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The International Energy Agency Technology Collaboration Programme on Hydropower

Decision Support for Comprehensive Utilization of Basin Water Resources

IEA Hydro Task 18

China Yangtze Power Co., Ltd.
International Center on Small Hydro Power

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THE INTERNATIONAL ENERGY AGENCY AND THE TECHNOLOGY COLLABORATION PROGRAMME

The International Energy Agency (IEA) is an intergovernmental organization that works to shape a secure and sustainable future for all, through our focus on all fuels and all technologies, and our analysis and policy advice to governments and industry around the world.

The Technology Collaboration Programme was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of thousands of experts across governments, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Technology Collaboration Programme on Hydropower ("IEA Hydro")

The IEA Technology Collaboration Programme on Hydropower (IEA Hydro) is a working group of International Energy Agency member countries and others that have a common interest in advancing hydropower worldwide. Current members of IEA Hydro are Australia, China, EU, Finland, Japan, Norway, Switzerland, USA. Sarawak EB is a sponsor. Member governments either participate themselves, or designate an organization in their country to represent them on the Executive Committee (ExCo) and the working groups (Tasks), through which the work of IEA Hydro is carried out. Some activities are collaborative ventures between the TCP and other hydropower organizations.

Vision

Through the facilitation of worldwide recognition of hydropower as a well-established and socially desirable energy technology, advance the development of new hydropower and the modernization of existing hydropower.

Mission

To encourage through awareness, knowledge, and support the sustainable use of water resources for the development and management of hydropower.

To accomplish its Mission, the Executive Committee has identified the following programme-based strategy to:

- Apply an interdisciplinary approach to the research needed to encourage the public acceptance of hydropower as a feasible, socially desirable form of renewable energy.
- Increase the current wealth of knowledge on a wide array of issues currently associated with hydropower.
- Explore areas of common interest among international organizations in the continued use of hydropower as a socially desirable energy resource.
- Bring a balanced view of hydropower as an environmentally desirable energy technology to the worldwide debate.
- Encourage technology development.

IEA Hydro is keen to promote its work and to encourage increasing involvement of non-participating countries. All OECD and non-OECD countries are eligible to join. Information about membership and research activities can be found on the IEA Hydro website www.ieahydro.org.

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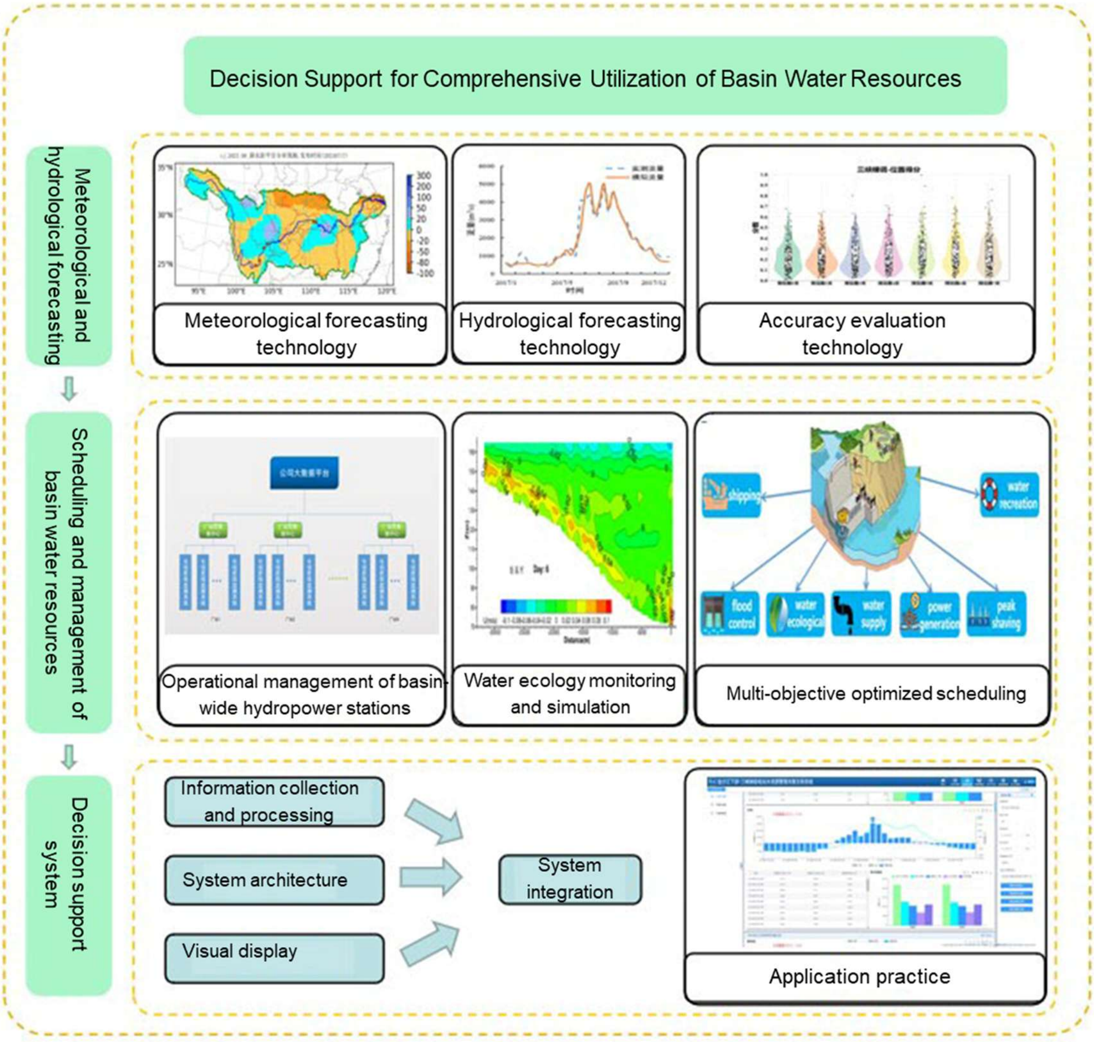
LIST OF ABBREVIATIONS

ACF	Apalachicola-Chattahoochee-Flint (River Basin)
ANN	Artificial Neural Network
BOD	Biochemical Oxygen Demand
CNN	Convolutional Neural Networks
CUBWR	Comprehensive Utilization of Basin Water Resources
DO	Dissolved Oxygen
DEM	Digital Elevation Model
DPSA	Dynamic Programming with Successive Approximation
DSS	Decision Support System
EFDC	Environmental fluid dynamics code
GTDSS	Georgia Tech Water Resource Decision Support System
HAD-DSS	Aswan High Dam Decision Support System
IEA	International Energy Agency
LNFDC	Lake Nasser Flood and Drought Control
MIP	Mixed Integer Programming
MODE	Modified Threat Score
O&M	Operation and Maintenance
POA	Progressive Optimization Algorithm
SAL	Spatial Absolute Limit
SVM	Support Vector Machines
SWAT	Soil and Water Assessment Tool
TCP	Technology Collaboration Programme
TS	Threat Score
WRMDSS	Water Resources Management Decision Support System

EXECUTIVE SUMMARY

Globally, issues related to uneven water resource allocation and scarcity are becoming increasingly prominent. It is particularly important to explore and implement strategies for the Comprehensive Utilization of Basin Water Resources (CUBWR). This report focuses on three key aspects of CUBWR: meteorological and hydrological forecasting technologies, basin-wide water resource scheduling management, and Decision Support Systems (DSS) for the comprehensive utilization of water resources. The report emphasizes that strengthening meteorological and hydrological forecasting technologies is essential for the effective implementation of CUBWR. It highlights the importance of multi-objective water utilization—including flood control, power generation, irrigation, and ecological preservation—and demonstrates how reservoirs, as essential tools, can be optimized for sustainable water management. Additionally, the report underscores the crucial role of DSS in ensuring the successful implementation of CUBWR.



Chapter 1: Introduction

The first chapter provides an overview of the global water distribution and scarcity problems, identifying the need for strategies of CUBWR. Water shortages have emerged as a severe issue in many regions, significantly constraining sustainable development and triggering a host of socio-economic and political challenges. According to data from the World Resources Institute (WRI), approximately one-quarter of the global population is currently facing extreme water scarcity. Given this critical situation, the efficient CUBWR is essential to ensure sustainable development.

Reservoirs are identified as pivotal in mitigating the impacts of water scarcity, particularly in terms of flood control, power generation, irrigation, navigation, and ecological conservation. By transforming potentially destructive floodwaters into valuable resources, reservoirs play a key role in managing annual and inter-annual water variability. This chapter emphasizes the importance of optimizing reservoir operations through both engineering and non-engineering measures to maximize the socio-economic and environmental benefits of water resource management. However, it also acknowledges the ecological challenges posed by reservoirs, such as disrupted natural water flows, habitat alterations, and the reduction of sediment transport capacity, which can threaten river ecosystems. Therefore, the need for sustainable reservoir scheduling that meets both human and ecological demands is stressed.

Additionally, Chapter 1 emphasizes the critical role of meteorological and hydrological forecasting, basin water resource scheduling management, and Decision Support Systems (DSS) in the comprehensive utilization of water resources.

Chapter 2: Key Technologies for Meteorological and Hydrological Forecasting

This chapter explores the role of both meteorological and hydrological forecasting technologies in the comprehensive utilization of basin-wide water resources. Accurate forecasting is fundamental for making informed decisions regarding water resource allocation, flood control, and reservoir operations.

The chapter begins by providing an overview of meteorological forecasting, which includes short-term, medium-term, and long-term predictions of weather conditions such as precipitation, temperature, and wind patterns. Short-term forecasts are particularly crucial for real-time decision-making, especially in anticipating extreme weather events like heavy rainfall, which can lead to flooding. Medium- and long-term forecasts provide insights into broader weather trends that influence water resource availability over extended periods, allowing for better strategic planning.

In addition to meteorological forecasting, the chapter also covers hydrological forecasting technologies, which focus on predicting river flows, runoff, and water levels within watersheds. Hydrological forecasts are crucial for managing water resources effectively across different sectors, including agriculture, power generation, and ecological protection. The chapter discusses various methods of hydrological forecasting, including simulation-based approaches, which use hydrological models to simulate water flow processes, and data-driven approaches that leverage large datasets and machine learning algorithms to improve forecasting accuracy.

The chapter goes beyond theory and discusses the practical applications of these technologies in water resource management. The chapter presents specific case studies demonstrating the effectiveness of these forecasting methods in real-world scenarios.

Chapter 3: Basin-Wide Water Resource Scheduling Management

Chapter 3 addresses the key challenges of water resource scheduling management in large basins, with a particular focus on the use of multi-objective optimization to balance competing demands. Water resources serve various functions such as flood control, hydropower generation, irrigation, navigation, and ecological protection, and managing these diverse demands within a single scheduling framework is challenging. Traditional single-objective scheduling methods often fall short, as they typically focus on maximizing one function (e.g., power generation) while neglecting broader basin-wide needs.

To overcome these limitations, the report advocates for a multi-objective optimization approach, which allows water resource managers to balance competing priorities such as flood control, power generation, and ecological sustainability. By considering multiple objectives simultaneously, managers can achieve a more efficient and equitable distribution of water resources.

Beyond discussing theoretical methods, the chapter also presents practical applications of these approaches. Case studies illustrate how multi-objective optimization has been successfully applied in real-world basin management. For example, in some large river basins, integrated water scheduling has enabled operators to optimize hydropower production while also maintaining ecological water flows and minimizing flood risks. These applications demonstrate the tangible benefits of multi-objective scheduling in improving both resource efficiency and sustainability.

In addition to the optimization methods, the chapter stresses the importance of sustainability. With growing environmental pressures and the need for carbon neutrality, water resource scheduling must account for both economic benefits and environmental impacts. Sustainable scheduling involves not only meeting current demands but also ensuring future water availability. Real-world examples show how water resource managers have successfully integrated economic and ecological considerations, demonstrating the benefits of long-term, sustainable management practices that balance agriculture, industry, and ecosystem preservation.

