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# The improvement approaches of water security through systematic thinking

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**ABSTRACT**

Water is the life vein, and the foundation to production and sound ecological system. China suffers from water scarcity, uneven spatial and temporal distribution of water resources, and frequent flood and drought disasters, making water management a challenging task. Since the founding of the People's Republic of China, the Central Committee of the Communist Party led the people of the country to carry out large-scale water conservancy engineering projects, gradually forming a complete flood control and disaster reduction system, water resource allocation engineering system, and non-engineering measure system. The country has significantly improved its response capabilities to water and drought disasters, laying a solid foundation for rapid economic and social development. In the new era, with the significant changes in China's engineering, social, and water conditions, strengthening the systematic thinking has become a fundamental requirement for quality water control in the water conservancy projects. Focusing on water supply security, this paper uses the theory of systematic thinking to analyze the new problems encountered in the existing engineering projects and the new situations in the planning of new engineering projects, thereby determining the causes and exploring the systematic approach suitable for ensuring China's water security.

*Keywords:* Engineering system; Water demand forecasting; Ecological protection; Carbon peaking and carbon neutrality actions; Food security; Energy security; Systems thinking

## 1. Introduction

In February 2020, the 12th meeting of the Central Committee on Deepening Reform was convened by General Secretary Xi Jinping of CPC in China approved the Opinions on Promoting High-Quality Development of Infrastructure. The meeting proposed to optimize and integrate both the existing and new infrastructure, and create an intensive, efficient, economically applicable, intelligent, green, and safe and reliable modern infrastructure system. These have become guidelines for the quality development of infrastructure in China. Then, in a meeting on May 14, 2021, General Secretary Xi Jinping stressed the need to follow a systematic approach for promoting quality development of the follow-up South-to-North Water Diversion Project. According to General Secretary Xi Jinping, problems should be analyzed through systemic thinking and the relationship between resources generation and conservation, stock and increment, time and space should be handled. This series of important speeches and related policies have pointed out the direction for the quality development of water conservancy projects. One of the core principles behind high-quality development of water conservancy projects is to achieve high efficiency and performance. As a way of thinking based on system theory, systematic thinking considers systemic, relational, hierarchical, dynamic, and temporal characteristics as fundamental features of all systems. The harmony, order, and integrity of the system is crucial for the smooth operation of the system. Therefore, using a systematic thinking approach to build water security is an effective way to establish a highly efficient, high-performance water conservancy infrastructure network system, which is fundamental to promoting quality water projects in the new era.

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Since the establishment of the People's Republic of China, remarkable achievements have been made in water conservancy construction. Nearly 100,000 reservoirs have been built and more than 300,000 km of river embankments of level 5 or above have been constructed, creating the world's largest water conservancy engineering system. The investment in water conservancy construction has continued to increase since 2004. The total investment in water conservancy construction exceeded 800 billion yuan in 2020 and reached a record high after reaching 1 trillion yuan in 2022, as shown in Fig. 1. The number of reservoirs has increased by almost 17% and that of sluices by 163% from 2004 to 2020, as shown in Fig. 2. With powerful engineering system, China's major rivers can defend against the largest floods since the founding of People's Republic of China. The pattern of "water resource allocation between the north and south and the east and west" has gradually taken shape, and the country's water conservancy engineering water supply capacity exceeds 870 billion m$^3$, significantly improving the water supply.

In the new era, to implement the new development concept and build a new development pattern, it is necessary to further enhance water security and solve diverse and complex issues. It is of great significance to explore how to use systems thinking to coordinate the development needs of existing infrastructure and related fields, deploy and implement necessary new infrastructure to maximize the benefits of the water conservancy engineering system to realize the quality development of the water conservancy industry.

