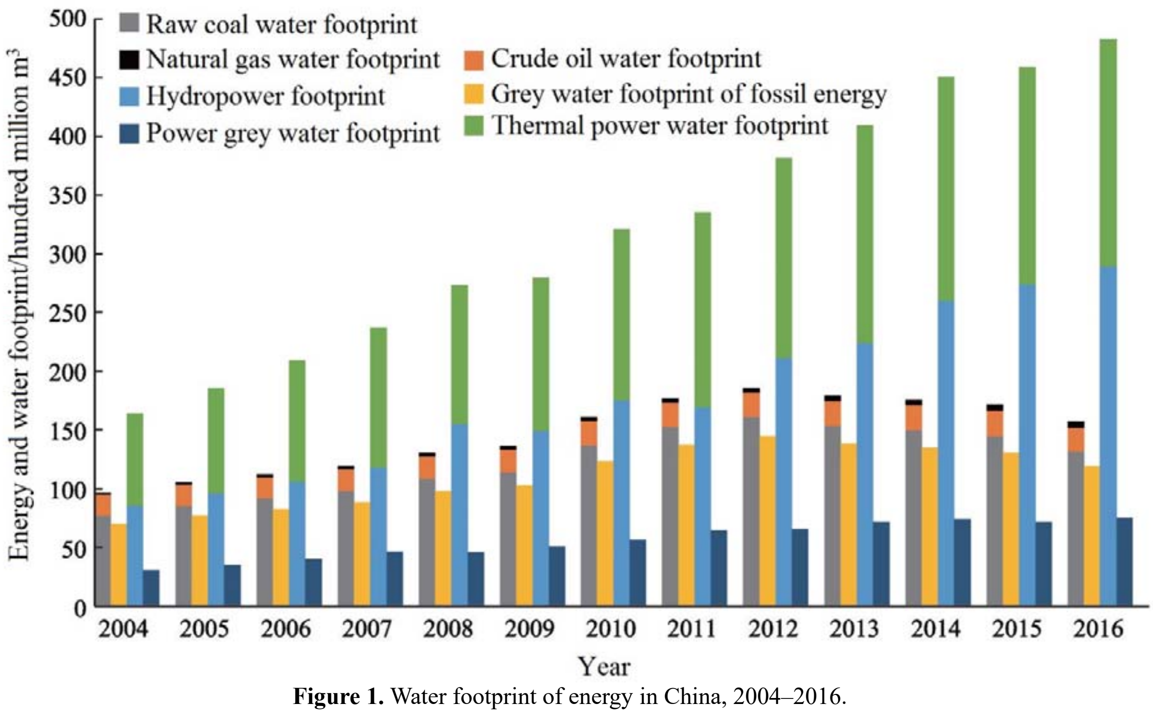


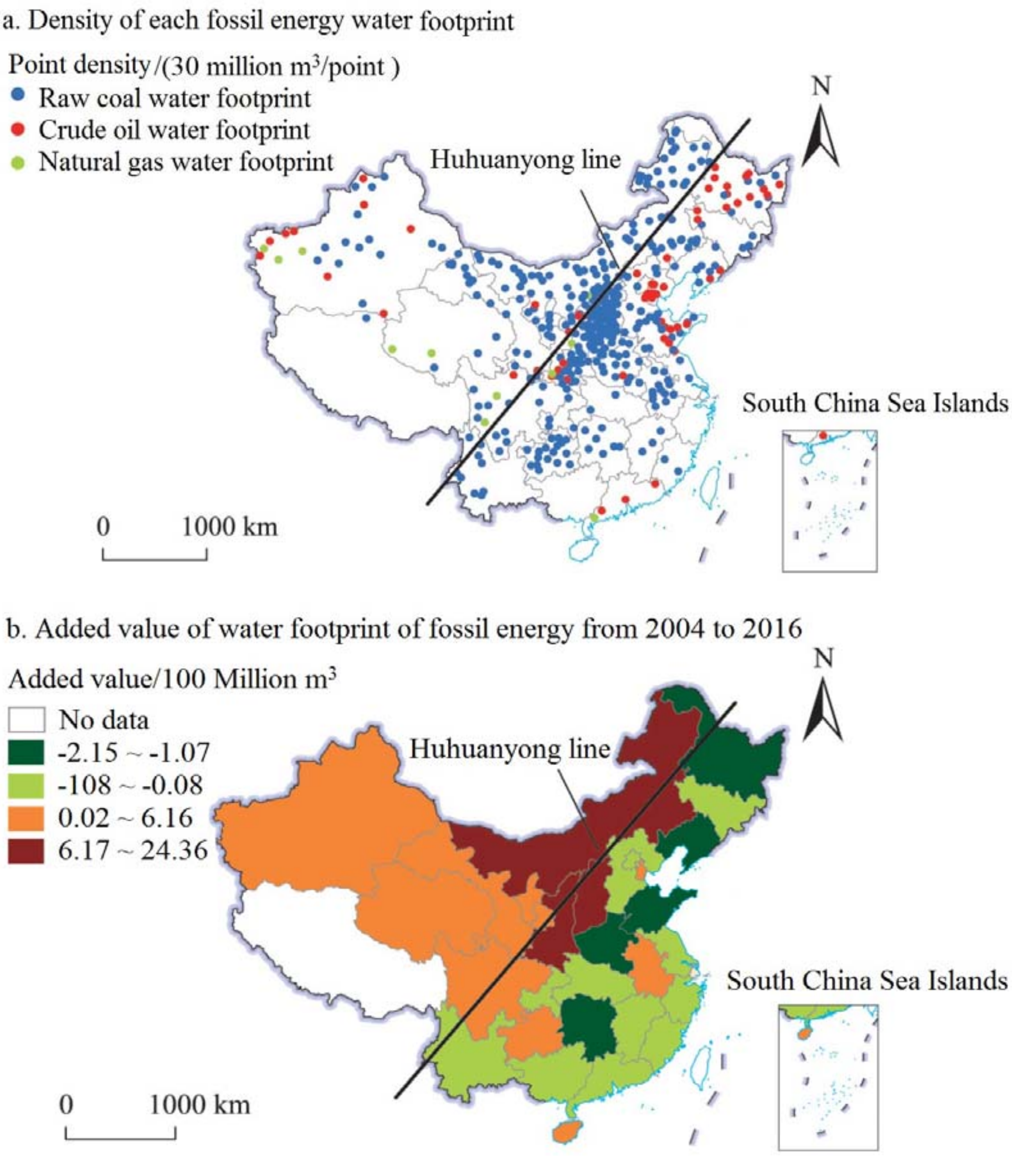
Figure 1. Water footprint of energy in China, 2004–2016.

Comparing the fossil energy and electric water footprints in **Figure 1**, it is found that the electric water footprint is larger than the fossil energy water footprint, and the gap between the two is gradually increasing. The ratio of fossil energy water footprint to electric water footprint gradually increased from 1:1.71 in 2004 to 1:3.07 in 2016. Among the five types of energy and water footprints, the growth rate of hydropower and water footprints is the fastest, with an average growth rate of 1.293 billion m^3/a. As a result, the rapid growth of power and water footprints has not led to a significant increase in power grey water footprints. By 2016, the power grey water footprints were only 63% of the fossil energy grey water footprints. This shows that under a certain amount of energy production, the increase in the proportion of hydropower in the energy production structure not only makes full use of water resources, but also directly reduces the pollution of energy production to water resources.

3.1.2 Analysis on spatial evolution characteristics of energy and water footprint

The spatial distribution of China's energy and water footprints is quite different, which is caused by different conditions such as resource endowment, economic development direction and policy support in various regions. In order to reveal the spatial evolution characteristics of China's energy and water footprint, based on the energy and water footprint values of 30 provinces (cities, autonomous regions) in China, ArcGIS 10. 2 software is used to map and analyze the spatial distribution and evolution characteristics of various energy and water footprints, as shown in **Figure 2** and **Figure 3**.

As shown in **Figure 2a**, the distribution of water footprint of fossil energy is consistent with the layout of main fossil energy producing areas. Raw coal and water footprints are widely distributed with high-density, forming major high-value agglomeration areas in Inner Mongolia, Shanxi, Shaanxi and Henan along Taihang Mountain and Helan Mountain, and relatively high-value agglomeration areas in Sichuan, Guizhou and Yunnan. Compared with the raw coal water footprint, the crude oil water footprint and natural gas water footprint are scattered, and no obvious high-value agglomeration area is formed. The high value areas of crude oil water footprint mainly include Northeast China, Bohai Rim region, Shaanxi, Guangdong and Xinjiang, and the high value areas of natural gas water footprint mainly include Sichuan, Xinjiang, Shaanxi, Qinghai, Heilongjiang and Guangdong. It can be seen from