Chapter 4: Decision Support Systems (DSS) for Comprehensive Utilization of Water Resources

The final chapter focuses on the importance of Decision Support Systems (DSS) in water resource management, highlighting their ability to integrate complex data and technologies into a comprehensive framework that supports decision-making. DSS serves as a critical link between hydrological models, data analytics, reservoir scheduling model and decision-makers, enabling informed decisions that balance competing demands for water resources. By collecting, storing, analyzing, and visualizing data from sources such as meteorological stations, satellite observations, and hydrological models, DSS supports decisions related to reservoir operations, water allocation, and flood control.

In this chapter, the integration of scheduling models with DSS is emphasized, showing how the coupling of these models with real-time data and forecasting systems enhances the overall efficiency of water management. DSS allows for dynamic adjustments in reservoir scheduling, helping decision-makers respond to changing conditions like potential floods or droughts. This integration ensures that water resources are allocated efficiently, meeting the needs of various users while minimizing water waste.

The chapter also provides case studies to demonstrate the effectiveness of DSS in real-world scenarios. For example, DSS has been successfully used in large-scale river basins to optimize water release during periods of anticipated drought while maintaining sufficient water levels for power generation and agricultural needs. These applications show how DSS improves decision-making by providing actionable insights based on both real-time data and predictive models.

1 INTRODUCTION

1.1 Comprehensive utilization of basin-wide water resources (CUBWR)

Globally, issues of uneven water resource allocation and water scarcity are becoming increasingly prominent. It is particularly important to explore and implement the CUBWR strategies. Data from the World Resources Institute (WRI) indicates that approximately one-quarter of the global population is currently facing an extreme water shortage crisis[1]. This scarcity is a constraint on the sustainable development of numerous countries and regions, triggering a range of social, economic, and political challenges. The efficient CUBWR has emerged as a key factor in sustainable development.

The core of CUBWR is the rational development and utilization of water resources. This is achieved through a combination of engineering and non-engineering approaches, aiming to reduce flood losses and satisfy the multifaceted societal demands for power generation, navigation, irrigation, ecological preservation, and water supply for industry and households. Reservoirs are pivotal in this endeavor. Reservoirs not only transform the destructive nature of floods into a valuable resource but also significantly improve the efficiency of water resource utilization through regulation and storage mechanisms[2, 3]. As the pace of global water infrastructure projects quickens, the construction of large-scale reservoirs has redefined the spatial and temporal allocation of water resources worldwide. This development has underscored the strategic role of reservoirs in global water resource management. Consequently, the effective management and optimization of reservoir operations are essential for maximizing the CUBWR benefits.

Reservoirs serve as a primary method for managing the annual and inter-annual variability of water resources. They are instrumental in flood prevention and offer a range of benefits, including water supply, irrigation, power generation, and navigation. However, the construction and operation of reservoirs can have unintended consequences. They can disrupt the natural flow of water, which is essential for maintaining ecological cycles, alter the habitats of aquatic life, reduce the rivers' sediment transport capacity, and threaten the ecological health of waterways. The escalating demands of a growing global population and socio-economic development have increased the pressure on water resources for both agricultural and domestic use. Prolonged closure of some reservoirs to impound water has led to a reduction in river flow. In extreme cases, this has resulted in the shrinkage of lakes and the drying up of rivers, causing significant harm to the riverine ecosystem. **To address these challenges, it is imperative to optimize the reservoir scheduling modes. This involves adjusting the allocation of water resources on an annual, inter-annual, and inter-regional basis, while ensuring that the ecological flow needs are met with a sustainable water volume. By doing so, we can increase the availability of water resources and enhance their overall carrying capacity, thus achieving an efficient and sustainable CUBWR.**

1.2 Decision Support for CUBWR

Decision making involves the analytical and judgmental process of selecting a satisfactory solution from various alternatives. This is done by using scientific methods and tools to achieve specific objectives. The correctness and rationality of decisions are influenced by several factors, including the decision-maker's capabilities, the quality of information at hand, and the methods and technologies used to implement the chosen plan. The overarching goal of CUBWR is to maximize socio-economic and environmental benefits. This entails striving for optimal benefits in areas such as power generation, navigation, water supply, and ecological preservation, all while ensuring the safety of flood control measures.

The correctness and rationality of decisions on CUBWR are influenced by the quality of pertinent information, such as hydrology and water quality, as well as the scientific nature of water resource management technologies. These technologies include "basin water resource scheduling management" and "information processing systems" which are vital for effective decision-making in this domain. To enhance decision-making efficiency and quality, it is essential to enhance the monitoring and forecasting capabilities of important information like meteorology, hydrology, and water quality. Continuous development and optimization of water resource scheduling management, as well as information processing systems, are crucial. The report presents an array of technologies pivotal for water resource management, including: meteorological and hydrological forecasting technologies, basin water resource scheduling management, and the decision support system.

1.2.1 Meteorological and hydrological forecasting technologies

Meteorological and hydrological forecasting is a key technical support for CUBWR. By leveraging existing meteorological and hydrological data, these forecasting methods are capable of anticipating the weather and water conditions over a specified leading time. They offer predictive insights into variables such as precipitation, water levels, and streamflow, which are vital for informed decision-making in CUBWR.

In terms of flood disaster defense, meteorological and hydrological forecasting enables decision-makers to anticipate inflow conditions by predicting precipitation, water levels, and streamflow. With this foresight, they can devise and implement targeted measures aimed at mitigating flood peaks and safeguarding public and property safety. For example, upon forecasting imminent heavy rainfall, decision-makers can enhance river monitoring, stockpile flood control supplies, and take other preemptive actions to prepare for potential flooding events.

In terms of water resource allocation, meteorological and hydrological forecasting is instrumental in facilitating informed decision-making. By predicting key parameters such as precipitation, water levels, and streamflow for the upcoming period, these forecasts empower decision-makers to allocate water resources reasonably. This strategic planning enhances the efficiency of water use and ensures the continuity of agricultural operations and the daily life of the populace. For example, in the event of a predicted drought, decision-makers can utilize forecasting results to formulate appropriate water resource scheduling schemes, ensuring the demands for agricultural irrigation and people's domestic water.

In terms of hydroelectric power generation, meteorological and hydrological forecasting provides vital support for strategic planning. These forecasts, by predicting future precipitation, water levels, and streamflow, enable decision-makers to optimize power generation schedules. This foresight allows for the reduction of water waste and enhances the economic benefits of hydroelectric power generation. For example, anticipating a significant inflow, decision-makers can tailor power generation plans to capitalize on the increased water flow. Such planning ensures the efficient harnessing of water resources for power generation, which in turn boosts the stability and reliability of power supply.

In terms of ecological preservation, meteorological and hydrological forecasting is a key asset for decision-makers. These forecasts allow for the anticipation of future precipitation, water levels, and streamflow over a specified period, enabling the creation of balanced water resource development plans. By doing so, they help prevent the over-exploitation and subsequent ecological harm that can arise from excessive water resource utilization, thereby promoting the comprehensive benefits of the ecosystem. For example, when forecasts indicate a significant inflow, decision-makers can devise water resource development strategies that align with these predictions. These strategies aim to prevent over-exploitation of water resources, which might otherwise lead to ecological degradation. Moreover, such foresight offers a scientific foundation for the conservation and rehabilitation of the ecological environment.

Therefore, strengthening meteorological and hydrological forecasting technologies is conducive to the effective implementation of CUBWR. It is a critical strategy that empowers decision-makers with the necessary foresight to adopt appropriate measures and make informed decisions.

1.2.2 Basin water resource scheduling management

Water resource scheduling management can be divided into conventional scheduling and optimized scheduling according to scheduling methods. In terms of scheduling timeframes, it encompasses annual, monthly, decadal (ten-day), and even more frequent intervals such as weekly, daily, and real-time scheduling. Regarding the scheduling content, it includes specialized types like flood control, power generation, ecological, irrigation, water supply, and sediment discharge scheduling. Additionally, it can be bifurcated into comprehensive and single-purpose scheduling. **Regardless of the categorization, the essence of water resource scheduling revolves around two primary elements: hydraulic engineering (primarily referring to reservoirs) and water quantity.** Specifically, this entails the artificial manipulation of the natural runoff's spatial and temporal distribution through hydraulic engineering. The objective is to meet the needs of national economic development, daily life, and ecological preservation. The goal is to mitigate adverse effects and enhance beneficial ones, thereby achieving CUBWR. **Therefore, this report introduces "water quantity scheduling" or "hydraulic engineering scheduling" to represent "water resource scheduling".**

The inherent characteristics of water resources within their natural basins require scheduling management on a basin-wide scale. The fluidity and cyclicity of water endow water resources with watershed-based attributes, creating a unified and systematic structure within water basins. The unity of water basins is mainly reflected by the harmonious diversity of the rivers themselves. This encompasses the interconnectedness of various elements such as the upper, middle, and lower reaches, the left and right banks, the mainstream and tributaries, as well as the integration of water quality and quantity, surface and groundwater resources. Furthermore, the unity extends to the multifunctional aspects of rivers, which serve purposes such as flood control, power generation, water supply, navigation, irrigation, and tourism. The inherent unity, systematicity, and diversity of water basins underscore the objective necessity for a unified management of water resources on a basin scale.

Furthermore, the multi-functionality of resources calls for a unified approach to water resource scheduling management across the entire basin. Basin water resources offer a spectrum of values and serve various functions, including flood control, power generation, water supply, navigation, irrigation, and ecological preservation. However, the execution of these functions often entails differing demands regarding water quality and quantity. For instance, agricultural irrigation demands considerable water volumes, particularly during critical growth periods for crops. Insufficient water at these times can result in crop failure. While the water consumption for industrial and urban domestic use may not be as substantial in volume, it requires a high level of reliability. Power generation at cascade hydropower stations along the upper reaches of rivers must be aligned with the power grid's requirements. To mitigate river channel siltation, a sufficient water discharge volume and peak flow is essential for sediment transport. For ice prevention, the release from reservoirs is not allowed to exceed the safe discharge flow of the river channel. Additionally, to maintain environmental ecological balance and prevent water pollution, a certain flow rate must be maintained in certain sections of rivers and estuaries that are prone to heavy pollution. Some of these water uses can be harmonized, but often they present conflicting needs. The absence of unified management and scheduling would fail to reconcile these conflicts, potentially leading to significant adverse outcomes.

Currently, a growing number of nations globally prioritize the unified scheduling management of water resources within their respective basins. Efficiently executing this basin water resource scheduling management has become a global consensus.

1.2.3 Decision support system (DSS)

DSS is a vital information processing tool designed to aid decision-makers in the decision-making process[4, 5]. They facilitate access to essential information and knowledge for decision-making through various methods, including data collection, analysis, and visualization. This support enables decision-makers to more effectively understand situations and enhances the accuracy and efficiency of their decisions. Water resource managers can utilize DSS technologies and concepts to develop a specialized Water Resources Management Decision Support System (WRMDSS). This system is capable of collecting, integrating, and storing a range of water resource-related data, such as precipitation, runoff, groundwater levels, hydrological forecasts, and ecological simulation results of the basin. The WRMDSS operates reservoir scheduling models, presenting the results visually to assist decision-makers in setting scheduling boundaries, formulating reservoir scheduling schemes, conducting risk assessments, and implementing scheduling strategies. It also aids in enhancing the decision-makers' understanding of reservoir scheduling, ensuring that the decisions made are more precise and dependable. Furthermore, the system supports the rational planning of water resource allocation and the strategic implementation of flood control and disaster mitigation measures.