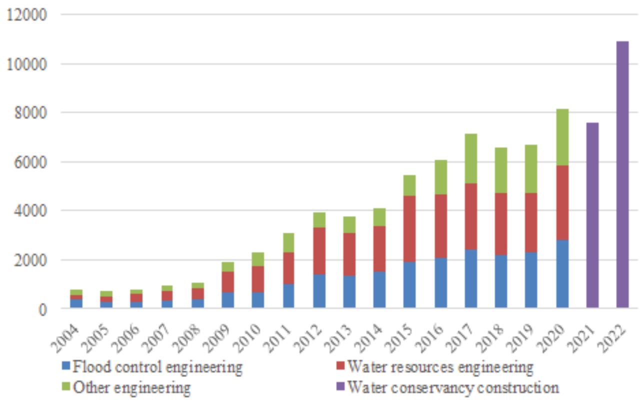


Fig. 1. Investment in water conservancy construction completed from 2004 to 2022.

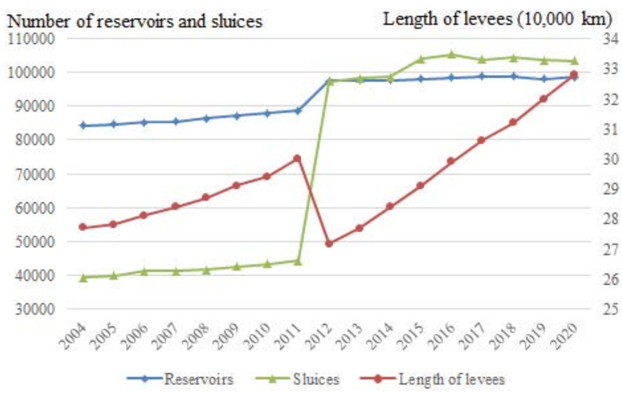


Fig. 2. The situation of Chinese reservoirs, sluices, and levees during 2004–2022.

## 2. New conditions facing existing projects

In terms of engineering scale, large-scale water conservancy projects play a greater role in flood control, water supply, power generation, and so on. Large-scale reservoirs in China accounts for only about 0.8% of the total number of reservoirs, but their total capacity reaches 79.6% of the total capacity, as shown in Fig. 3. At the same time, these large-scale water conservancy projects have a greater impact on river morphology, hydrological rhythms, ecological environment, and social stability, so higher requirements have been proposed for water ecological protection and water security. A comprehensive understanding of the new situations faced by existing projects under the requirements of \quality infrastructure development, accurate understanding of the benefits of existing projects, especially large-scale projects, has become a key link in scientifically deploying new projects and further improving the water security system.

### *2.1. Further improvement required in the efficiency of engineering benefits*

Some projects, even after many years of operation, still cannot take their design benefits to the full play. For example, a 370,000 mu reservoir for irrigation and power generation was completed in 1997. However, its supporting irrigation area project did not begin until 2021. Although the reservoir has undertaken some urban water supply tasks, its scale is small and well below the water supply system's intended design. Another illustration is a sizable reservoir that was built in 1979 and was initially intended to irrigate 130,000 mu of land, but it currently only irrigates 2,000 mu and can only provide nearby towns with water supply benefits. After many years of operation, the efficiency of a large-scale inter-basin water transfer project has fallen far short of expectations due to issues like the absence of a reliable institutional system for the utilization of diverse water sources and major price disparities in water. Despite the

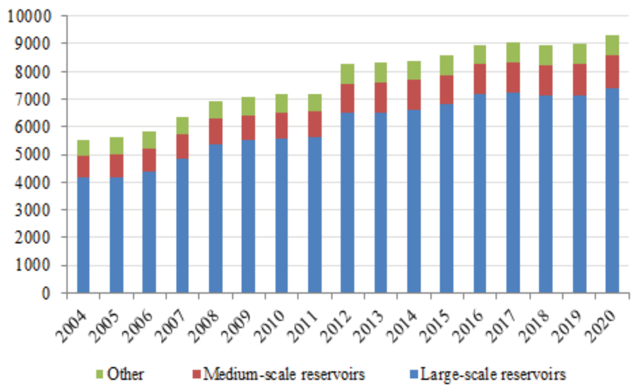


Fig. 3. Scale of national reservoir projects from 2004 to 2022 (unit: 100 million m$^3$).

small number of these projects, it is still common for projects to be delayed and inefficient as a result of poor collaboration in project arrangement and planned design. At present, there is still a certain gap between the operation of the water conservancy infrastructure system and the requirements of quality development, including improving quality and efficiency, optimizing and upgrading, green and safe development, integrating and sharing, and innovative reform.