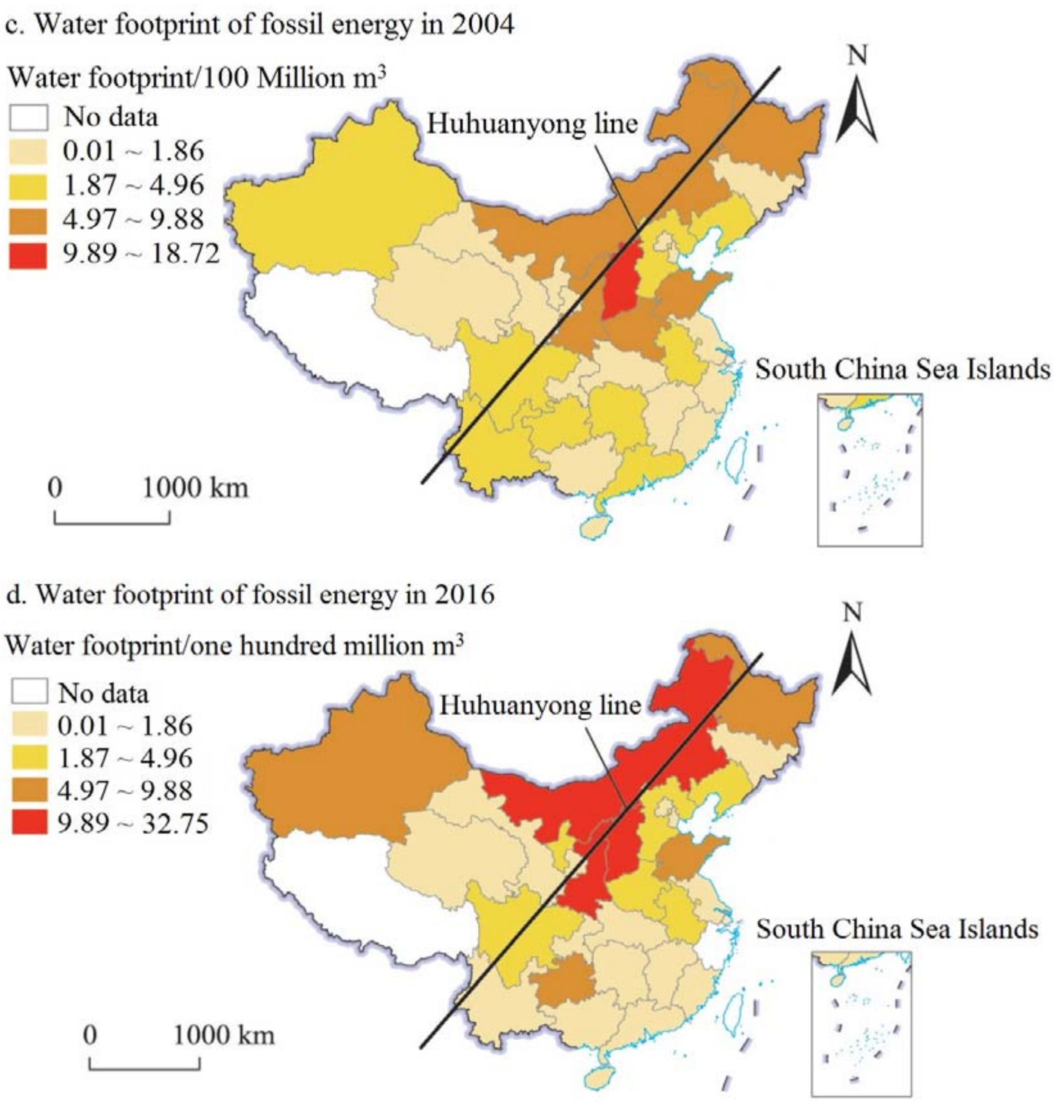


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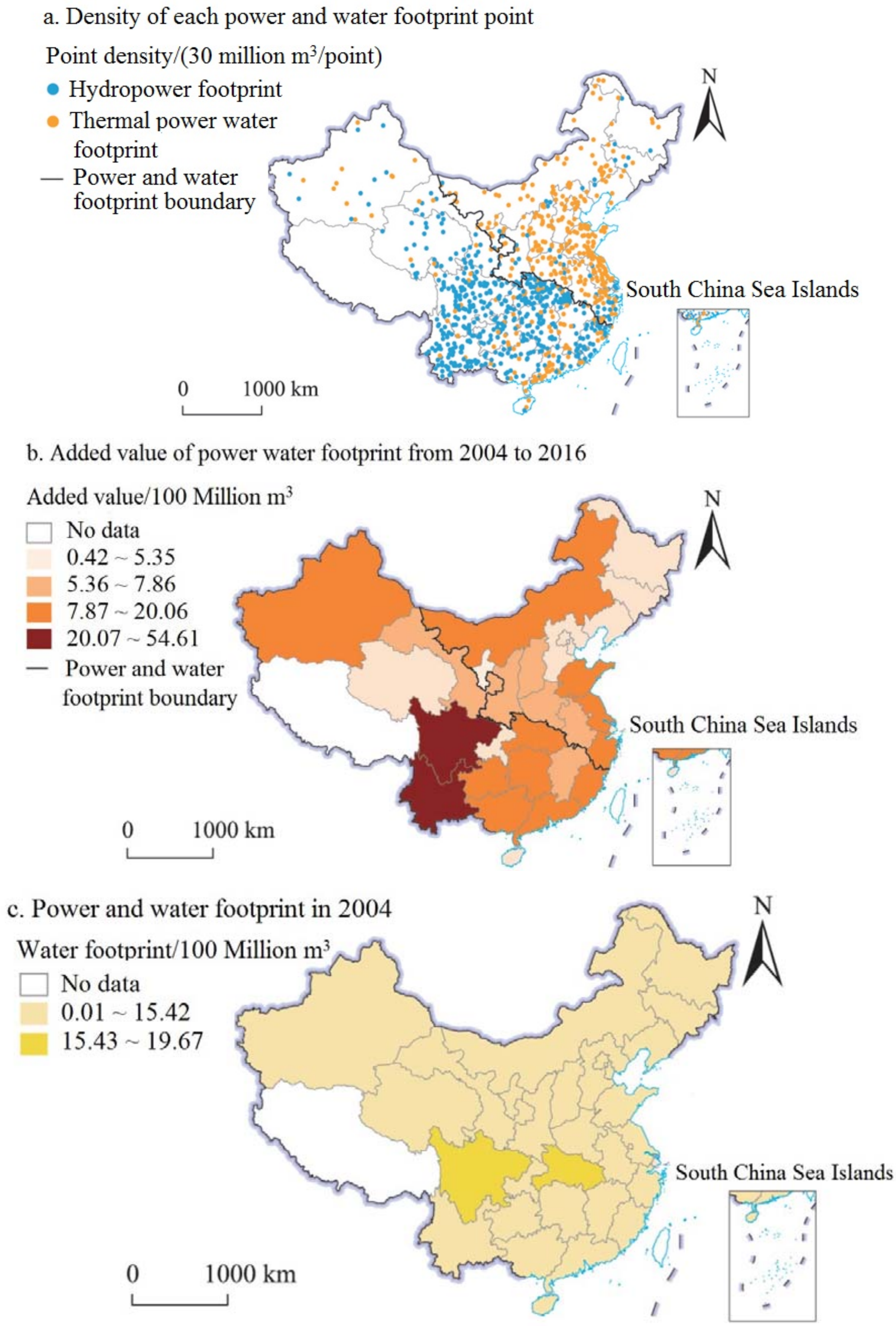
Figure 2. Distribution and spatial variation of the water footprint of fossil energy in 30 Provinces of China, 2004–2016.

Figure 2b that the water footprint of fossil energy during the study period is mainly bounded by the Huhuanyong line, increasing in the West and decreasing in the East. Since most of China's major energy production areas, which are composed of five national comprehensive energy bases in Shanxi, Inner Mongolia, Ordos Basin, Xinjiang and southwest China, are located in the west of Huhuanyong line, with the increase of fossil energy production, the water footprint of fossil energy shows an increasing trend, with an increase of 0.02–24.36 billion m^3. The increment of fossil energy in Shanxi, Inner Mongolia, Shaanxi and Northwest China is mainly raw coal. In particular, the output of raw coal in Shanxi and Inner Mongolia provinces (autonomous regions) has increased the most, and the increment of water footprint of fossil energy in the two provinces (autonomous regions) is the highest. Only natural gas production in Sichuan has increased, and the increment of its fossil energy water footprint is much smaller than that in other regions. As the main energy consumption area in China, the area to the east of Huhuanyong line has significantly reduced the output of fossil energy in most areas, and the water footprint of fossil energy has decreased, with a decrease of 0.08–2.15 hundred million m^3. It is found that the Huhuanyong line is not only the dividing line of China's population, but also an important dividing line of the spatial evolution of China's fossil energy water footprint. With the westward migration of the national energy supply strategy, it also has a great impact on the spatial pattern of China's fossil energy water footprint. Compared with **Figure 2c–d**, it can be found that the evolution trend of high-value area changes form concentrating along the Huhuanyong line in 2004 to focusing on the Inner Mongolia Shanxi Shaanxi region 2016.