The WRMDSS acts as a critical bridge between hydrological and water resource experts, managers, and decision-makers. It can transform water resource management decisions into mathematical problem through the use of physical or empirical models crafted by hydrology specialists. This allows decision-makers to understand and engage with the decision-making process from a scientifically informed position, thereby enhancing the efficiency of their decisions. Therefore, WRMDSS will play a significant role in subsequent management of global, regional, and basin-wide water resources. As the government and regulatory agencies increasingly demand a multifaceted approach to reservoir scheduling and operation, the role of reservoirs has evolved beyond the traditional focus on flood control and power generation dispatching. Reservoir scheduling is now progressively embracing a holistic approach that encompasses navigation, irrigation, and ecological considerations. Concurrently, the WRMDSS is transitioning from a specialized tool for singular scheduling needs to a more integrated platform aimed at facilitating comprehensive utilization.

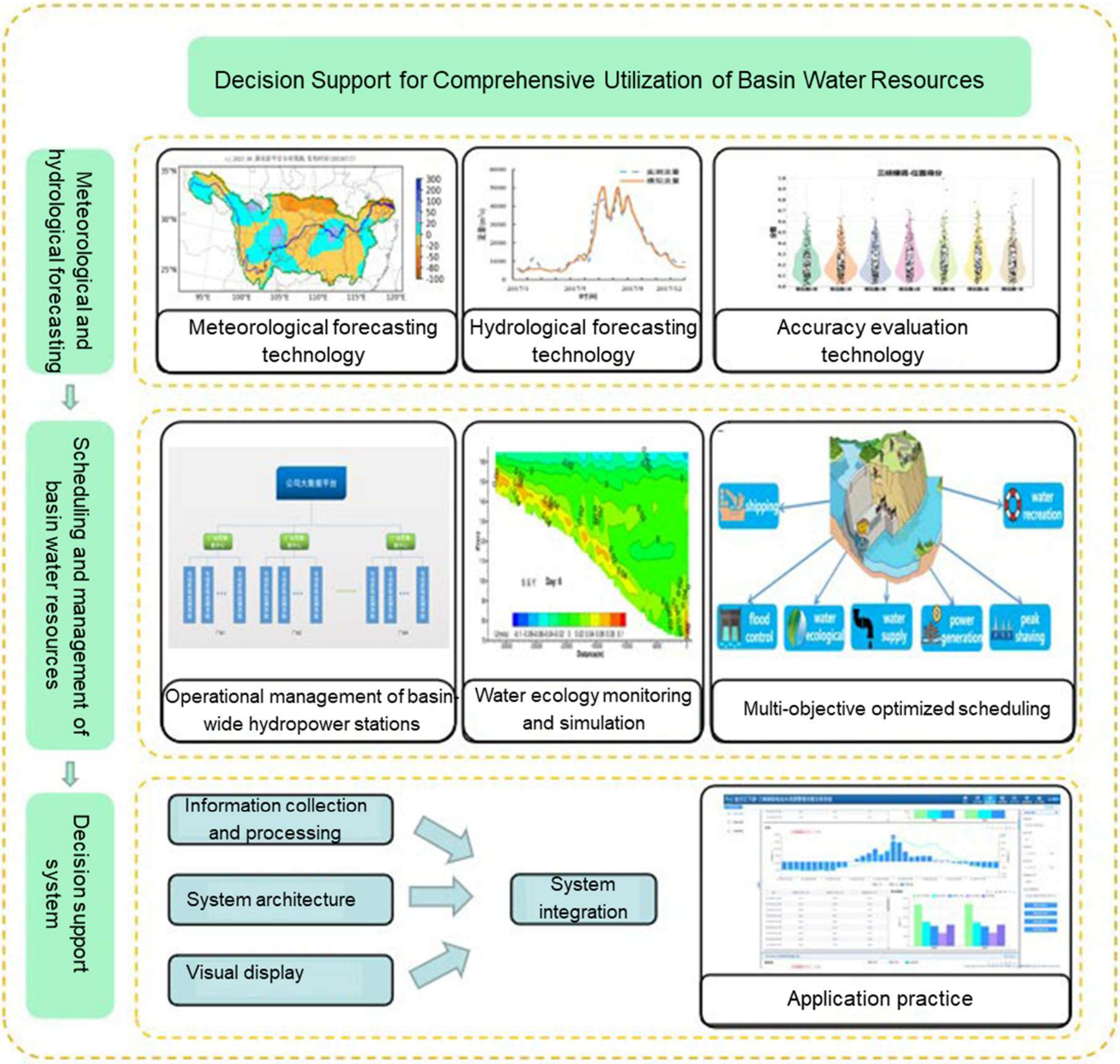


Figure 1-1 Report framework

2 KEY TECHNOLOGIES FOR METEOROLOGICAL AND HYDROLOGICAL FORECASTING

2.1 Overview

2.1.1 Development status of meteorological forecasting

Meteorological forecasts encompass various elements, including weather conditions, air temperature, precipitation, humidity, wind speed, and direction. Precipitation, with its direct bearing on CUBWR decisions, is the focal point of forecasting for the scheduling of basin-wide reservoirs and reservoir systems. These forecasts are distinguished by their time scales into short- to medium-term (0-10 days), extended-range (11-30 days), and long-term trend forecasting (covering months to seasons, critical period and annual forecasting). To ensure the CUBWR, the precipitation forecasting within a basin mainly focuses on the precipitation process and later trend in the reservoir-controlled watersheds.

2.1.1.1 Short- to-medium term precipitation forecasting

Short-to-medium term precipitation forecasting is pivotal for the optimal utilization of basin-wide water resources. This technology enables decision-makers to accurately identify the timing, location, and intensity of precipitation events expected within 0 to 10 days across various regions of interest within a basin. Such insights facilitate the proactive planning of reservoir scheduling and the strategic utilization of water resources. Particularly, short-term precipitation forecasts for the 0-3 days offer highly accurate "atmospheric intelligence" that is invaluable to decision-makers. These forecasts provide the technical support necessary for the precise and efficient utilization of water resources such as flood control, power generation, and ecological water replenishment.

2.1.1.2 Extended-range precipitation forecasting

In the field of weather and climate predictions, the 10-30d extended-range forecasting is a difficult point in "seamless forecasting". The complexity of this forecasting horizon arises because it extends beyond the theoretical upper limit of approximately two weeks for the validity of deterministic forecasting, while also not aligning with the longer time scales typically associated with monthly and seasonal climate prediction.

Currently, the practice of extended-range forecasting in meteorology primarily relies on three pivotal methodologies: Method 1: Extending Integration Length. By integrating the interpretation and application of dynamic forecasting model outputs, this approach directly extends the integration length of the meteorological forecasting models to facilitate extended-range forecasting. Method 2: Statistical Physical Analysis Approach. It uses atmospheric low-frequency signal data to discern cycles and oscillation amplitudes of these signals, subsequently employing extrapolation techniques for the extended-range forecasting. Method 3: Big Data-driven Modeling Forecasting. This method adopts data decomposition, expansion, and transformation techniques to extract effective data from vast scientific datasets that exhibit high data correlation and multifaceted attributes. This process yields a more holistic understanding of mid-latitude atmospheric low-frequency variations than traditional sampling analyses, thereby laying a more robust foundation for the 10–30 day extended-range forecasting of extreme weather events.

2.1.1.3 Long-term precipitation trend forecasting

The utility of monthly and seasonal precipitation trend forecasting in the context of basin-wide water resource utilization is similar to that of extended-range precipitation forecasting. These forecasting provides an advance outlook on the prospective precipitation trend within the basin of interest, typically rendered as distributions of anomaly percentages. Given that climate prediction is subject to a myriad of complex factors across the Earth's spheres, the accuracy of long-term precipitation trend forecasting currently lags significantly behind that of both extended-range and short- to-medium term precipitation forecasting. Nonetheless, when the area of concern is expansive, gaining insights into the potential distribution of temperature and precipitation in key areas over monthly, seasonal, and annual timeframes still holds substantial value for devising strategic planning and decision-making for the foreseeable future.

2.1.2 Development status of hydrological forecasting

The current global research status of hydrological forecasting can be broadly categorized into two main approaches: simulation paradigm-based hydrological forecasting and data paradigm-based hydrological forecasting.

2.1.2.1 Simulation paradigm-based hydrological forecasting

For simulation paradigm-based hydrological forecasting, it first proposes possible hydrological mechanism hypotheses and the construction of corresponding models, then collect relevant data, which is then utilized to forecast the runoff process at the basin outlet through computational simulation. The efficacy of simulation paradigm-based hydrological forecasting is heavily dependent on the progressiveness and rationality of the employed hydrological models. Consequently, advancements in the development of hydrological models are intrinsic to the evolution of this forecasting paradigm.

From the 1930s to the 1950s, flood forecasting was in its pioneering and early developmental stage. Hydrological research during this period mainly focused on deciphering the mechanisms governing the progression of the hydrological cycle. Significant contributions from this era encompass Sherman Unit Hydrograph, Horton Infiltration Capacity Curve, Muskingum Method, Penman-Monteith Equation, Nash Instantaneous Unit Hydrograph, etc.

In the late 1960s, the creation of Stanford-IV, the world's first hydrological model in the United States, held milestone significance. It signified the beginning of an era where hydrologists started to integrate the ideas of systems theory. They began to study the various elements of the hydrological cycle within a basin as an organic whole. From the 1960s to the 1990s, the application of systems theory deepened and computer technology advanced rapidly. This period marked a phase of robust development in the creation and application of basin-wide hydrological models. Notable models that were developed during this time include: the Sacramento model and API model from the United States, the Xin'anjiang model from China, the TANK model from Japan, the HBV model from Sweden, the NAM model from Denmark, the TOPMODEL model from the UK, the GR4J model from France, the LPM model from Ireland, and the CLS model from Italy.

Following the 1990s, the ongoing development of ground station infrastructure, coupled with the ongoing innovation and widespread adoption of 3S technologies, as well as the establishment of numerical elevation models, spurred rapid advancements in distributed hydrological models. Notable models that emerged during this period include: the SHE model from Europe, the TOPKAPI model from Italy, the SWAT model and VIC model from the United States, and the GBHM model from China. These distributed hydrological models take into account the physical characteristics, boundary conditions, and the spatio-temporal variation of hydrological processes within watersheds. They provide a more nuanced understanding of the mechanisms governing hydrological processes, facilitating improved hydrological forecasting and water resource assessments, particularly in un-gauged basins. However, the application of these models in flood forecasting remains largely experimental due to challenges such as insufficient underlying surface data and other limitations.

2.1.2.2 Data paradigm-based hydrological forecasting

Traditional hydrological forecasting technology, constrained by data limitations, has typically relied on simulation paradigms for their research. However, the rapid development of computer technology and the Internet has ushered in an era of vast data availability. Advanced observation technologies now provide an overwhelming amount of data related to regional water cycles, basin runoff yield and flow concentration. This dense data set is capable of not only meticulously detailing the "causes" behind hydrological phenomena but also precisely outlining their "effects"[6-8]. As a result, numerous hydrological forecasting technologies has emerged, distinct from the traditional simulation-based approaches. These are data-intensive, paradigm-based hydrological forecasting technologies, which have quietly made their way into the field.

The basic idea of the data-intensive paradigm is that observational data serves as a record of the formation and spatio-temporal variation of natural phenomena. By analyzing this data, we can understand the mechanisms behind these phenomena and uncover their spatio-temporal variation patterns or laws. In this paradigm, let's denote X as the intensive data, and Y as the underlying mechanisms or the spatio-temporal variation characteristics and laws of natural phenomena. The data-intensive approach can thus be expressed as follows:

$$Y = \psi(X) \tag{1}$$

Where, $\psi(\cdot)$represents an algorithm.

As can be seen from Equation (1), data paradigm-based hydrological forecasting technology require two conditions: (1) Data Requirement: It necessitates the availability of comprehensive, abundant, accurate, and intensive observational data that captures both the "causes" and "effects" of hydrological processes. (2) Algorithm Requirement: It demands the presence of sophisticated algorithms that can extract the underlying mechanisms of hydrological processes and discern the spatio-temporal variation characteristics or laws of hydrological elements from vast datasets. For data-intensive paradigms, "data" is the foundation, the subject, and must be obtained, analyzed, and stored in a scientific way. "Algorithm" is also very important; without robust algorithms, the potential value of the data may be significantly diminished.