### *2.2. Changes in engineering tasks and capabilities*

Some current water conservation schemes have undergone major changes to their functional location and capacity. Firstly, with the urbanization, some water resource allocation projects have undergone changes in their responsibilities or water supply targets. For example, the implementation of flood control scheduling has somewhat reduced the benefits of a large-scale reservoir that was primarily intended for power generation and water supply but was required to perform flood control tasks due to the rapid development of downstream urbanization. In addition, some reservoirs mainly for irrigation have squeezed agricultural irrigation due to an increase in urban water supply demands. Secondly, some projects can no longer meet their design capacity after being operated for many years. For example, some reservoirs have silted up beyond expectations, making it difficult to meet the water storage requirements. Thirdly, even though some projects were built and run at an enlarged scale, their actual water storage levels consistently fall below the flood level, making it challenging to realize the intended benefits. Finally, some current water conservation and hydropower projects need to be renovated or demolished in order to meet the new standards for ecological preservation. Water conservation and hydropower project destruction is often done on a small scale. Some provinces have also recently conducted feasibility studies on the demolition of big and medium-sized water conservancy and hydropower projects. For example, the dams (Lianhu Reservoir) with a total capacity of over 2 billion m$^3$ and a power generation task have been demolished.

## 3. New situation faced by project engineering

Historically, large-scale water conservation programs demand a cautious approach, with a coordinated deployment taking into account aspects like the carrying capacity of water resources and level of water resource development. Future construction of significant water conservation projects is still being explored in accordance with pertinent planning, and some projects have already undergone extensive preliminary research spanning several decades. Due to the close relationship between these initiatives and the engineering, social, and hydrological conditions of the basin, it is critical to improve our grasp of new situations and objectivity.

### *3.1. Further development of systematic relationships between existing and newly established projects*

However, the systemic relationship between new projects and existing ones is not fully analyzed in some new project plans. Also, there is short of evaluation and analysis of the actual capacity, performance, and engineering potential of the existing construction system at different scales. In addition, the impact of the formed engineering system on the development degree of the basin's water resources and ecological environment protection has not been fully demonstrated. For example, according to incomplete statistics, there are 42 large-scale reservoirs built in the Yellow River basin, with a total storage capacity of over 95 billion m$^3$, close to two times the average annual runoff of the Yellow River. Artificial water dispatch has been basically realized. Among them, 17 were constructed in the 1950s–1960s, with a total storage capacity of over 46 billion m$^3$; 4 were constructed in the 1970s–1980s, with a total storage capacity of over 25 billion m$^3$; 8 were constructed from the 1980s to the beginning of this century, with a total storage capacity of over 18 billion m$^3$; and 13 were constructed since the 21st century, with a total storage capacity of over 6 billion m$^3$. Moreover, there are large-scale intercepting river projects, such as the San Sheng Gong Water Conservancy Hub, and various types of small and medium-sized water conservancy projects with a greater total design storage capacity. However, based on the overall water resources conditions and development and utilization, the total amount of water resources in the Yellow River basin (Huayuankou) ranged from 40.3 billion to 83.9 billion m$^3$ from 1998 to 2021. The amount of water resources after deducting water consumption (Huayuankou) was 2.081 billion to 43.387 billion m$^3$. On this basis, after deducting the amount of water flowing into the sea (Huayuankou), the amount of water resources ranged from –11.053 billion (2006) to 15.803 billion (2003) m$^3$. Therefore, the development intensity of water resources in the Yellow River basin has already reached a very high level, as evidenced in Fig. 4. While artificial water volume regulation ensures the Yellow River's mainstream will flow continuously, it also introduces new issues, such as the annual flattening of flood peaks. For example, due to the large amount of water storage in the flood season of Longyangxia and Liujiaxia reservoirs, the amount of water entering the Ningmeng River section, especially the amount of water in the flood season and the amount of water in the ephemeral time of