As shown in **Figure 3a**, the distribution of thermal power water footprint is highly related to the raw coal production area, while the distribution of hydropower water footprint is mainly affected by the abundance of water resources. Based on the proportion of thermal power water footprint and hydropower water footprint in the power water footprint, Inner Mongolia, Shanxi, Shaanxi, Henan, Shandong and other regions to the north of the power water footprint boundary are rich in coal resources, and the proportion of thermal power water footprint is higher than 50%, forming a

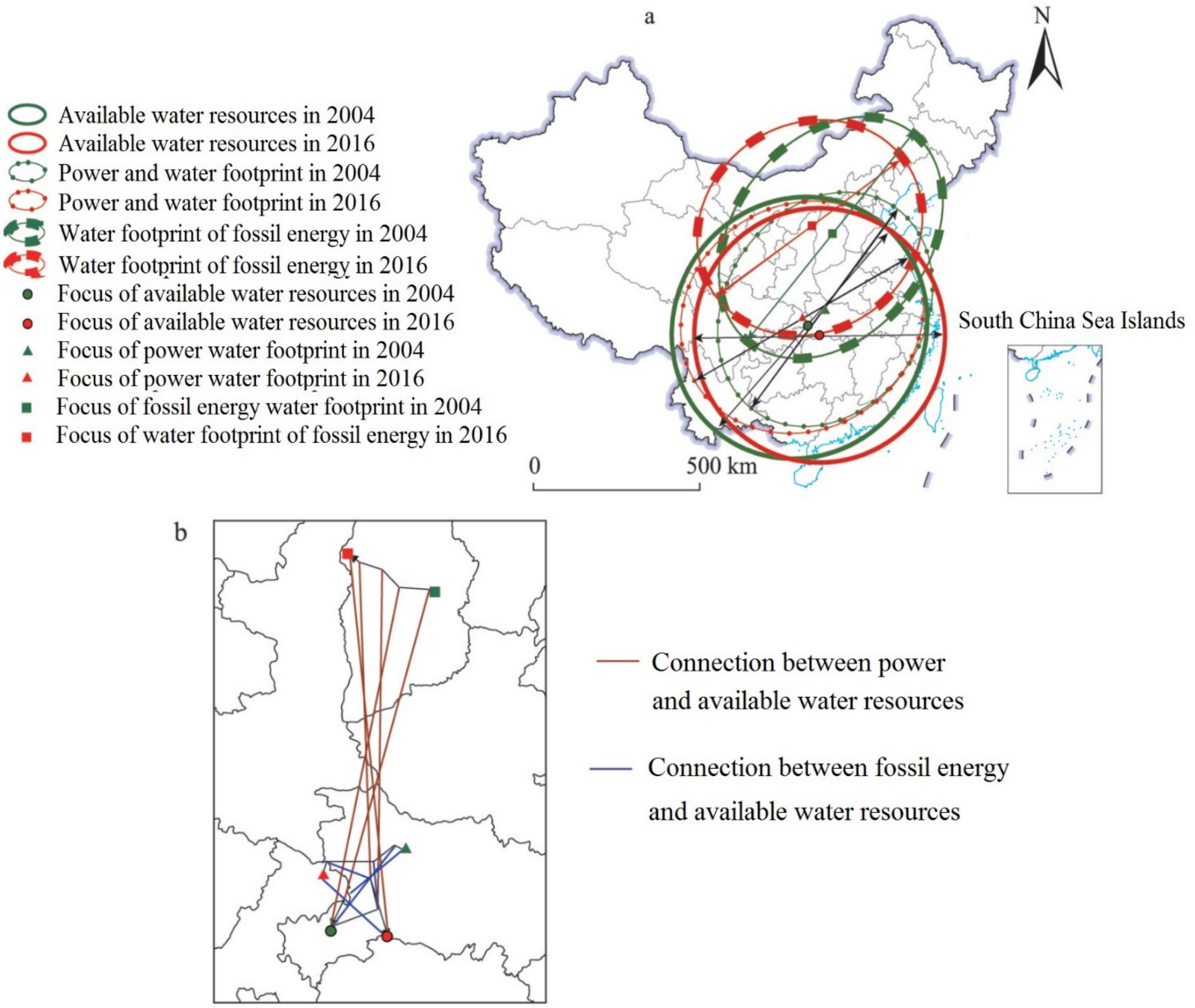


Drawing review No.: GS (2019) No.1825.
Figure 3. Distribution and spatial variation of the water footprint of power in 30 Provinces of China, 2004–2016.

thermal power water footprint agglomeration area; Sichuan, Hubei, Yunnan, Guizhou, Guangxi and other regions to the south of the power water footprint boundary are abundant in water resources. The proportion of hydropower water footprint is higher than 50%, forming a hydropower water footprint agglomeration area. As can be seen from **Figure 3b**, the power and water footprints of all provinces (cities and autonomous regions) in China showed an increasing trend year by year from 2004 to 2016, with an increase range of 0.42–54.61 billion m^3. The power and water footprint increment in the south of the power and water footprint boundary is generally higher than that in the north of the boundary. This is because the Yangtze River Basin, the Pearl River Basin and the southeast coast to the south of the power water footprint boundary have abundant water flow and the terrain conditions suitable for the construction of hydropower stations. With the strong support of national policies, their hydropower projects have developed rapidly. In particular, after 2013, Jinping Hydropower station in Sichuan Province and Xiangjia hydropower station at the border of Sichuan Province and Yunnan Province have been put into operation, which has greatly increased the hydropower production of Sichuan and Yunnan, Maximize the power and water footprint increment. In the area north of the power water footprint boundary, Beijing, Tianjin, Hebei, Shanxi and Henan region is under strict control, and its large and medium-sized cities and nearby areas will not be equipped with new coal-fired power plants, thus limiting the growth rate of its thermal power water footprint. Inner Mongolia and Xinjiang have more coal resources. In order to promote the rapid development of local economy, new thermal power projects have been added, resulting in more increment of thermal power water footprint. The rapid development of hydropower and the effective control of thermal power have gradually increased the spatial difference of China's power water footprint. Compared with **Figure 3c–d**, it can be found that from 2004 to 2016, the power water footprint gradually formed a spatial evolution trend of high-value concentration along the Yangtze River Basin, the Pearl River Basin and the southeast coast.

3.2 Spatial matching relationship between China's energy and water footprint and water resources

The geographical and spatial differences in China's water resources restrict the development of the energy industry. At the same time, the increase in energy production has also increased the pressure on water use in various regions to varying degrees. In some regions where water resources are scarce, the growth of energy and water footprint is easier to accelerate the shortage of local water resources and water pollution. In order to analyze the matching relationship between China's energy and water footprint and the spatial pattern of water resources, ArcGIS 10.2 software is used to generate the ellipse of the center of gravity and standard deviation of the energy and water footprint and available water resources from 2004 to 2016. Formula (5) is used to calculate the center of gravity coordinates of the energy and water footprint and available water resources at five time nodes from 2004 to 2016, and then calculate the relative center of gravity distance, as shown in **Figure 4** and **Table 2**. For the convenience of observation, only the standard deviation ellipse of the start and end years is displayed.



Drawing review No.: GS (2019) No.1825.

Figure 4. Gravity center and standard deviation elliptic distribution of the water footprint of energy and available water resources in China.

Table 2. Gravity center relative distance between the water footprint of energy and available water resources in China, 2004–2016

Classification	**2004**	**2007**	**2010**	**2013**	**2016**
Relative center of gravity distance between fossil energy water footprint and available water resources/km	728.177	789.021	773.555	721.311	876.097
Distance of relative gravity center between electric power water footprint and available water resources/km	189.075	256.811	123.271	98.302	208.090

It can be seen from **Figure 4a** that the standard deviation ellipse of available water resources and electric power water footprint covers most of central and southern China, and the standard deviation ellipse of fossil energy water footprint covers most of central and Northern China with high fossil energy output. The intersection area of the standard deviation ellipse of the electric power water footprint and the standard deviation ellipse of the available water resources is large, which indicates that the electric power water footprint and the available water resources are highly matched in the spatial pattern. The intersection area between the standard deviation ellipse of fossil energy water footprint and the standard deviation ellipse of available water resources is relatively small, indicating that the matching degree between fossil energy water footprint and available water resources is lower than that between electric power water footprint and available water resources.

It can be seen from **Table 2** and **Figure 4b** that the distance between the center of gravity of the fossil energy water footprint and the available water resources is larger than that of the electric power water footprint. It has been further verified that the spatial matching degree between the fossil energy water footprint and the available water resources is low. From 2004 to 2016, the center of gravity of available water resources moved irregularly, the center of gravity of fossil energy water footprint moved to the northwest as a whole, and the center of gravity of electric power water footprint moved to the southwest as a whole. The distance between the center of gravity of fossil energy water footprint, electric power water footprint and available water resources showed a fluctuating growth trend. It shows that the matching degree of fossil energy water footprint, electric power water footprint and available water resources in spatial pattern has decreased. After 2013, the distance between the center of gravity of fossil energy water footprint, electric power water footprint and available water resources has increased significantly, that is, the commissioning of West–East power transmission, Xinjiang outward power transmission and other projects has a certain impact on local water resources in the geographical and spatial dimension.

3.3 China's energy and water footprint pressure index

There is a "barrel" principle in the matching degree between energy water footprint and available water resources, that is, it is jointly restricted by the pressure index of fossil energy water footprint and the pressure index of electric power water footprint. If either index is too high, it will put pressure on water resources. **Figure 5** shows the spatial matching degree of energy and water footprints and available water resources of China's provinces (cities and autonomous regions) in 2016. According to the research, they are divided into three types according to the matching degree: (1) when F > 40%, it is an energy–water relationship tense area, that is, energy production has caused great pressure on the local water resources environment, and even caused pollution and shortage of water resources, and the relationship between energy and water resources is tense; (2) when F is between 10%–40%, it is a restricted area of energy–water relationship, that is, energy production has a certain pressure on the local water resources environment, and the development of the local energy industry is restricted by water resources; (3) when F < 10%, the energy water relationship is moderate, that is, the pressure of energy production on the local water resources environment is small, and the relationship between energy and water resources is relatively mild.