While both simulation paradigm-based and data-intensive paradigm-based hydrological forecasting technologies have emerged from the invention and development of electronic computers, they exhibit fundamental differences. In simulation paradigm-based forecasting, the process typically begins with the formulation of possible theories and the construction of corresponding models. Subsequently, relevant data is collected, and computational simulations are employed to validate the proposed theories. For example, basin-wide hydrological models can be utilized to elucidate the mechanisms and spatio-temporal variation characteristics or laws of rainfall-runoff within river basins. Conversely, in data-intensive paradigm-based forecasting, the approach starts with the acquisition of extensive and comprehensive observational data on hydrological phenomena. From this data, unknown theories are then extracted through the process of data mining. The simulation paradigm mainly utilizes the computational simulation capabilities of electronic computers, while the data-intensive paradigm capitalizes on the powerful data storage and analytical capabilities of computers.

The current data-intensive paradigm-based hydrological forecasting technology is mainly divided into the following two categories:

(1) Machine learning-based hydrological forecasting

Machine learning is an approach that involves learning from data to derive forecasting models. In the context of hydrological forecasting, this involves primarily the use of machine learning algorithms to construct models for various hydrological processes, such as rainfall, runoff, and water level predictions, and then to forecast hydrological variables and phenomena. Where, data is crucial. To implement machine learning-based hydrological forecasting, a substantial volume of hydrological data is essential for both training and testing the models. This data should be collected to develop high-accuracy forecasting models. The types of data that need to be collected encompass meteorological, hydrological, and topographical information. In addition, operations including preprocessing and feature extraction of data are required to improve the accuracy and generalization ability of the forecasting models.

At present, machine learning has been widely applied in the field of hydrological forecasting. Numerous machine learning algorithms have been integrated into both the research and application of hydrological forecasting. These include, but are not limited to, Support Vector Machines (SVM), Random Forest, and Artificial Neural Networks (ANN). For example, SVM can be used to derive key indicators for early warning of critical rainfall volumes, thereby enhancing the effectiveness of early warnings and forecasts for hydrological disasters like floods. Additionally, ensemble learning algorithms such as Random Forest can be utilized to generate runoff forecasts, which can significantly improve the accuracy and reliability of medium- to long-term runoff forecasts. Meanwhile, deep learning method has also achieved good results in hydrological forecasting. For example, Convolutional Neural Networks (CNN) can be applied to predict precipitation based on radar data, aiming to achieve higher levels of forecasting accuracy.

(2) Data mining-based hydrological forecasting

Data mining is a method for the automatic or semi-automatic extraction of useful information from vast datasets. In the context of hydrological forecasting, this method can explore the laws of hydrological processes and reveal hidden relationships within the data. For example, through clustering analysis of datasets that include variables such as water levels, rainfall, and evaporation, we can identify the law governing hydrological processes across various time scales. This understanding can, in turn, improve the accuracy and reliability of hydrological forecasts. Data mining-based hydrological forecasting boasts the benefits of high data utilization rates and good model interpretability. However, it necessitates appropriate data preprocessing and feature extraction to be effective. In hydrological forecasting, data mining enables forecasting of hydrological events from multiple dimensions. For example, hydrological data can be modeled and analyzed through multiple dimensions, including time, space, and physical processes, to enhance the accuracy and stability of forecasts. In the temporal dimension, time series analysis methods can be used to model hydrological data. In the spatial dimension, spatial interpolation methods can be used to spatialize hydrological data. In the physical dimension, physical models can simulate and predict hydrological processes.

In recent years, the growing scale of data has led to a surge in the application of data mining methods within the field of hydrological forecasting. Data mining is instrumental in predicting hydrological events such as floods, droughts, and water quality, thereby aiding in decision-making for hydrological monitoring and water resource management. For example, by applying clustering analysis to historical hydrological data, we can identify patterns of similar hydrological events. This process allows us to construct forecasting models that anticipate future occurrences. Mining the association rules from historical data helps to uncover relationships among various hydrological indicators, which in turn supports predictions of future trends. Additionally, categorical analysis of historical data and the development of categorical models enable the classification of future hydrological events. Analyzing historical data and establishing forecasting models also allows us to forecast upcoming hydrological events, including potential changes in water levels.

2.1.3 Challenges and needs

2.1.3.1 Needs for meteorological forecasting in the context of climate change

In the context of global climate change, atmospheric circulation and weather systems have grown increasingly intricate, complicating the task of forecasting common weather events like rainfall and typhoons. The frequency and severity of extreme weather and climate events, including rainstorms, droughts, and snowstorms, have escalated globally. The rules governing these events are often elusive, transcending the comprehension derived from years of experience, thereby presenting significant challenges to the predictability of forecasts. Moreover, with the rapid development of information technology, societal sectors are continually elevating their expectations for the accuracy and duration of both meteorological forecasts and climate predictions. In this new era, there is a demand for meteorological forecasts that are more precise, diverse, and intelligent. Meteorological forecasting capabilities face multiple challenges to meet the evolving demands and developments of the modern age.

Additionally, in the face of climate change, there is an increasing need for more objective and rational methods to evaluate meteorological forecasts[9, 10]. Within the current practices and research of rainfall forecast evaluation, the Threat Score (TS) method is commonly utilized to evaluate the accuracy of grid-based rainfall forecasts. However, as the precision of grid-based rainfall forecasts improves, the traditional TS evaluation method, which relies on grid point matching, becomes less suitable. This method is prone to the "double punishment" effect, which can skew the evaluation results. Although various methods for evaluating the spatial distribution accuracy of rainfall forecasts have been developed, such as the Modified Threat Score (MODE) and the Spatial Absolute Limit (SAL), these may not be fully applicable to the context of hydrometeorological coupled forecasting. This is due to their limited consideration of the relationship between the accuracy of rainfall forecasts and that of hydrological forecasts.

2.1.3.2 Needs for hydrological forecasting in the context of climate change

In recent years, the advent of global climate change, coupled with shifts in natural and terrestrial ecosystems, has led to a frequent occurrence of extreme weather anomalies. These anomalies exhibit significant multi-scale spatio-temporal variation characteristics. Significant changes have been observed in precipitation patterns worldwide, including changes in the amount, intensity, and type of rainfall. Notably, in the Northern Hemisphere, there has been a substantial increase in precipitation amount in high-latitude areas. Conversely, low-latitude areas have experienced both local increases and decreases in precipitation amount, accompanied by a notable rise in inter-annual fluctuations. The occurrence of floods and droughts is trending towards more frequent events. From the perspective of temporal variation, a global upward trend in the incidence of floods and droughts is evident, particularly in the early 21st century, where a significant surge in the number of these events has been recorded.

As climate conditions evolve, the complexity of hydrological forecasting intensifies. For medium- to long-term forecasting, it is imperative to account for the influence of climate change on runoff to forecast the future hydrological conditions more accurately. For short-term forecasting, the influence of climate change on the nature and intensity of precipitation must also be thoroughly evaluated to better respond to the occurrence of extreme weather events. Therefore, in the hydrological forecasting, the impact of climate change must be fully considered.

2.1.3.3 Needs for hydrological forecasting under the impact of human activities

The ongoing influence of human activities is progressively altering the patterns of runoff yield and flow concentration within river basins. This evolution complicates the modeling of these changing conditions using traditional hydrological models and parameters, which are calibrated based on historical hydrological data. The inherent unpredictability of human activities, such as shifts in underlying surface land use within basins and the scheduling of reservoirs, further complicates the modeling of basin runoff yield and flow concentration. Presently, the challenges faced in hydrological forecasting within basins under the influence of human activities include:

(1) Difficulties in forecasting for uncontrolled intervening basins

Following the establishment of hydraulic engineering, numerous uncontrolled intervening basins have emerged, both within the projects themselves and between them and the areas protected by flood control measures. The forecasting of these uncontrolled basins remains a significant challenge in the flood forecasting for the "river-reservoir system". The rivers in these uncontrolled basins are typically of small to medium size, and there is a lack of precision in both the real-time monitoring network and the zoning of rainfall forecasts, making it challenging to accurately gauge the actual inflow volumes. As a result, forecasting models are often constructed using a method of parameter approximation transfer. Hence, there is an urgent need for in-depth research into model calibration and parameter correction.

(2) Difficulties in simulating the channel flood routing under multiple blocking conditions

The implementation and operation of hydraulic engineering has altered the patterns of flood waves upstream and downstream of the dams, posing challenges to the applicability of the original river confluence models. Consequently, there is an immediate need for focused research on flood routing models for channels within the reservoir area and below the dam. In the case of channel-type reservoir areas, the inflow point fluctuates with the water level and inflow of the reservoir. The dynamic shifts in the extents of smooth water zone, transition zone, and channel zone necessitate an adaptable calculation of reservoir inflow. Influenced by the dynamic reservoir capacity, for flood control calculations, it is recommended to employ a multi-model parallel solution approach, with the hydraulic model as the primary tool and the static reservoir capacity flood regulation model as a supplementary resource. For the downstream river sections adjacent to the dam, the abrupt changes in reservoir outflow endow the flood waves with discontinuous characteristics.

(3) Difficulties in medium- to long-term runoff forecasting

With the implementation and operation of multiple hydraulic engineering projects within basins, the demand for medium- to long-term forecasting has evolved from Qualitative to Quantitative predictions. However, the mechanisms behind weather system changes at these scales remain largely unknown, and the distribution of runoff is increasingly influenced by these hydraulic engineering. As a result, medium- to long-term inflow forecasting has emerged as a critical and challenging aspect of the hydrological forecasting domain. There is a requirement to establish a stable and reliable long-term series database, to analyze the key factors influencing medium- to long-term runoff forecasting and the factors related to reservoir impoundment and release. By integrating multiple models, including mechanism models, data mining, and knowledge-based rules, with new approaches such as artificial intelligence, machine learning, and ensemble forecasting, it is possible to achieve medium- to long-term trend analysis and runoff forecasting. This integration aims to develop a suite of multi-driver basin-wide medium- to long-term runoff forecasting technologies, with the expectation of enhancing the accuracy of such forecasts.

2.1.3.4 Needs for hydrological forecasting in the context of energy transition

In the current era of global energy transition, the demand for hydrological forecasting is experiencing significant shifts. Energy transition, especially the transition towards renewable energy, is impacting not only the patterns of energy production and consumption but also presenting new challenges for water resource management and forecasting. This is primarily evident in several key areas:

Firstly, as renewable energy, particularly hydropower, gains a larger share in the energy mix, reliance on hydrological systems intensifies. Accurate hydrological forecasting becomes essential for balancing the efficiency of hydropower generation with the health of river ecosystems. For large-scale hydropower stations, the accuracy of these forecasts is pivotal to the planning, construction, and operational effectiveness of the facilities. Given that large-scale hydropower stations often involve extensive reservoir scheduling, precise forecasting of rainfall, runoff, and impoundment volumes are vital for maintaining both the power generation efficiency and the sustainable use of water resources. Meanwhile, small-scale hydropower stations face distinct challenges related to local hydrological conditions and ecological impacts. Typically causing fewer disturbance to the natural river flow, these stations necessitate more precise hydrological forecasting to optimize power generation efficiency without harming the river ecosystem. Moreover, due to their widespread distribution and heightened sensitivity to local hydrological variations, small-scale hydropower stations demand hydrological forecasts that offer more localized and specific information.

Meanwhile, the complementarity between hydropower and other renewable sources like wind and solar power has emerged as a key strategy for improving the stability and efficiency of energy supply systems. The integrated hydro-wind-solar system leverages the advantages of each energy type, streamlining energy production and allocation. When wind and solar resources are limited, hydropower can offer a consistent power output; conversely, during dry spells, wind and solar power can compensate for the shortfall in energy supply. This complementarity not only improves the overall efficiency of renewable energy utilization but also decreases reliance on fossil fuels, contributing to a reduction in greenhouse gas emissions. Consequently, there is an urgent need to improve the capability of hydrological forecasting to ensure a balanced and reliable energy supply.