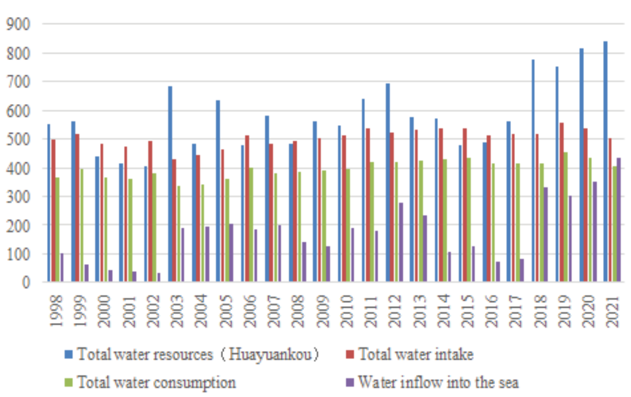


Fig. 4. Comparison of total water resources, total water intake, total water consumption and water inflow into the sea in the Yellow River basin from 1998 to 2021 (unit: 100 million m$^3$).

the occurrence of moderate floods, has been significantly reduced (as shown in Fig. 5), which has an adverse effect on the water-sediment relationship of the Ningmeng River. Under the aforementioned baseline conditions, if major water resource development and utilization projects continue to be implemented, it will have an impact on the water-sediment relationships, ecological environment protection, and restoration. Thus, the engineering system will be significantly challenged.

### *3.2. Establishment of a scientific and reasonable water security guarantee indicator system*

Currently, China's flood control capability has been improved to a relatively safe level [1]. When planning new water conservancy projects in the future, it is urgent to establish a reasonable water security guarantee indicator system. For instance, most water resource allocation projects have always mentioned the uneven distribution of water resources in time and space and the problem of insufficient per capita water resources in the necessity demonstration. However, the "water scarcity index" is not applicable to different regions due to different climatic conditions and economic structures [2]. Furthermore, while some planning increasingly downplays the water supply guarantee rate indicator and highlights the water supply safety coefficient, the selection principle and application range for this indicator have not been made explicit. The water security guarantee indicator system is crucial for basin, regional, and urban water management objectives. It should be deeply implemented according to the "water governance guideline" and the "four kinds of water and four kinds of determination" requirements while strengthening resource constraints. According to basin characteristics, it should coordinate ecological protection, population development changes, regional strategies, economic layout, and other factors, handle the relationship between "supply depending on demand" and "demand depending on supply", and determine reasonable safety thresholds for establishing a water security guarantee indicator system based on the basin's baseline conditions. This will prevent a governance approach from going too far to the "left" or "right".

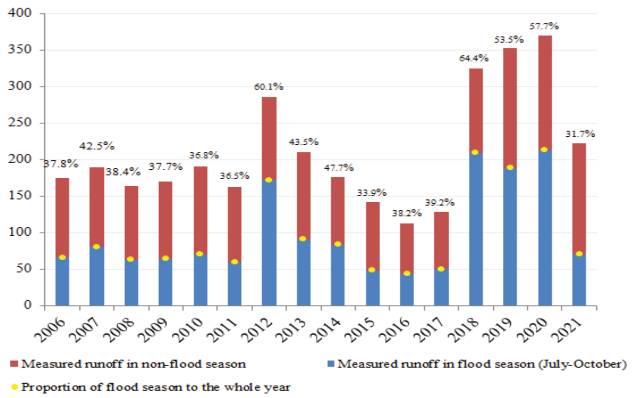


Fig. 5. Schematic diagram of measured runoff at Toudaoguai Hydrographic Station of the Yellow River from 2006 to 2021 (unit: 100 million $m^3$).