It can be seen from **Figure 2**, **Figure 3** and **Figure 5** that regions with high water footprint pressure index of fossil energy are mainly distributed in high-value coal water footprint concentration areas in Taihang Mountain and Helan Mountain, and regions with high power water footprint pressure index are mainly distributed in high-value thermal power water footprint concentration areas in the eastern region. On the whole, the matching degree of energy and water footprint and available water resources is high in the south and low in the north. In the north, the energy water relationship is tense and the energy water relationship is restricted, while in the south, the energy water relationship is moderate. The proportion of raw coal water footprint and thermal power water footprint of energy and water footprint in regions with energy water relationship tension and energy water relationship restriction is large. Most of the regions are both high value regions of raw coal water footprint and thermal power water footprint, and regions with high pressure of energy water matching, indicating that the spatial distribution pattern of raw coal water footprint and thermal power water footprint is the main factor negatively affecting the spatial matching of energy and water footprint and water resources. The energy

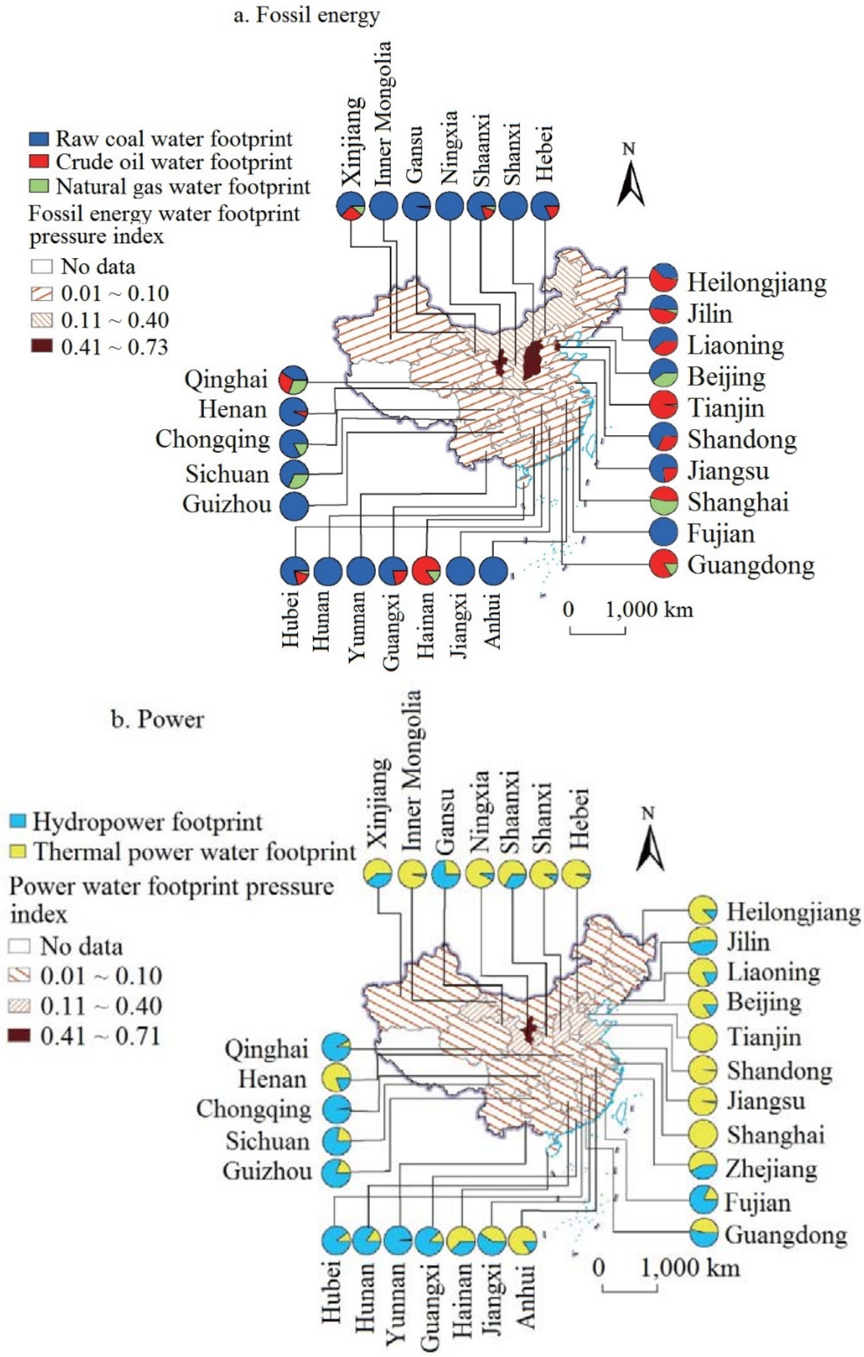


Figure 5. Spatial matching relation between the water footprint of energy and available water resources in 30 Provinces of China, 2016.

water contradiction between raw coal production and thermal power generation is the most prominent.

There are three provinces (cities and autonomous regions) with tight energy water relationship, namely, Ningxia, Tianjin and Shanxi. These regions are extremely deficient in water resources, and their available water resources rank first, second and fifth from the bottom of the country. The water footprint of fossil energy in Ningxia and Shanxi is dominated by that of raw coal, and the water footprint of electric power in the three regions is dominated by that of thermal power. Among them, although the water footprint of fossil energy and electric power in Ningxia is small, the serious scarcity of water resources in Ningxia has led to a tense relationship between local energy and water resources. Shanxi's raw coal water footprint and thermal power water footprint are both high, resulting in its fossil energy water footprint pressure index and electric power water footprint pressure index being much higher than that of other regions.

In addition, Tianjin is rich in oil resources. Its original oil-water footprint is high and accounts for a large proportion in the water footprint of fossil energy, resulting in a prominent contradiction between Tianjin's crude oil production and local water resources.

There are seven provinces (cities and autonomous regions) with restricted energy–water relationship, namely, Inner Mongolia, Gansu, Shaanxi, Hebei, Shandong, Beijing and Shanghai, all of which are relatively short of water resources, and the water footprint of fossil energy in these regions (except Shanghai) is mainly raw coal water footprint, and the water footprint of electric power in these regions (except Gansu) is mainly thermal power water footprint. Among them, the economic development of Shandong, Inner Mongolia and Shaanxi is dominated by the secondary industry, with large energy output and high energy and water footprints. Their energy production has caused certain pressure on local water resources. The Yangtze River Basin in Gansu Province is rich in water resources. A certain number of hydropower projects have been built, resulting in the proportion of hydropower water footprint in Gansu Province is greater than that of thermal power. However, the distribution of water resources in Gansu Province is extremely uneven and in general is relatively short, resulting in certain restrictions on its energy production. In addition, Beijing and Shanghai have a high degree of economic development and a large population density. Under the influence of industrial structure, national policies and other factors, their fossil energy production structure is relatively optimized. The proportion of natural gas water footprint is much higher than that of other regions. The overall energy and water footprint are low, but their available water resources are small, ranking the third and fourth from the bottom of the country, resulting in a large pressure index of power and water footprint in Beijing and Shanghai.

The number of regions with moderate energy water relationship accounts for 60%, including the southern region, the three northeastern provinces, Xinjiang and Qinghai. The southern region has less fossil energy reserves, more water resources reserves, and the overall water footprint of fossil energy is low. In most regions, hydropower is the main mode of power production, and the proportion of hydropower and water footprint is high. Therefore, the local energy and water footprint is relatively matched with water resources. Xinjiang is a vast and sparsely populated region with uneven distribution of water resources. The overall water resources and energy reserves are large, and the types of fossil energy are rich. However, due to the backward economic development and the lower degree of energy development than other regions, the pressure index of its energy and water footprint is small. Although the three provinces in Northeast China are rich in coal resources, the poor geological conditions of raw coal mining restrict the development of coal and thermal power industries, making their energy and water footprints smaller than other regions rich in energy reserves, and the local energy production has less pressure on water resources.

4. Conclusion and discussion

4.1 Conclusion

This paper adopts the bottom-up energy and water footprint evaluation model, which overcomes the characteristics of the inability of the top-down input-output model to reflect the current situation of energy and water footprint due to data limitations. Through the empirical study on the time sequence and spatial pattern evolution of China's fossil energy water footprint and electric power water footprint, the change tracks of China's fossil energy water footprint and electric power water footprint in time and space are depicted, and the spatial matching relationship between China's energy water footprint and water resources is analyzed by combining the center of gravity, standard deviation ellipse model and energy water footprint pressure index. The following conclusions are obtained:

(1) In terms of time, the water footprint of fossil energy increased first and then decreased in the study period with 2012 as the boundary, and the proportion of natural gas water footprint continued to increase, but the proportion was small; the electricity and water footprint continued to grow during the study period, and the proportion of

hydropower continued to increase. The electric water footprint is larger than the fossil energy water footprint, but the electric grey water footprint is smaller than the fossil energy grey water footprint. Under a certain amount of energy production, the increase in the proportion of hydropower in the energy production structure not only makes full use of water resources, but also directly reduces the pollution of energy production to water resources.