Pumped storage, as an effective energy storage technology, plays a key role in energy transition. It helps balance electricity supply and demand by storing energy during low demand periods and releasing it during peak demand times. This technology is especially adept at handling the storage of intermittent energy sources like wind and solar power, thus improving the flexibility and reliability of the entire power system. For pumped-storage hydropower stations, the precise forecasting of available water resources for energy storage is essential to ensure the efficient functioning of the energy storage system.

In summary, within the framework of energy transition, precise and efficient hydrological forecasting is indispensable for both large-scale and small-scale hydropower stations, as well as for hydro-wind-solar complementary and pumped-storage hydropower systems. As climate change continues to exert its influence and renewable energy technologies advance, hydrological forecasting is poised to become increasingly significant. It will play a pivotal role in areas such as resource planning, ecological preservation, energy optimization, and disaster mitigation in the future.

2.2 Key technologies and their application

In this section, the focus is on addressing the challenges and needs in meteorological and hydrological forecasting through the following areas of research: 1) Advanced meteorological forecasting technology that provide technical support for improving the accuracy of weather predictions in the face of climate change; 2) Hydrometeorological coupled forecasting technology designed to meet the hydrological forecasting needs arising from climate change scenarios; 3) Methods for extracting scheduling rules from upstream reservoirs to meet the hydrological forecasting demands influenced by human activities; 4) Data-intensive paradigm-based hydrological forecasting technology aimed at tackling the challenge of increasing the accuracy of hydrological forecasts.

2.2.1 Meteorological forecasting technology

2.2.1.1 Short- to medium-term precipitation forecasting technology

With the advancement of computer science, meteorological forecasting has evolved from subjective extrapolation to numerical weather forecasting and is progressively moving towards greater precision and intelligence. For example, in the meteorological service system of the Lower Reaches of the Jinsha River - the Three Gorges area in China, the current intelligent grid forecasting system employs two primary methods for short- to medium-term precipitation forecasting: 1) Modeling method: It utilizes raw data from both large-scale and mesoscale models, applying bilinear interpolation to integrate data of varying resolutions onto a unified 5 km × 5 km fine grid, thereby creating 0-10 day short-to-medium term objective precise precipitation grid forecasting outputs. 2) Multi-model ensemble: An optimal ensemble method has been developed, which is based on multi-factor fine zoning and forecasting. This method dynamically tests multiple numerical model precipitation forecasts, establishes a performance ranking system for graded and time-limited precipitation forecasts in each basin zone, and incorporates the experience of forecasters to ultimately provide the optimal precipitation forecasts. In addition, leveraging the 51 member outputs of the EC ensemble forecasting, the performance of statistical outputs (such as ensemble mean, quantiles, and Mode values) in the Yangtze River Basin has been evaluated. These statistical outputs have been compared with deterministic forecasts for analysis, leading to the establishment of a fusion scheme that utilizes advantageous statistical measures for different precipitation levels. This represents a significant application of precipitation ensemble forecasting in reservoir scheduling.

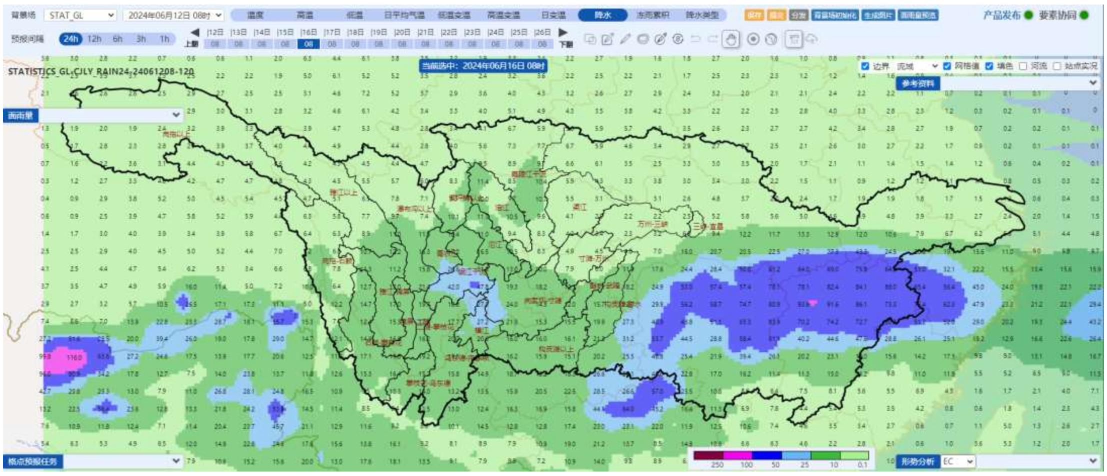


Figure 2-1 Schematic diagram of short- to medium-term grid (5 km×5 km) forecasting in the Yangtze River Basin

Extended-range precipitation forecasting technology

Currently, in the Lower Reaches of the Jinsha River - the Three Gorges area in China, the two methods are being integrated for forecasting, and the research and application of big data-driven modeling forecasts are progressively advancing. The approaches include: 1) Utilizing the DERF model outputs from the National Climate Center, China Meteorological

Administration, and applying the L-J classification method to decompose the Sea Level Pressure (SLP) field. This analysis determines its correlation with precipitation in the Yangtze River Basin and ultimately leads to the establishment of a forecasting model, as depicted in Figure 2-2) Employing CFSv2 model outputs and using downscaling interpolation techniques to conduct extended-range precipitation process forecasting and areal rainfall process forecasting for representative stations within the Yangtze River Basin, as illustrated in Figure 2-3. 3) Employing statistical climate physical analysis approach, in conjunction with atmospheric oscillations and feature similarity extrapolation techniques, to forecast the future precipitation trends in the basin of interest over a specified period.

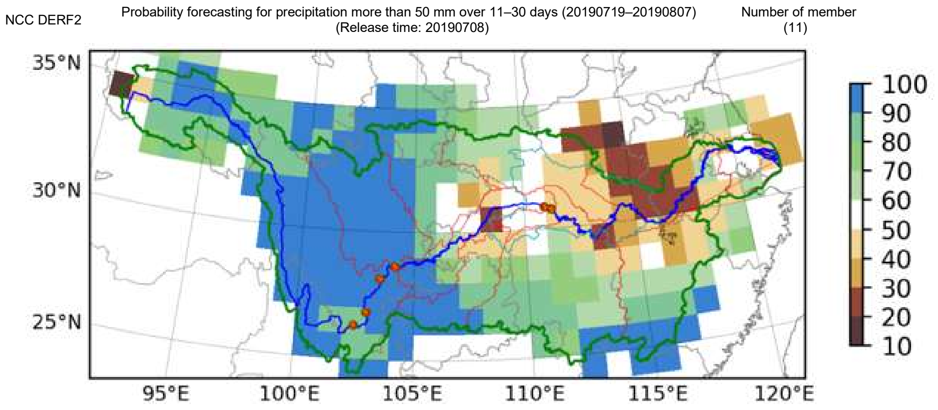


Figure 2-2 Schematic diagram of extended-range precipitation probability forecasting in the Yangtze River Basin by DERF model

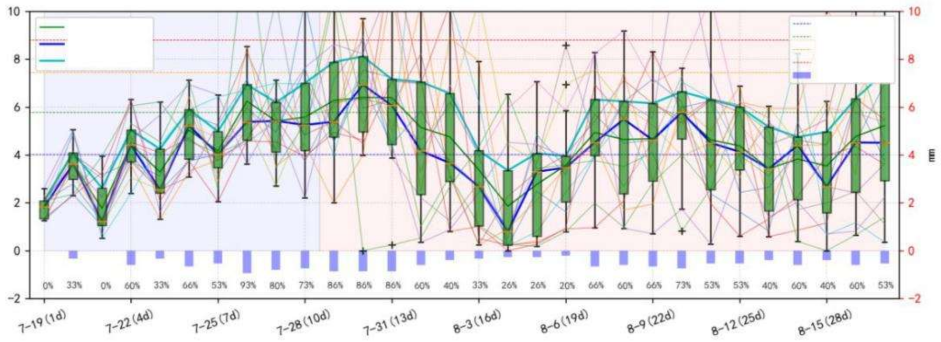


Figure 2-3 Schematic diagram of extended-range areal rainfall process forecasting in the Jinsha River Basin in China by CFSv2 model

Extended-range forecasting extends beyond conventional weather forecasting periods, offering decision-makers insights into future trends, which is pivotal for strategic planning and management of water resources. For example, in the Yangtze River Basin in China, a swift shift from dry to wet conditions occurred in the upper reaches during the autumn of 2021, while a record-breaking extreme high temperature and drought affected the middle and lower reaches in 2022. The extended-range precipitation forecasts issued by the Chinese meteorological forecasting team provided decision-makers with a more precise understanding of the impending precipitation trends two weeks in advance. This foresight allowed them to contemplate scheduling plans for power generation and water replenishment ahead of time, thus offering crucial support for the efficient use of water resources in the basin.

2.2.1.2 Long-term precipitation trend forecasting technology

Currently, in the Lower Reaches of the Jinsha River - the Three Gorges area in China, the long-term precipitation trend forecasting primarily employs a technology that integrates model forecasting outputs with a synthesis of climate feature similarities. The methodology involves: 1) Utilizing CFSv2 model outputs and applying a multi-sample ensemble method to process the forecasting of precipitation anomaly distribution in the Yangtze River Basin for the upcoming nine months. 2) Leveraging the chaos similarity theory of atmospheric motion, which posits that early-stage features are consistent with historical patterns, and within a certain time frame, later-stage trends exhibit characteristics that align with historical patterns of subsequent. By analyzing early-stage abnormal climate features, forecasters can identify the most similar historical years and perform a combinatorial analysis of these similar years to estimate the evolution trend of precipitation in the next natural month. Figure 2-4 shows the customized precipitation anomaly forecasting outputs for the Yangtze River Basin in August 2023.

Cj_2023_08_ precipitation anomaly percentage forecasting,
release time (20230717)

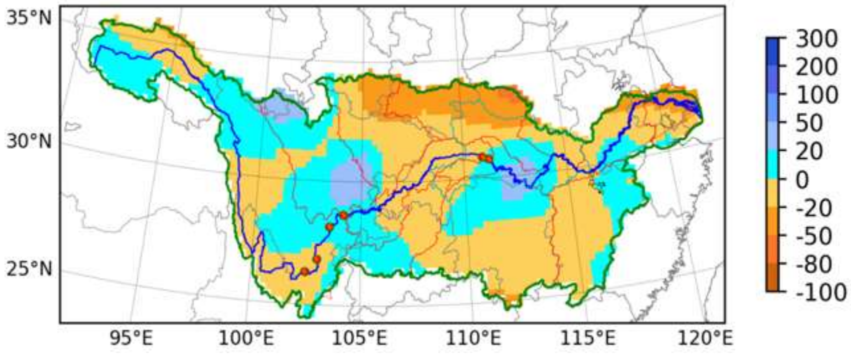


Figure 2-4 Customized precipitation anomaly forecasting outputs for the Yangtze River Basin in August 2023

2.2.1.3 Intelligent evaluation technology for meteorological forecasting

This report delves into the evaluation technology for precipitation forecasts tailored to the requirements of hydrological forecasting, and it evaluates and tests the effectiveness of this technology in gauging the accuracy of precipitation forecasts. The technology provides a comprehensive evaluation of rainfall forecasting accuracy, incorporates multi-dimensional evaluation indicators, and applies a weighted summation of these indicators to derive an overall precipitation forecasting score. By effectively mitigating the "double punishment" effect, this approach more precisely aligns with the demands of hydrological forecasting.