### *3.3. Establishment of a collaborative relationship with top-level planning in relevant professions*

As one of the key elements of water engineering planning and design, water demand forecasting frequently suffers from overestimation. Inaccuracies like "economic development will inevitably lead to a significant increase in water consumption," "industrial development requires substantial consumption of water resources," "reducing irrigation loss will lead to agricultural water conservation," and "having water in the river and trees on land equals to ecological protection" are largely to blame. These beliefs result in an inaccurate evaluation of the water constraints posed by technical breakthroughs, the development of a water-saving society, and the optimization of industrial and agricultural infrastructure. The layout of water engineering is closely related to population, urban-rural development, and industrial and agricultural development. Many recent water projects, however, have failed to effectively integrate these elements, leading to a restricted focus on engineering alone. For instance, since 2019, the total resident population and the urban population have been declining in a particular region. The rate of urbanization is continually rising despite the declining population number. The household registration population, which is higher than the actual resident population, is used as the baseline when planning water source projects, and population growth and increased urbanization rates are still taken into account in population forecasting, which results in an overestimation of future urban water consumption. Similarly, in some resource-based cities with similar geographic locations and water resource situations, demands to enhance industrial water usage have arisen as a result of the growth of sectors like black energy. While this may be reasonable for a specific water supply area, it may lead to overestimating the total water demand when taking into account the cumulative impact on all cities. This fact is further illustrated by the real drop in China's industrial water use over the past 10 y and changes to water usage patterns. Additionally, many new projects have used rice for irrigation calculation, resulting in huge design capacity and low engineering utilization. Furthermore, the layout of the agricultural industry may not be compatible with the enormous irrigation area created for rice.

The current total population in China has already experienced negative growth, with some regions experiencing continuous negative growth for many years. The demand for various fundamental materials is strongly impacted by changes in population size and composition as well as higher living standards. Regarding the security of the food supply, China's direct consumption of grains, particularly of staple foods, has been steadily declining while consumption of fruits, vegetables, and animal products (meat, poultry, eggs, milk, and aquatic products) has been rising. While per capita consumption of aquatic and livestock products climbed from 63 to 72 kg between 2013 and 2018, per capita grain consumption for both urban and rural populations declined from 149 to 127 kg (grains decreased from 139 to 116 kg). This trend is expected to continue for a considerable period in the future [3,4]. The main challenges to food security include the limited land area, insufficient production capacity for soybeans and corn, and the size of land, technology and management that need to be improved to enhance food security. From the perspective of ensuring the security of the energy supply, encouraging the energy transition to satisfy the needs of ecological conservation, carbon peaking, and carbon neutrality have become necessary. In order to ensure that the proportion of non-fossil energy consumption reaches about 20% by 2025 and about 25% by 2030, it is necessary to expedite the construction of a clean energy supply system based on the principle of "establishment and then demolition". As can be seen in Fig. 6, although China continues to produce more primary energy, the share of raw coal and crude oil in this total output has declined. In terms of industrial water use efficiency, in 2022, the six ministries and commissions of China jointly issued the Industrial Water Efficiency Improvement Action Plan, proposing to reduce the water consumption of the steel industry and the paper industry by 10% per ton of steel and per unit of major product, respectively, and reduce the water consumption of the petrochemical industry per unit of main product by 5%, and reduce the water consumption of the textile, food and non-ferrous metals industries by 15%. In addition, the industrial wastewater recycling should be further improved, striving to achieve a reuse rate of about 94% for industrial water use above a certain scale nationwide. The above new situations will have a significant impact on the layout of the water security engineering system [5,6].