(2) From the perspective of spatial pattern, the water footprint of fossil energy generally increases in the west and decreases in the east with the Huhuanyong line as the boundary. The spatial pattern has changed from areas along the Huhuanyong line as the main high-value area in 2004 to on the evolution trend of agglomeration with the Inner Mongolia Shanxi Shaanxi region as the high-value center in 2016; the power and water footprints in all regions are increasing year by year. The power and water footprint dividing line divides Inner Mongolia, Shanxi, Shaanxi, Shandong, Henan and other regions to the north of the boundary into thermal power water footprint concentration areas, and Sichuan, Hubei, Yunnan, Guizhou, Guangxi and other regions to the South of the boundary into hydropower and water footprint concentration areas. The rapid growth of hydropower and water footprint makes the power and water footprint increment in the south of the boundary generally higher than that in the north of the boundary, and gradually forms along the Yangtze River Basin The evolution trend of high-value agglomeration in the Pearl River Basin and the southeast coast.

(3) The spatial matching degree of energy water footprint and available water resources fluctuates and decreases, and the spatial matching degree of fossil energy water footprint is lower than that of electric power water footprint and available water resources. The matching degree between energy and water footprint and available water resources is high in the south and low in the north. In the north, the energy water relationship is tense and restricted, and in the south, the energy water relationship is moderate. The energy water mismatch area accounts for 1/3 of the whole country, mainly distributed in North China and Shaanxi Gansu Ningxia region. North China is not only an area with high pressure of energy water matching, but also a high value area of raw coal water footprint and thermal power water footprint. The energy water contradiction between raw coal production and thermal power generation is the most prominent.

4.2 Discussion

As a whole, China's energy and water footprint is growing, and the mismatch between energy and water footprint and water resources is becoming increasingly prominent, which undoubtedly aggravates the problem of water shortage in China. While reducing the water footprint per unit output in the life cycle of energy production through technological innovation, the spatial pattern of the energy industry should be reasonably adjusted to optimize its water demand allocation. In the 13th five–year plan for energy development, it is proposed that the energy industry should develop according to water resources, develop and adjust the energy industry in areas rich in water resources, and fully consider the regional resource carrying capacity while promoting economic development. This paper holds that the shortage of water resources caused by energy production in the energy–water relationship tense region has affected other local economic activities and residents' lives, and energy production should be reduced to alleviate the pressure on water resources; energy water relationship restricted regions should reasonably adjust the energy industrial structure of such regions, increase the proportion of clean energy with less energy and water footprint per unit output such as natural gas, and make economic development and water resources protection go hand in hand; regions with moderate energy water relationship can reasonably develop energy industry according to local resource endowment, and regions with small fossil energy reserves can appropriately develop new energy such as wind energy, nuclear energy and tidal energy. In addition, the formulation of laws and regulations on energy water related management and the clarification of relevant indicators will also promote the coordinated development of energy and water resources.

The main contributions of this paper are as follows: firstly, the energy and water footprint is used as an indicator to measure the occupation and pollution of water resources in the life cycle of energy production. Compared with the indicators such as energy and water consumption, the energy and water footprint is closer to the real water consumption, which makes up for the deficiency of the existing domestic multi resource correlation research on the quantitative correlation analysis between energy and water resources; secondly, compared with many single year energy and water footprint studies, multi-year data make up for the lack of research on the evolution trend of energy and water footprint in time and space dimensions; thirdly, in view of the deficiency of the existing research on the relationship between energy and water footprint and water resources matching, the energy and water footprint pressure index is used to measure the pressure caused by energy production on water resources, and then the difference degree of spatial matching between energy and water resources in each region is compared.

This paper is in the stage of basic exploration, and there are inevitably some shortcomings: as China has not yet formulated the standards for unit water consumption and COD emission of some energy, it will bring some deviation to calculate with the results of existing literature; this paper does not consider the deviation of water footprint per unit energy output caused by the use of alternative water sources and recycled water in various regions, the type and degree of fossil energy processing or washing, the nature of mined coal seams and the evaporation rate of stored water; since the relevant data of new energy such as wind energy, nuclear energy and tidal energy cannot be obtained, the impact of its water footprint on the overall energy and water footprint is not calculated in this paper.

Conflict of interest

The authors declared no conflict of interest.

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ORIGINAL RESEARCH ARTICLE

Bottleneck and development path of water resources protection and utilization in Henan Province in the new era

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ABSTRACT

Objective: to promote the sustainable and efficient utilization of water resources in Henan Province, accelerate the optimization of the water resources management system, innovate the government administrative management mode, and provide new strategic countermeasures and path choices for the industrial upgrading and transformation in water resources related fields and the high-quality development of regional economy in Henan Province. **Methods:** by combing the current situation and existing problems of water resources utilization in Henan Province, this study focuses on analyzing the strategic opportunities faced by the field of water resources in Henan Province and expounds on the innovation and application of cutting-edge key technologies for water resources protection and utilization in Henan Province. **Results:** while the protection and utilization of water resources in Henan Province have achieved great results, it still faces great challenges: low water-saving results, imperfect advanced technology system, unstable water pollution control results, and imperfect water resource management mechanism. **Conclusion:** in the future, we must coordinate the relationship between water resources development and protection, establish the idea of harmonious development, give full play to the regional advantages of Henan Province, strengthen the research and development of cutting-edge key technologies, innovate the government management mechanism, and realize the efficient and sustainable utilization of water resources.

Keywords: Water Resources Protection; Utilization of Water Resources; Food Security; Technological Innovation High-quality Development

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1. Introduction

Water is one of the indispensable resources for human survival and development. The protection and utilization of water resources have the dual characteristics of natural resources and economic resources[1]. Henan, as an emerging industrial province, has witnessed active economic development in recent years, making a significant contribution to the national economic development and energy consumption growth. At the same time, it is also an important major grain-producing area in the main functional zoning of China along the nine provinces and regions of the Yellow River (Qinghai, Sichuan, Gansu, Ningxia, Mongolia, Shanxi, Shaanxi, Henan, Shandong)[2-4]. According to the announcement of the National Bureau of statistics on the grain production data in 2019, the national grain planting area in 2019 was 1.2×10^8 hm^2; the total grain output is 663.84 million tons, of which the sown area in Henan is the second in China, reaching 1.1 × 10^7 hm^2; the total grain output is 66.95 million tons, exceeding 1/10 of the national total. However, the economy of Henan Province has been an "extensive" development for a long time, and the problems of wa-water resources waste and environmental pollution are serious. Economic development is increasingly restricted by the environment and resources. In order to support the national food security, provide the basic guarantee of agricultural water resources, strengthen engineering water conservation and agronomic water conservation, enhance the efficiency of water resources utilization and management, and build a water-saving and efficient modern irrigated agriculture and modern dry farming agriculture with rainwater harvesting efficiency, it has important strategic significance for the regional economic and social development of Henan[1,5-7]. Although some scholars have conducted in-depth research on the carrying capacity, sustainable utilization, evaluation and prediction, development strategy, and other aspects of water resources in Henan Province, the in-depth exploration and Research on water resources protection, utilization efficiency, and key technologies are still relatively weak[8-11].

As the development of the Yellow River Basin has been identified as a major national strategy, Zhengzhou, Henan Province, as the strategic hub of the National Central City, is expected to continue to deepen the industrialization of the province, and the rise of the Central Plains will inevitably lead to the consumption of more water resources. On the other hand, the development concept of Xi Jinping's thought on ecological civilization in the new era has its inherent requirements of keeping "lucid waters and lush mountains" and building a bridge from "lucid waters and lush mountains" to "golden mountains and silver mountains", so that the lucid waters and lush mountains contain huge The ecological benefits, economic benefits and social benefits will continue to help the transformation of the Yellow River Basin to high-quality development[12-15]. On the whole, the above new development situation provides a new strategic opportunity for the protection and utilization of water resources and the transformation and upgrading of related industries[1,16-18]. In practice, further controlling and reducing the waste of water resources and the emission of environmental pollutants has a very important impact on the high-quality economic development and transformation of Henan Province. By combing the current situation and existing problems of water resources utilization in Henan Province, this study probes into the bottleneck of water resources protection and utilization, and based on the relevant cutting-edge key technologies and their application prospects, attempts to provide scientific reference and theoretical basis for the ecological protection and high-quality development of water resources in Henan section of the Yellow River Basin.

2. Current situation of water resources protection and utilization in Henan Province

2.1 Characteristics of water resources in Henan Province

2.1.1 Water resources are in short supply, and the per capita occupancy is small

The annual average total water resources of Henan Province are 40.353 billion m^3, less than 1.45% of the national total, of which the total available is 19.524 billion m^3. At the same time, due to the large population base, the per capita water resources are only 376 m^3, which is 1/5 of the national per capita water resources and 1/16 of the world per capita water resources. It is a province with insufficient self-produced water resources carrying capacity and a serious water shortage area. The total water resources of the Haihe River, the Yellow River, the Huaihe River, and the Yangtze river basins under the jurisdiction of the province in 2018 were 2.31 billion, 4.54 billion, 21.19 billion, and 5.94 billion m^3 respectively, a decrease of 16.2%, 22.5%, 13.9%, and 16.7% respectively compared with the multi-year average.