This technology involves four evaluation indicators: S, A, L, and DTS. "DTS" evaluates the magnitude difference in rainfall forecasts at grid points, with values closer to 1 indicating higher accuracy at each grid point. "S" evaluates the structural accuracy of the rainfall forecasts, where a value closer to 0 suggests a more precise forecasted precipitation area; a value greater than 0 indicates an overestimation of the forecasted precipitation area, and vice versa. "A" evaluates the volume accuracy of the rainfall forecasts, where a value closer to 0 suggests a more precise total precipitation forecast; a value greater than 0 indicates an overestimation of the total precipitation, and conversely, the lower it is. "L" evaluates the positional accuracy of the rainfall forecasts, with a value closer to 0 indicating a more accurate centroid position of the forecasted precipitation. The overall Score is determined using a random forest algorithm, which calculates the weights of each indicator by establishing a functional relationship between these indicators and the accuracy of hydrological forecasts, thereby yielding the score.

The application effectiveness of this method is demonstrated in Figure 2-5. As depicted in the figure, S, A, L, and DTS serve to objectively evaluate the precipitation area, volume of rainfall, centroid position, and the magnitude of errors in grid point precipitation. The Score generated aligns with visual perceptions, indicating its effectiveness in evaluation.

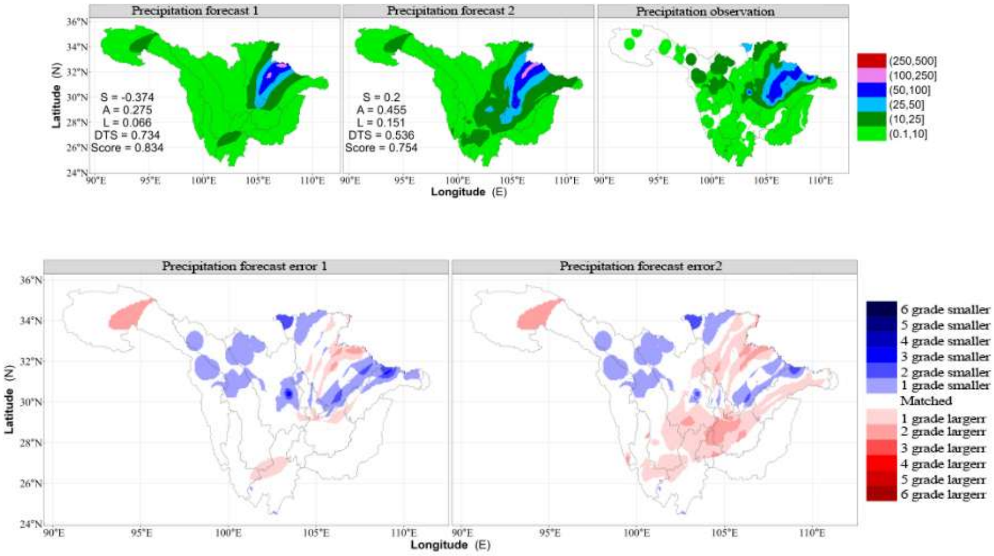


Figure 2-5 Evaluation of precipitation forecasts in the Yangtze River Basin

2.2.2 Hydrometeorological coupled forecasting technology

The intensification of global climate change has led to a frequent occurrence of extreme weather events with significant multi-scale spatio-temporal variability. Consequently, the frequency and severity of meteorological disasters have been on the rise annually. Traditional hydrological forecasting, which relies on "ground rain" data from rainfall stations inputted into hydrological models. Its effective leading time that does not exceed the watershed's flow concentration time. This limitation makes it difficult to meet the practical needs of flood risk management, as well as forecasting and early-warning in a changing environment. Therefore, there is an urgent need for using hydrometeorological coupled forecasting technology to improve the accuracy of flood forecasting. Numerous countries, including the United States, the UK, China, and Japan, have conducted extensive research in this field. This report delves into the hydrometeorological coupled forecasting technology and illustrates its application effects. The case analysis is presented as follows.

Hydrometeorological coupled forecasting technology typically employs a one-way approach. It integrates numerical weather models with distributed hydrological models by utilizing outputs such as precipitation, temperature, and wind speed from the numerical weather models. These outputs serve as a bridge, and data including precipitation and temperature are extracted from the numerical weather model's output files to drive the distributed hydrological model. The framework for the hydrometeorological coupled forecasting technology discussed in this report is depicted in Figures 2-6, while the forecasting results of this technology are illustrated in Figure 2-7.

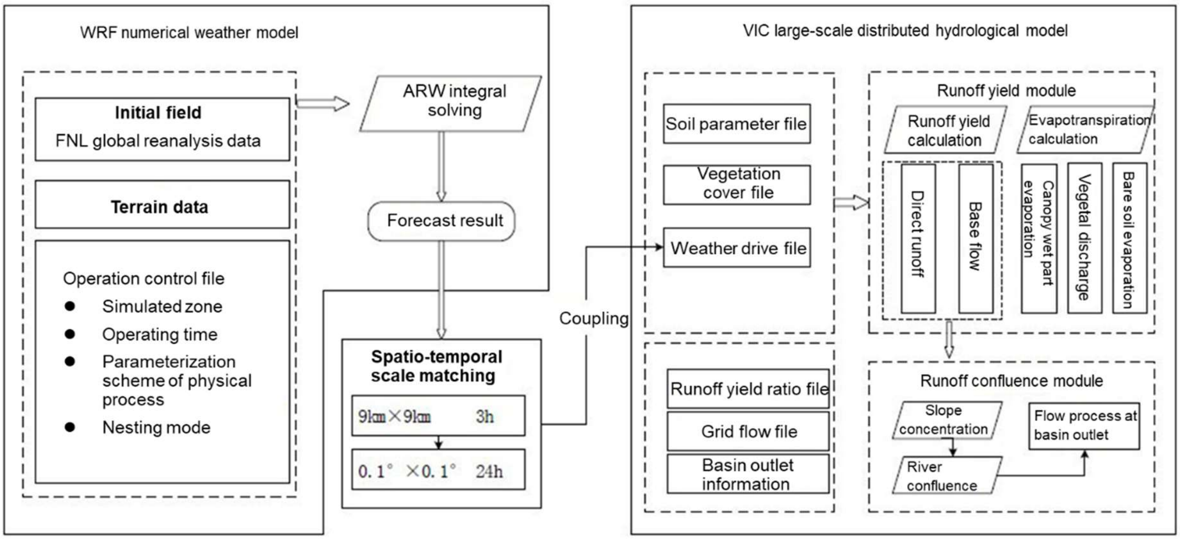


Figure 2-6 Hydrometeorological coupled forecasting technology

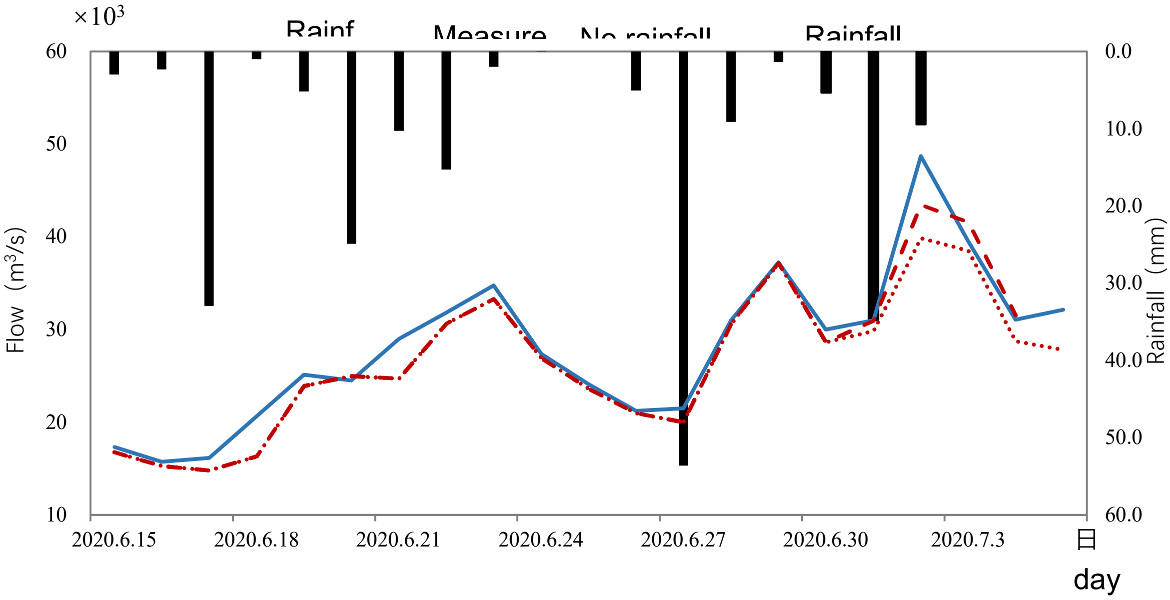


Figure 2-7 Forecasting results of No. 20200630 Flood

Figure 2-7 illustrates that the relative error for the flood peak flow forecasting is -10% in the rainfall forecasting mode (i.e., the coupled mode), while that for the flood peak flow forecasting is -18% without the rainfall forecasting mode.The integration of meteorological and hydrological forecasting provides future meteorological data for the hydrological forecasting, enabling early understanding of the rainfall information in the research area, which in turn enhances the models' forecasting accuracy. Given that the research area in this report is an open basin, the flow at the basin outlet is notably influenced by the inflow from the watershed. Consequently, the forecasting conducted without the rainfall forecasting model also anticipated a flood peak on June 30, but it exhibited a greater error in the flood peak compared to the results obtained using the coupled model.

2.2.3 Hydrological forecasting technology for multiple blocked basins

The impact of hydraulic engineering compels natural river channels to transform into elongated river systems characterized by multiple blockages. The flood processes within the watershed are altered due to reservoir regulation. However, the accuracy of hydrological forecasting in these multi-blocked basins is hindered by the challenges associated with extracting reservoir scheduling rules and determining their outflow. Consequently, research teams globally have been developing and refining models to identify reservoir scheduling rules, in an effort to provide technical support for hydrological forecasting in watersheds. This report delves into the identification model of reservoir scheduling rules and demonstrates their application effects.

Regarding the identification model for reservoir scheduling rules, it is essential to consider both the upstream controlling reservoirs with strong regulation capabilities and those at the basin outlet. The model leverages historical operational data of reservoirs, employing a machine learning model to extract the scheduling and operation laws of the upstream reservoir system, which assists in simulating the discharge flows from these reservoirs. This report utilizes operational data from multiple reservoirs spanning the years 2014 to 2017. By applying the radial basis function neural network (RBF) algorithm, we have established an identification model for reservoir scheduling rules, specifically extracting the scheduling rules for the primary controlled reservoirs in the upper reaches of the Yangtze River Basin. The model's inputs and outputs are detailed in Table 2-1.

Table 2-1 Table for inputs and outputs of single-reservoir scheduling rules extraction model on different time scales

Time scale	Input	Output
Ten-day period	Current ten-day period, reservoir water level of current ten-day period, reservoir inflow, reservoir outflow, reservoir inflow forecasted for next ten-day period	Reservoir outflow in the next time period
Day	Current days, current reservoir water level, reservoir inflow, reservoir outflow, reservoir inflow forecasted for next day	Reservoir outflow in the next time period

The model's output results are presented in Tables 2-2 and 2-3. In the ten-day scale simulation of reservoir outflow, the mean relative error of the simulations generally falls below 20%, aside from a few reservoirs in the Jialing River Basin The pass rate generally meets the requirements, and the deterministic coefficient is predominantly above 0.8. Similarly, in the daily scale simulation of reservoir outflow, the mean relative error of the simulations generally falls below 20%, aside from a few reservoirs in the Jialing River Basin and the Wujiang River Basin. The pass rate generally meets the requirements, and the certainty coefficient is predominantly above 0.8. In summary, the model's simulation of reservoir outflow is deemed accurate on both the ten-day and daily scales. Owing to the length constraints of the report, only the simulation process for the outflow of the Liyuan Reservoir is depicted, as illustrated in Figure 2-8.