## 4. Systematic approaches to water governance

The issues can be summed up as the absence of a completely developed system thinking in enhancing water security work and the requirement to increase one's capacity for comprehensive, systematic, and universal problem analysis and solution. The following crucial work needs to be done in order to solve:

### *4.1. Strengthening system evaluation*

Many basins lack control initiatives in the early stages of studying basin management, putting people's lives and property in danger from water and drought crises. The

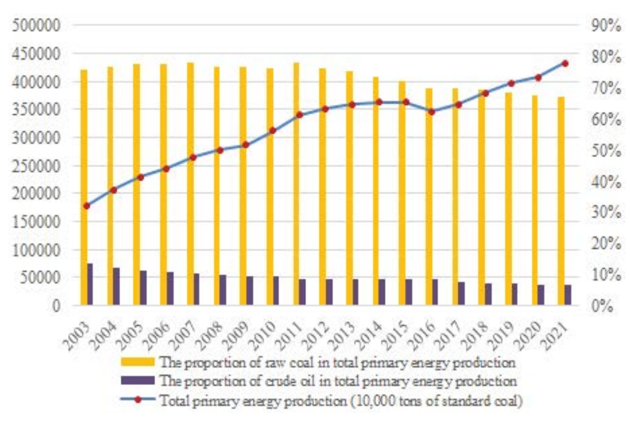


Fig. 6. Primary energy production in China from 2003 to 2021 (unit: 100 million $m^3$).

need for engineering exists, and it is vital to build a system to safeguard the basin, control local flooding, and ensure the security of the water supply. However, with the development of massive projects like the Three Gorges Project, Xiaolangdi Project, and the South-to-North Water Diversion Project, as well as the formation of the world's largest water conservancy engineering system, it is necessary to conduct in-depth research on governance issues and root causes in the current stage of engineering, society, and water situation in the new era. It is particularly important to optimize and improve existing projects, plan and implement necessary new projects, maximize the potential of existing projects, fully tap into the comprehensive benefits of water conservancy engineering, improve the capacity of water security projects and create conditions for effective investment in water conservancy infrastructure [7,8].

### *4.2. Deepening industry reform*

It is necessary to continuously conduct reform to improve water governance efficacy. The water resources department proposed changing the term "flood control" from "flood prevention" to "flood management" at the turn of the century. They also suggested changing the term "water resource management" from "water supply management" to "water demand management" and "ecological governance" from "targeted prevention" to "comprehensive management with ecological restoration". In addition, the administration of water has shifted from primarily using administrative tools to applying a wide range of legal, economic, administrative, and technological tools for a more all-encompassing approach to change. In a new era, both technology advancement and the idea of creating twin river basins should be used to further future efforts to promote smart water resource management. Exploring the best use of intelligent technologies to tap into the full benefits of the current building system is essential for achieving fine, precise management. Under the aegis of new development stages, efforts to investigate novel investment models in water resources must also continuously rise. Research on sustainable operation for water resources engineering needs to be consistently strengthened as well. In accordance with the guiding principle of "establishing the system before implementing engineering projects," it is crucial to look into and develop an efficient safeguard mechanism for engineering efficiency as well as research the establishment of pertinent security systems at the legal level.

### *4.3. Strengthening system planning*

Over the years, the water conservancy sector has developed a relatively comprehensive planning system, including national-level water conservancy development plans, water security plans, water network plans, as well as basin-level flood control plans, water resource integrated plans, and corresponding regional and local plans [9]. These plans have scientifically guided the water conservancy construction at different levels, promoting the overall development of the water conservancy industry. However, faced with new situations and challenges, it is essential to explore further ways to enhance water security through a systematic thinking approach. This requires strengthening coordinated planning and systematic deployment with population changes, economic and social development, ecological protection, and related industry construction, while emphasizing the value creation and embodied in engineering and engineering systems. To assess the positive and negative, tangible and intangible, direct and indirect, local and overall, explicit and implicit, short- and long-term, micro and macro manifestations, it is necessary to integrate science, technology, finance, economics, society, culture, technology, resources, environment, and other diverse dimensions [10].

## 5. Conclusions

Since the founding of the People's Republic of China, large-scale water conservancy projects have been implemented, considerably enhancing water and drought defense capability, and providing a firm foundation for rapid economic and social development. The water conservation business faces more problems and challenges in the modern era, which makes it necessary to develop systematic thinking in research and governance. In order to increase systematic evaluation, deepen water conservancy reform, and strengthen systematic planning, more effort must be made to ensure quality economic and social development through.

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