2.1.2 Uneven spatial and temporal distribution of water resources and mismatching of water and soil resources

The water resources in Henan Province vary greatly from year to year. In 2018, the total amount of water resources in Henan Province was

33.98 billion m^3, 16.7% less than the multi-year average and 19.7% less than that in 2017. In addition, the annual distribution of river runoff in Henan Province is uneven, and the runoff is mostly concentrated from June to September. The annual average maximum runoff for four consecutive months accounts for 45% to 90% of the annual runoff. The difference between the annual average monthly maximum and the monthly minimum is 9.5 times, which is very easy to cause drought and flood disasters. Spatially, the water and soil resources in Henan Province do not match, as shown in **Table 1**. In 2018, the total water resources in the northern and eastern plains of Henan province accounted for only 30.17% of the province, and the average water resources per mu and per capita were insufficient; the southern and western hilly areas account for 1/2. However, by the end of 2018, the population of the northern and eastern plains of Henan province accounted for 56.23% of the total population of the province, the GDP accounted for 59.76% of the province, and the grain output accounted for 57.52% of the province. Water and soil resources do not match, economic and social development does not adapt to the distribution of water resources, and water resource allocation is difficult, which restricts the high-quality development of Henan Province to a certain extent.

Table 1. Population, GDP, cultivated land area, grain yield, and total water resources proportion of Henan province in 2018 (%)

District	Population	GDP	Cultivated land area	Grain yield	Water resources proportion
Northern and Eastern Henan plains	56.23	59.76	50.73	57.52	30.17
Southern and Western Hills	43.77	40.24	49.27	42.48	69.83

Note: The data involved in this section are collected from the water resources bulletin, statistical yearbook, ecological environment status bulletin, and government documents of Henan Province.

2.1.3 The water environment is seriously polluted by human activities

In recent years, the rapid economic development of Henan Province has also caused great damage to the ecological environment. According to the statistical data of Henan Province, the wastewater discharge in Henan Province increased from 2.507 billion tons to 4.113 billion tons from 2004 to 2017. Among the 141 monitoring sections in the province in 2018, 85 sections with water quality meeting the class I–III standards, accounting for only 60.4%, lower than the national average level; there are 5 sections whose water quality is inferior to class V, accounting for 3.5%. In 2019, of the 94 surface water national examination sections, 64 were class I–III water quality sections, accounting for 68.1%, and there were no sections with inferior class V water quality; the standard rate of centralized drinking water source is 97.7%.

2.1.4 Unreasonable water supply structure and serious groundwater overexploitation

In 2018, the total water supply of Henan Province was 23.46 billion m^3, among them, groundwater supply accounts for 9.5% of the total water supply, and unconventional water sources such as rainwater collection account for only 2.6%. Due to unreasonable water supply structure and overexploitation of groundwater, the total area of shallow groundwater funnel in the province was 9,756 km^2 in 2018, an increase of 2,509 km^2 compared with 2004. In 2018, the agricultural water consumption, industrial water consumption, and comprehensive water consumption of urban and rural living environments in Henan province accounted for 51.1%, 21.5%, and 27.4% of the total water consumption respectively. However, due to the differences in economic structure and water resource conditions among cities, there are certain differences in water use structure among regions.

2.2 Current situation of water resources protection and utilization in Henan Province

2.2.1 The utilization efficiency of water resources is improved, but the water-saving effect is low

Henan province takes the strictest water resources management system as an important measure to promote the construction of water ecological civilization, and constantly improves the efficiency of water resources utilization, as shown in **Figure 1**. The water consumption per 10,000 yuan of GDP in Henan Province decreased from 226 m^3/10,000 yuan in 2004 to 37 m^3/10,000 yuan in 2018; the water consumption of 10,000 yuan industrial added value decreased from 10^3 m^3/10,000 yuan to 26 m^3/10,000 yuan in 2018, but the GDP output per cubic meter of water in the province is only 1/3 of the world average level, and the water consumption of 10,000 yuan industrial added value is still 3–4 times that of developed countries. In 2018, the utilization coefficient of farmland irrigation water in Henan Province was 0.61, the reuse rate of industrial water above the designated size was 90%, and the utilization rate of urban renewable water was 24.4%, which was a certain gap with the advanced regions in China. Water deficient cities above the prefecture level have not yet reached the national water-saving city standard, and the construction and development of a water-saving society is unbalanced, which is still far from the requirements of all-around and whole process water conservation.

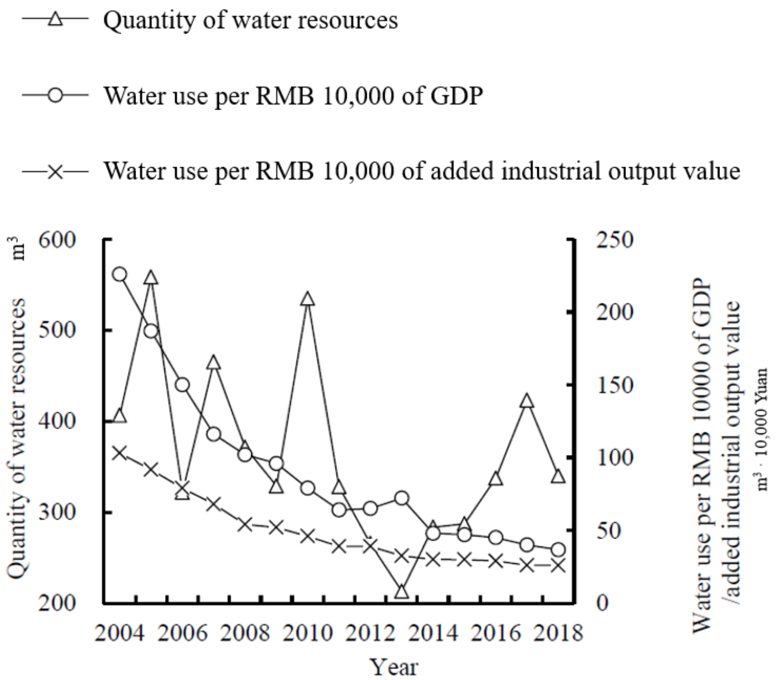

Figure 1. Annual variation of quantity of water resources and water use in Henan Province.

2.2.2 Vigorously develop advanced technology, but the technical system is not perfect

As a major agricultural province, Henan Province has continuously accelerated the pilot work of agricultural water-saving technologies such as border irrigation, furrow irrigation, sprinkler irrigation, and micro irrigation, so that the average water consumption per mu of farmland irrigation decreased from 176 m^3 in 2004 to 155 m^3 in 2018; strengthen the research and development of new technologies and equipment for domestic sewage and industrial wastewater treatment and resource utilization to realize the recycling of water resources; combining remote sensing and network monitoring technology, we will basically form an intelligent control supervision system for the construction of ecological civilization. However, in many areas of Henan Province, agricultural irrigation methods are still relatively extensive, and there are still phenomena of blindly building high water consumption and heavy pollution projects in water resource shortage and ecologically fragile areas[7-9]. The development, promotion, and application of advanced and practical high-efficiency water-saving technologies are not enough, and the engineering technology system for high-efficiency utilization of water resources is not perfect.

2.2.3 The effect of water environment treatment is obvious, but the pollution source control is insufficient

Henan Province has carried out an in-depth battle for the protection of clean water, the water quality level of groundwater quality assessment points has remained stable, the black and odorous water bodies have been gradually eliminated in the built-up areas of cities under the provincial jurisdiction, and the water quality of Danjiangkou reservoir, the water source of the middle route of the South-to-North Water Transfer Project, has reached class II. In 2019, Henan Province newly revised its regulations of Henan Province on the prevention and control of water pollution, putting forward higher requirements for the prevention and control of water pollution. The Henan provincial government adheres to “governance” and “construction” at the same time. It plans to build Zhengzhou into a leading ecological construction area in the Yellow River Basin by 2020, with a wetland area of no less than 628,000 hm^2 and a wetland protection rate of more than 50%. However, due to the backward treatment idea and the neglect of the harmonious relationship between man and nature, the discharge of urban domestic sewage and industrial wastewater increases year by year, the water quality fluctuates greatly, and the problem of water pollution has not been fundamentally treated. At the same time, the excessive use of pesticides, fertilizers, and so on has led to the continuous increase of point source pollution and the increasingly prominent non-point source pollution[20], which increases the difficulty of water resources system treatment and protection.

2.2.4 The supervision ability of water resources is gradually improved, but the management mechanism is not perfect

Although Henan Province has implemented a series of water resources management measures in recent years, issued the “implementation plan for deepening the reform of comprehensive administrative law enforcement of ecological environmental protection in Henan Province”, promoted the pilot construction of water rights, ecological water volume regulation, water ecological civilization, and improved the level of water resources management, there is a lack of coordination mechanism and management technology among departments, and the efficiency of water resources management system is low, including water intake licensing system, water rights trading system The water ecological compensation system and other systems are still not perfect, the market allocation mechanism is not perfect, citizens’ awareness of water resources protection is weak, and the integration of water resources protection supervision is not high, which is not conducive to the comprehensive management, scientific planning and unified scheduling of water resources.

3. Opportunities and challenges

3.1 Opportunities for water resources protection and utilization in Henan Province

3.1.1 Strong regional advantages

Henan Province is located in the Central Plains, spanning the Huaihe River Basin, the Yangtze River Basin, the Yellow River Basin, and the Haihe River Basin (with drainage areas of 86,100, 27,700, 36,000, and 15,300 km^2 respectively). It is a national comprehensive transportation hub and logistics center, as well as an important area of national development strategies such as the “Belt and Road” and the Central Plains Economic Zone. Its geographical advantages can strengthen the formulation of water resources policies, infrastructure construction, and water disaster prevention and control Cooperation at different levels such as scientific, technological, and cultural exchanges[19] provides support for the protection and utilization of water resources in Henan Province and the research and development of advanced technologies.