Table 2-2 Statistical table for testing results of RBF neural network model on ten day-scale

Reservoir		Mean relative error	Compliance rate	Certainty coefficient	Root mean square error
The Jinsha River	Liyuan	0.10	92	0.95	239.05
	Ahai	0.12	83	0.98	174.69
	Jin'anqiao	0.17	78	0.95	293.00
	Longkaikou	0.18	78	0.93	334.29
	Ludila	0.22	81	0.98	193.16
	Guanyinyan	0.16	67	0.93	372.94
The Yalung River	Jinping I	0.15	83	0.89	175.94
	Jinping Ⅱ	0.23	65	0.60	338.23
	Ertan	0.12	83	0.83	274.89
	Tongzilin	0.09	86	0.94	202.89
The Minjiang River	Pubugou	0.28	36	0.72	380.89
	Zipingpu	0.14	67	0.84	94.34

Table 2-3 Statistical table for testing results of RBF neural network model on daily scale

Reservoir		Mean relative error	Compliance rate (%)	Certainty coefficient	Root mean square error
The Jinsha River	Liyuan	0.18	70	0.92	335.38
	Ahai	0.19	63	0.92	414.40
	Jinanqiao	0.23	68	0.93	374.68
	Longkaikou	0.20	67	0.93	348.11
	Ludila	0.27	63	0.91	444.83
	Guanyinyan	0.14	77	0.95	344.03
The Yalung River	Jinping I	0.12	83	0.85	209.28
	Jinping Ⅱ	0.20	59	0.57	359.24
	Ertan	0.12	84	0.88	247.96
	Tongzilin	0.06	95	0.99	101.72
The Minjiang River	Pubugou	0.23	61	0.85	309.46
	Zipingpu	0.16	68	0.79	125.32

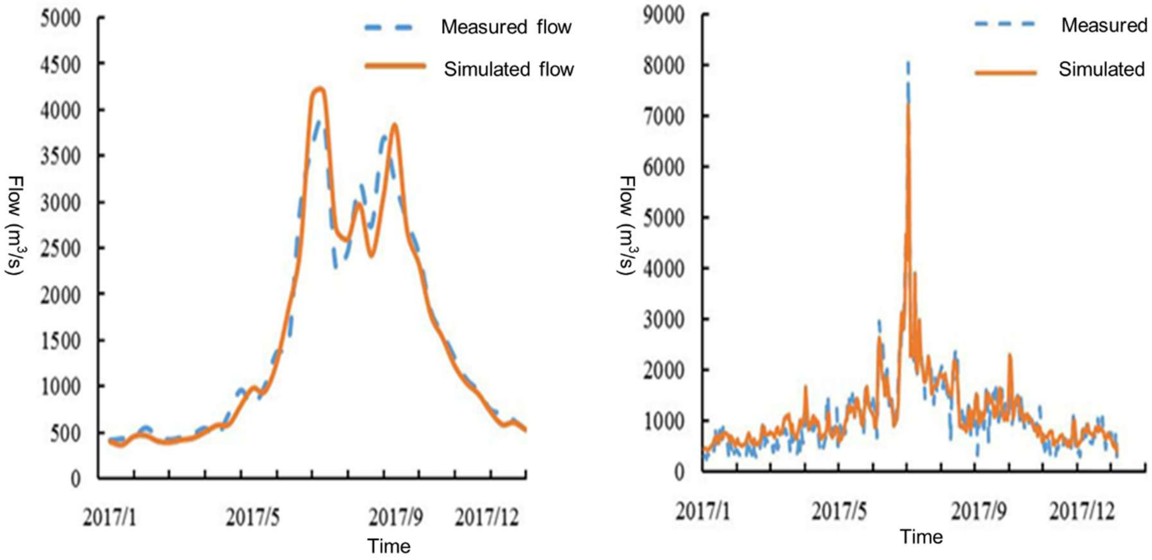


Figure 2-8 Testing results of reservoir inflow

2.2.4 Data-intensive paradigm-based hydrological forecasting technology

The data-driven model represents a data-intensive paradigm-based hydrological forecasting technology. It does not require a profound comprehension of the physical mechanisms within a basin's hydrological cycle, but directly explores the correlation among hydrological variables like runoff, rainfall, and evaporation at the data level. This approach boasts benefits such as ease of modeling, minimal basic data requirements, and reduced computational complexity.

This report delves into the accuracy of data paradigm-based hydrological forecasting technology and presents the runoff forecasting effects of various methods: data mining-based similar runoff forecasting, image recognition-based similar rainfall-runoff forecasting, machine learning-based medium- to long-term forecasting, and genetic similarity-based medium- to long-term runoff forecasting. The application cases are shown below.

2.2.4.1 Data mining-based similar runoff forecasting

Several sub-basins (range) situated in the upper reaches of the Yangtze River, such as the Jinsha River, Yalung River, Minjiang River, Tuojiang River, Jialing River, and Hengjiang River, along with other tributaries, have been chosen as the subjects of this study. Historical areal rainfall data for each sub-basin (range) and flow data from control stations within the basins were collected, serving as the foundational data for conducting a data mining-based similar runoff forecasting. The specific scheduling process involves the following aspects:

(1) Classification of flood events

Initially, a flood event classification model is used to categorize the historical rainfall-runoff data of the study basin (range) into distinct flood events. This process involves aligning the rainfall process with their corresponding flood process to generate independent flood event samples. It also facilitates the extraction and computation of characteristic indicators for rainfall and floods in each event.

(2) Extraction of precipitation characteristics

Following the classification of rainfall and flood events, characteristic indicators for floods and rainfall are computed for each event, encompassing both temporal and magnitude indicators. These indicators serve to provide a comprehensive description of the characteristics of rainfall and flood processes, including aspects such as duration and intensity.

(3) Model training and forecasting

Next, the model is trained and validated using the classified historical rainfall data and flood event samples, along with the extracted indicator results from each basin. Two approaches, the K-nearest neighbor (KNN) and the Custom method, are used to identify similar flood processes from the forecasted future rainfall. Subsequently, four machine learning models—KNN, Partial Least Squares Regression (PLS Regression), Random Forest, and Ridge Regression—are used to forecast flood indicators such as peak flow, the rise in flood magnitude, flood volume, and the time lag to peak.

The simulation results of peak flow and flood volume are shown below:

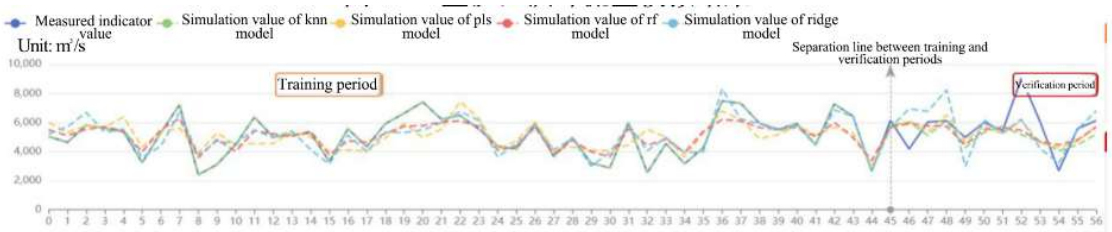


Figure 2-9 Simulation results of peak flow of the Jinsha River

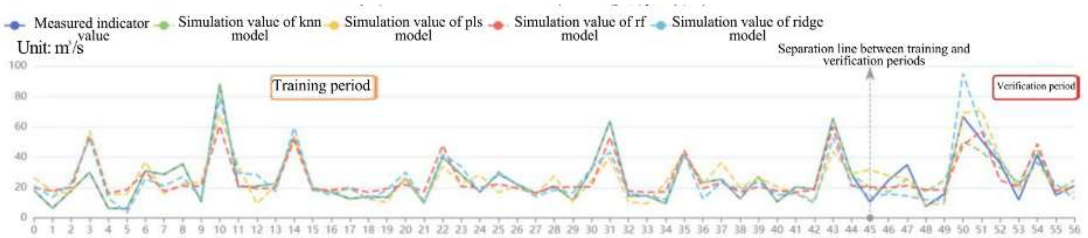


Figure 2-10 Simulation results of flood volume of the Jinsha River

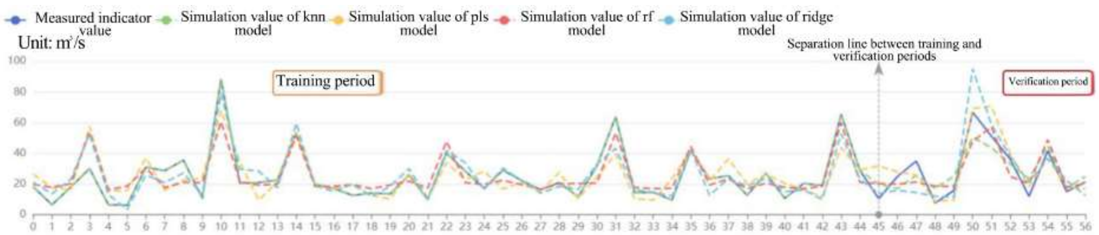


Figure 2-11 Simulation results of peak flow of the Yalung River

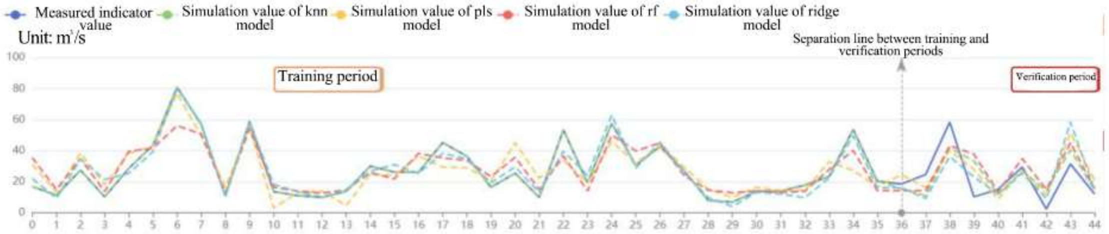


Figure 2-12 Simulation results of flood volume of the Yalung River

It can be seen from Figure 2-9 to Figure 2-12 that the data mining-based similar runoff forecasting is generally capable of predicting the trend of flow changes, yet its accuracy in actual flow forecasting is not high. Moving forward, there should be a focus on researching precipitation and flood characteristics and on developing indicators that more accurately reflect the spatio-temporal dynamics of precipitation and floods. This will contribute to the construction of more rational similar runoff forecasting models.

2.2.4.2 Image recognition-based similar rainfall-runoff forecasting

This method involves transforming historical measured rainfall data into spatial image format outputs using techniques such as spatial interpolation. Subsequently, it integrates these with grid-based quantitative rainfall forecasting outputs and employs image recognition-based approaches to conduct similar rainfall analysis. This process enables the rapid identification of historical rainfall patterns that are similar to the forecasted rainfall. Once similar rainfall patterns are identified, a runoff forecasting method that leverages similar rainfall data and deep learning is established to facilitate hourly runoff forecasting for of reservoir inflow in the next 10 days . The specific process is shown below:

(1) Image recognition-based similar rainfall model

Historical rainfall data, grid forecasting data, and flow data from control stations are gathered by zone, providing a basis for analyzing the rainfall-runoff relationship in the primary zone. The historical rainfall data from the stations are then converted into grid data using a spatial interpolation algorithm. A residual autoencoder-based model for similar rainfall is developed, incorporating advanced deep learning techniques such as autoencoders, residual blocks, and batch normalization. This model facilitates the comparison and retrieval of grid rainfall similarity.

(2) Runoff forecasting model based on similar rainfall and deep learning

Building upon the image recognition-based similar rainfall model, a runoff forecasting model that integrates similar rainfall with deep learning is developed. This model employs a long short-term memory neural network (LSTM) to learn the rainfall-runoff relationship. It then combines the similar rainfall patterns with runoff forecasting results using Lasso Regression to derive hourly forecasting results for the upcoming days at the forecasting section. In this way, it transforms the non-deterministic similar rainfall runoff-yield process relationship into a quantitative runoff forecasting approach. This method has proven to be highly accurate in practical applications, offering valuable technical support for precise forecasting.