3.1.2 Major national strategic needs

Henan Province involves the two national strategies of ecological protection and high-quality development of the Yangtze River economic belt and the Yellow River Basin. While building a well-off society in an all-around way and pursuing high-quality economic and social development, puts forward higher requirements for the protection and utilization of water resources in Henan Province. With the support of national strategies and national policies, it will help to give full play to the economic advantages of Henan Province, promote industrial transformation, increase investment in water conservancy projects and environmental governance, and promote the construction progress of the “top ten water conservancy projects”, build a livable environment in the process of “seeking development in protection and promoting protection in development", and realize the coordinated development of ecological civilization construction and economy.

3.1.3 Local governments attach great importance to it

Henan Province has issued a number of measures from the policy level to practice the idea of ecological civilization and the concept of high-quality development. In 2013, the opinions on the implementation of the strictest water resources management system was issued, which established the red line for the development and utilization of water resources, the red line for the control of water use efficiency, and the red line for the limitation of water function areas; in 2019, the "implementation plan of water saving action in Henan Province" was issued, which made it clear that the reuse rate of industrial water above Designated Size in the province should reach more than 91%, the effective utilization coefficient of farmland irrigation water should be increased to 0.616, the leakage rate of public water supply pipe network should be controlled within 10%, and the total water consumption should be controlled within 28.215 billion m^3; in February, 2020, a series of policies and regulations were issued, such as the notice on printing and distributing the implementation plan of the 2020 air, water and soil pollution prevention and control in Henan Province, which proposed that the surface water should eliminate the inferior class V water quality; the water quality compliance rate of centralized drinking water sources in cities under the jurisdiction of the province has reached 10%; the water quality of Danjiangkou reservoir, the water source of the middle route of the South-to-North Water Transfer Project, is stable and reaches class II; the water quality level of the groundwater quality assessment points remains stable, and the black and odorous water bodies are completely eliminated in the built-up areas of the cities under the jurisdiction of the province.

3.1.4 The external environment tends to be perfect

Although Henan Province is short of water resources, it is rich in transit water, with an average annual inflow of 41.364 billion m^3 and an outflow of 63.022 billion m^3. At the same time, as the main water receiving area of the South-to-North Water Transfer Project, the water allocation of the South-to-North Water Transfer Project in Henan Province is 2.994 billion m^3, which effectively solves the problems of water resources shortage, uneven spatial and temporal distribution and serious groundwater exploitation in Henan Province. The aforementioned series of water-saving policies and regulations, market mechanisms, and standard systems are further improved, which plays a positive role in improving the utilization efficiency of water resources in Henan Province, increasing water-saving measures, and protecting water ecological security.

3.2 Challenges faced by water resources protection and utilization in Henan Province

3.2.1 Contradiction between economic and social development and water ecological protection

Since entering the 21st century, the economy of Henan Province has developed rapidly. From 2005 to 2018, the per capita GDP of the province increased from 11,346 yuan/person to 52,114 yuan/person. The industrial structure has been optimized and upgraded, but the traditional industries with high energy consumption and high pollution still account for a large proportion. Economic development is accompanied by changes in population structure. According to statistics, from 2005 to 2018, the urbanization rate of Henan Province increased from 30.65% to 51.72%. Population growth and industrial scale expansion make the resource and environmental carrying capacity of Henan province close to the limit. Although relevant governments have always emphasized the pursuit of green and sustainable development, how to balance the relationship between economic and social development and water ecological protection, change the existing development model and achieve high-quality economic development is still an urgent problem to be solved.

3.2.2 Contradiction between water security engineering and technical system

Henan Province is endowed with insufficient water resources, the contradiction between humans and water is prominent, and drought and flood disasters are frequent. According to statistics, the annual average value of direct economic losses caused by natural disasters in the province from 2014 to 2018 was 8.38 billion yuan, and the affected area of crops was 1.4% × 10^5 hm^2. In order to realize the scientific development, rational allocation, and efficient utilization of water resources in Henan Province, we must build water conservancy projects such as high-quality water supply, flood control, and waterlogging elimination, and strengthen non-engineering measures such as disaster prediction. At the same time, it also needs a series of advanced technologies to improve the efficiency of water resource utilization, improve the water environment, repair the water ecosystem, and reduce flood and drought disasters. How to combine water conservancy projects and technical systems to achieve drinking water safety, water supply safety, and flood control safety will be the focus of further research in the future.

3.2.3 Contradiction between water safety system and administrative management mode

In recent years, under the guidance of the strictest water resources management system, Henan Province has strictly adhered to the "three red lines", established and continuously improved the "four systems", promoted the innovation of the system and mechanism of the same governance of the four rivers, formulated the river director system management system, and reorganized and reformed the relevant departments of water resources management. At present, the government functions of Henan Province are still inconsistent with the requirements of ensuring the sustainable and efficient utilization of water resources. In order to ensure the water safety of Henan Province, strengthen the management of water demand and water use process, formulate a complete set of scientific and effective administrative management systems, and ensure the implementation of various systems is urgent work to be carried out in the future.

3.2.4 Contradiction between traditional technology and advanced technology

Since the founding of new China, the water conservancy industry in Henan Province has experienced a development stage from primary to advanced, especially since the 21st century, with the rapid development of computer network technology, the continuous combination of modern technology and traditional water conservancy technology, so that the traditional water conservancy continues to transform to wisdom. However, "smart water conservancy" is not only the construction of water conservancy informatization but also the full use of the existing water conservancy construction experience. Based on traditional water conservancy, it organically combines big data, artificial intelligence, and other new generation technologies to intelligently handle all kinds of water affairs events and improve the efficiency of water resources management. At present, the "smart water conservancy" in Henan Province mainly focuses on discussion, research, technical preparation, etc., and only some areas rely on some basic network technologies such as 3S to realize real-time monitoring of water resources. Combining the existing experience and technology with advanced technology, it is still a great challenge to realize the intellectualization of water conservancy monitoring.

4. Solutions to water resources protection and utilization problems

With the deepening of the construction of ecological civilization and the marginal decline of the effect of administrative measures, technological innovation will play an increasingly important role in breaking the constraints of resources and the environment and achieving sustainable development. It can be seen from **Figure 2** that in order to strengthen the institutional reform of ecological civilization construction and strengthen the utilization and protection of water resources in Henan Province, it is necessary to treat ecological environmental protection from the perspective of the fundamental plan related to the sustainable development of the Chinese nation, combine the characteristics of water resources utilization in Henan Province, start from the current challenges, firmly grasp the new opportunities of water resources protection and utilization in Henan Province, and control environmental pollution with stricter standards, greater efforts, and more practical measures Improve the ecological environment.

4.1 Coordinate the dialectical relationship between development and protection

The key problems existing in the protection and utilization of water resources in Henan Province, such as insufficient water resources carrying capacity, aggravated water ecosystem and groundwater pollution, the prominent contradiction between supply and demand, frequent floods, and other disasters, are in the final analysis the contradiction between water resources protection and economic and social development. Therefore, the Henan government needs to clarify the dialectical relationship between development and protection, determine the important strategic position of water resources protection, and analyze the balance point between water resource utilization and economic development. It should not only meet people's needs for water resources development, but also ensure that it is within the bearing capacity of nature, so as to achieve the optimal state between economy, resources, and natural environment, and ensure the benign evolution of economic society and natural environment. Based on this, the relevant governments must be based on the current and long-term, systematically consider the requirements of open source, throttling, protection, and other aspects, and establish an economic structure and industrial layout suitable for regional water resources on the basis of ensuring the harmonious relationship between resource utilization and long-term stable economic and social growth, so as to realize the determination of production and city by water. In addition, accelerate the construction of ecological civilization, improve the utilization efficiency of water resources, and lay the foundation for the high-quality economic and social development of Henan Province. At the same time, the rapid economic and social development also provides greater fund support for environmental protection and promotes the further deepening of environmental governance, so as to create a harmonious and virtuous cycle between development and protection[21].

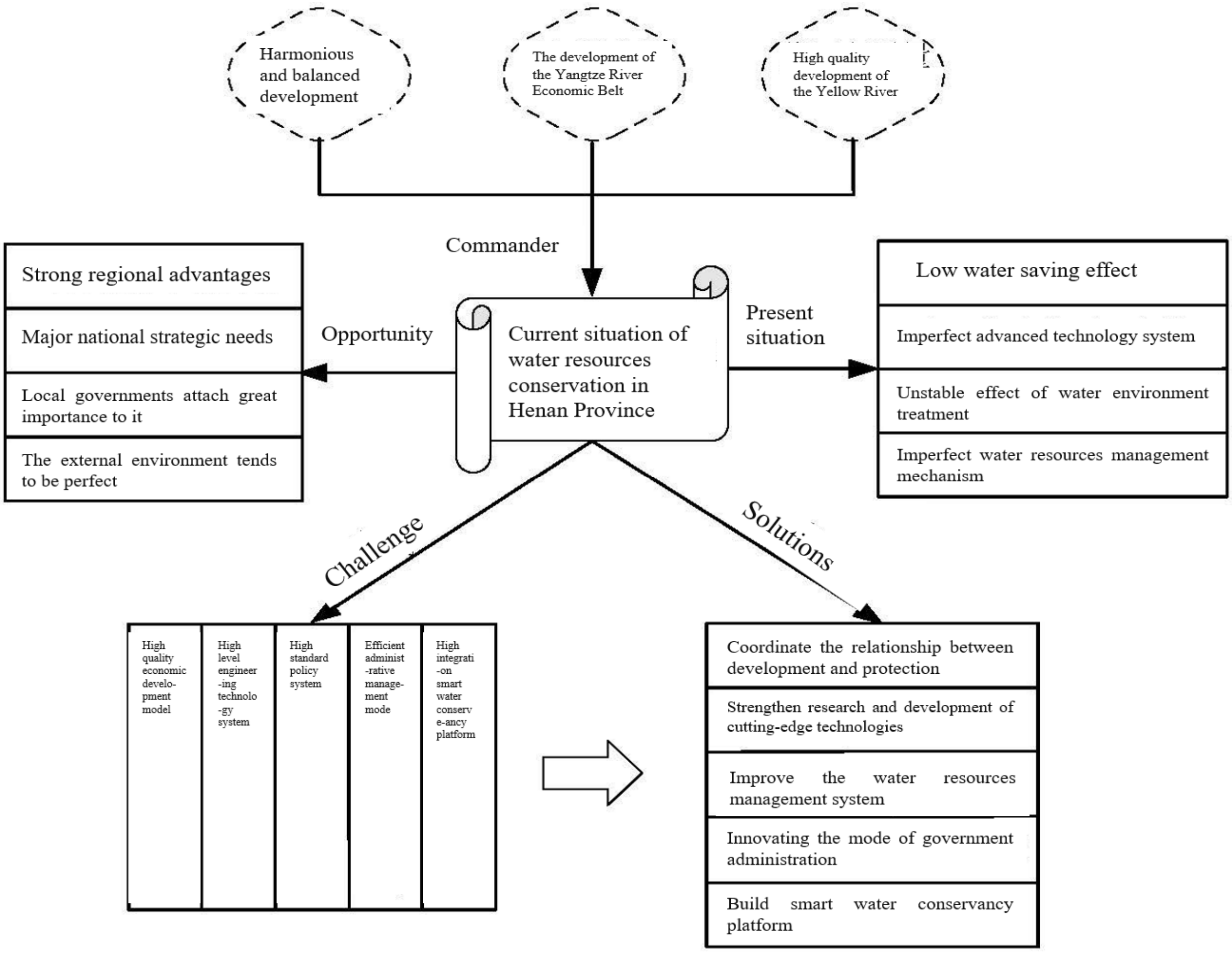

Figure 2. Current situation and path solutions in Henan Province water resources protection and utilization.

4.2 Strengthen the research, development, application, and promotion of cutting-edge key technologies

Scientific and technological innovation driving high-quality development has gradually become the consensus of most scholars to solve the problems of water resources protection and utilization, and the promotion and application of these cutting-edge key technologies in social development is the focus and new opportunity to win the battle for clear water and realize the efficient utilization of water resources under the new situation. Aiming at the key problems existing in the protection and utilization of water resources in Henan Province, the newly released and updated technical guidance catalog for energy conservation, low carbon, and environmental pollution prevention and control in Henan Province, as well as other more forward-looking technology integration, can be used as a reference and priority for users such as various industrial enterprises, industrial technology funds, funds in various green and low-carbon fields, and venture capital institutions in the upgrading and transformation of water resources protection technology. Combined with the actual situation of water resources in our province, some mature and promising cutting-edge key technologies are briefly introduced as follows:

1) Water resources protection. The integrated intercepting well and its control system reduce the pollution of black and odorous water, simulate the optimal operation scheme of the sewage treatment plant, and digital intelligent management system for the urban water environment. Five effectively stereo technology for the integrated treatment of hydrology, the construction and application of digital intelligent management system for urban water environment, the integration of lid (low impact development) and regulation and storage technology for rainwater purification and reuse, and the reduction of black and odorous water pollution by intercepting wells and their control systems.

2) Water saving. Intelligent motors and control systems for the electrical equipment of water-related enterprises such as tap water, domestic sewage, and industrial wastewater, cascade utilization technology for industrial and agricultural production and domestic water for urban residents, new technology for water-saving transformation of the production process, manufacturing technology of high-efficiency water-saving sanitary ware, water-saving technology for urban rainwater collection, purification and recycling, etc.

3) Resource utilization of industrial wastewater. High salt wastewater and miscellaneous salt resource utilization technology, high concentration ammonia nitrogen wastewater resource treatment technology, starch sugar electrodialysis desalination technology, acid salt separation and reuse technology of acid containing high salt wastewater, aniline high color wastewater treatment, and resource application, new activated carbon adsorption regeneration wastewater advanced treatment technology, coal mine drainage water preparation desalination technology, etc.

4) Technologies related to water resources in agriculture and aquaculture. High-efficiency micro drip irrigation new technology, livestock and poultry sewage treatment and biogas residue biogas liquid comprehensive utilization technology, research on compound probiotics in reducing river pollution, farm waste gas, kitchen waste treatment, soil improvement, sewage resource utilization technology, water-saving cloud and soil free plant intelligent cultivation technology, etc.

5) Groundwater. Real-time monitoring and evaluation technology of groundwater in major grain-producing areas, simulation technology of groundwater dynamics in watershed irrigation areas and administrative areas, dual control management technology of groundwater quality and quantity, calculation and post evaluation technology of pressure extraction capacity in groundwater overexploited areas, groundwater ecological restoration technology, and application, etc.

6) Hydrological environment effect and key technology of water security in Zhongyuan urban agglomeration. Research on the impact of Zhongyuan Urban Agglomeration on the associated process of the water cycle, the impact of the social water cycle on regional water quality and quantity, and the application-oriented development of the comprehensive regulation platform for hydrological environmental effects of Zhongyuan urban agglomeration.

7) Water ecosystem protection and restoration technology. Water ecological restoration and sustainable guarantee technology, construction and application of water ecological civilization system, comprehensive treatment technology and demonstration of mountains, rivers, and lakes, research, and application of river and lake dredging technology, river and lake wetland ecological restoration technology and application, water ecological assessment and monitoring research, etc.

4.3 Improve the water resources management system

Henan spans four river basins. According to the actual situation of Henan Province, we should establish a water resources management system according to the idea of unified management of the four river basins and coordinated management of administrative regions, strengthen the management of water safety by the water administrative departments of governments at all levels, strengthen the management of groundwater overexploitation and the operation of the South-to-North Water Diversion Project, so as to ensure the basic needs of economic and social development for water resources. At the same time, we should take planning as the starting point and strengthen the "four water simultaneous governance", Strictly implement the national water-saving action plan, constantly promote the optimal allocation and scientific management of water resources, and achieve water-saving efficiency in agriculture, water-saving and emission reduction in industry, water-saving and loss reduction in cities and towns, water-saving and open source in key areas, etc. In order to promote the construction of water ecological civilization, Henan Province also needs to continue to improve the laws and regulations related to ecological protection, promote the construction of a law enforcement team, comprehensively deepen the reform of water prices on the existing basis, promote the reform of water resources tax, strengthen the national awareness of water conservation, and give play to the supervisory role of the people in water resources management.

4.4 Innovate the government administration mode

In order to solve the problem of "multiple departments and multiple dragons governing water" and poor coordination ability among departments, a cooperation mechanism should be established, a unified supervision and management organization should be established, and the functions of the management organization should be strengthened. At the same time, due to China's unique political system, we cannot copy the western administrative management model. We should give full play to the unique advantages of the government, take government planning as the command, and establish a water market system that combines administrative allocation and market regulation. In addition, it is also necessary to innovate the government assessment mechanism, link the implementation of various water management policies and water resource utilization efficiency with the government work assessment, strengthen the assessment support, and "force" the government to improve the construction of water resource monitoring capacity and water resource utilization efficiency, promote the development of water conservation work in the whole society, and speed up the construction process of ecological civilization.

4.5 Construction of "smart water conservancy" platform

The primary task of building a smart water conservancy platform needs to cultivate high-level scientific and technological talents, and strengthen interdisciplinary exchanges in hydrology, water resources, water economics, ecology, computer networks, and so on. In the future, it is necessary to build a complete water conservancy information monitoring system in combination with big data and system network, so as to realize the automation of real-time monitoring of water conservancy information and the digitization of water system data; combining modern technical means such as Internet of things and 5 g, comprehensively considering multiple factors such as economic and social development, coupling multiple modules such as water supply, water demand and flood control, realizing real-time scheduling of water resources, flood control and disaster reduction based on cloud computing technology, and building an intelligent water conservancy "module integrated system"; combine smart water conservancy with smart city, build a "decision-making and service system" for smart water conservancy, realize information-based management and intelligent decision-making, achieve refinement of water resources management, and provide platform support for water resources protection, utilization and optimal allocation[22].

5. Conclusion

A series of documents of governments at all levels and relevant competent departments in Henan Province provide policy basis and cutting-edge key technical support for the protection and utilization of water resources; together, the two have created a foreseeable strategic opportunity for the protection and utilization of water resources in Henan Province, and these opportunities and challenges require more open thinking, innovative passion, and practical efforts. Looking forward to the future, the continuous innovative application of multidisciplinary cutting-edge technologies, management systems, and models in the field of water resources will permeate every corner of social and economic development, help the industrial upgrading and transformation of water resources protection and utilization industry, and open up a new situation of high-quality development of regional economy in Henan Province.

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Conflict of interest

The authors declare that they have no conflict of interest.

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