The simulation results of the image recognition-based similar rainfall model are shown in Figure 2-13. The identified historical similar rainfall areas are basically consistent with the forecasted rainfall, signifying that the search performance is satisfactory.

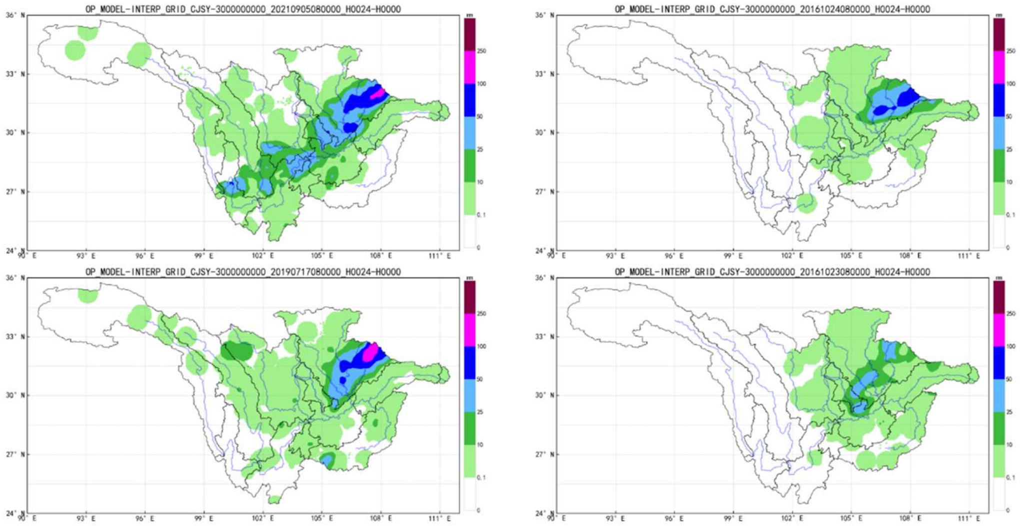


Figure 2-13 Single-day similar rainfall search case 2 in the Yangtze River Basin

The performance of the deep learning-based runoff forecasting model, which leverages similar rainfall, is illustrated in Figure 2-14. For the one-day ahead forecasting, the training set exhibits an accuracy of 92.8%, whereas the test set records an accuracy of 90.8%. When extending the forecasting to the next 10 days, the average accuracy for the training set is 71%, and for the test set, it is 68.4%.

These results indicate that the image recognition-based similar rainfall-runoff forecasting model, yields commendable results in flow forecasting, as detailed in section 2.2.4.2.

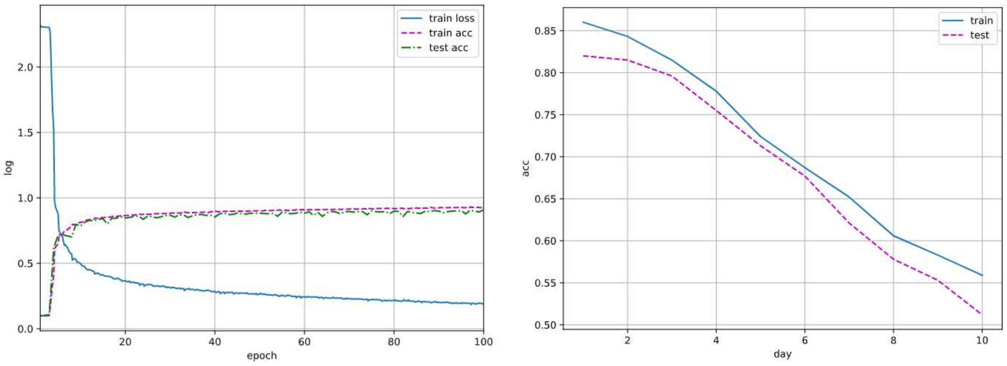


Figure 2-14 Forecasting accuracy of Beibei Station flow for the next 1 day and 10 days during the flood season in 2021

2.2.4.3 Genetic similarity-based medium- to long-term runoff forecasting

The genetic similarity-based medium- to long-term runoff forecasting employs machine learning algorithms to predict future inflow by identifying historical hydrological processes that are similar to the current situation. The key of the method is defining the concept of similarity and searching for analogous processes and identifying historical hydrological processes that are similar to the current situation. In this report, Euclidean distance is used to gauge the similarity between the runoff of several ten-day periods early in the forecast period and the corresponding periods in historical data. This approach selects K historical similar runoff processes to generate multiple potential scenarios for the later stages of the forecast period. The model's principle is depicted in Figure 2-15, while the model's forecasting results are presented in Figures 2-16 and 2-17.

The two figures demonstrate that the medium- to long-term runoff forecasted by this method aligns with the actual trend of flow over the same period. Compared to the multi-year average flow, the forecasted future flow process is more accurate, suggesting that this method delivers favorable forecasting results.

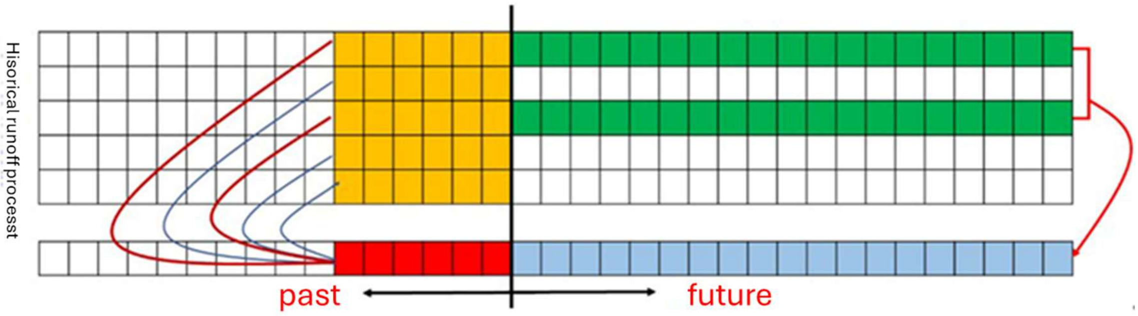


Figure 2-15 Principle schematic of genetic similarity-based medium- to long-term runoff forecasting

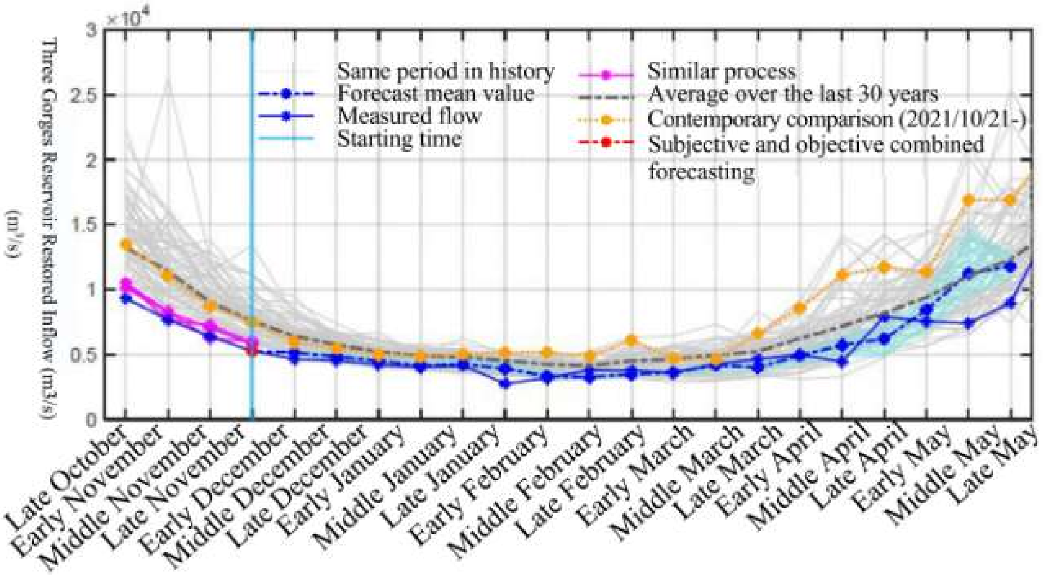


Figure 2-16 Genetic similarity-based medium- to long-term runoff forecasting: Restored reservoir inflow forecasting results of Power Station A

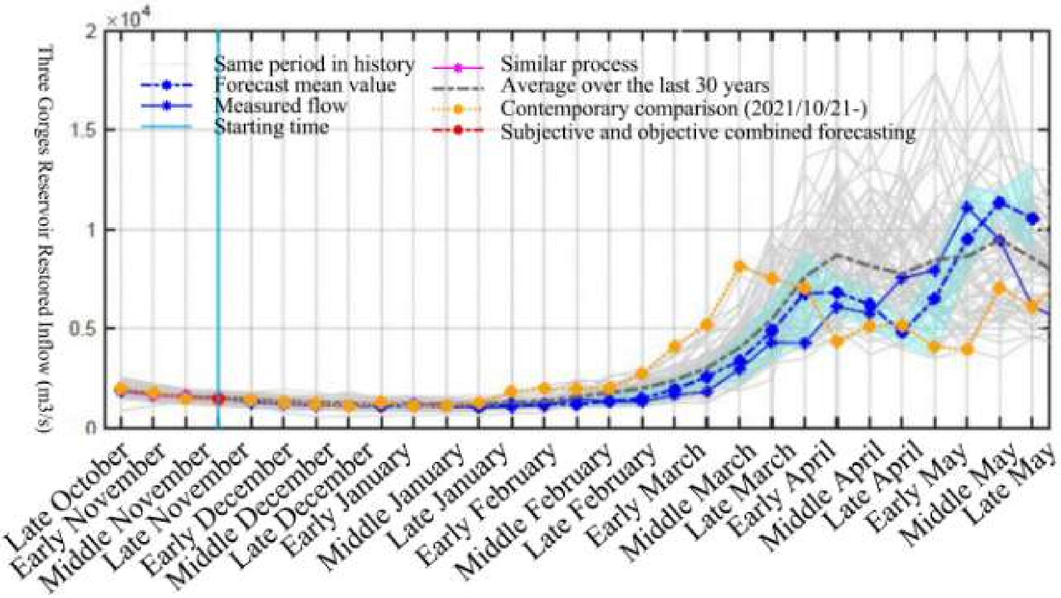


Figure 2-17 Genetic similarity-based medium- to long-term runoff forecasting: Restored reservoir inflow forecasting results of Power Station B

2.3 Conclusions and prospects

This section elaborates on the pivotal role of hydrological forecasting technology in CUBWR; it provides a systematic review of the current status of hydrological forecasting technologies; it thoroughly examines the hydrological forecasting requirements in the present environmental context; and it presents case studies on simulation paradigm-based hydrometeorological coupled forecasting technology, hydrological forecasting for multi-blocked basins, data-intensive paradigm-based hydrological forecasting technology, and the evaluation of meteorological and hydrological forecasting technologies. The main conclusions drawn in this chapter are as follows:

(1) Meteorological and hydrological forecasting technologies offer vital information for decision-making among water resource managers, playing a significant role in various areas of water resource utilization, including flood and drought mitigation, water allocation, power generation dispatching, and ecological preservation.

(2) With over 90 years of evolution, simulation paradigm-based hydrological forecasting has achieved a state of maturity. Currently, the advancement of this type of hydrological forecasting should concentrate on interdisciplinary or technological cross-integration to strengthen its applicability in CUBWR.

(3) Data-intensive paradigm-based hydrological forecasting technology operates by directly uncovering correlations among hydrological variables like runoff, rainfall, and evaporation at the data level. It benefits from easy modeling, minimal basic data needs, and reduced computational complexity. Nowadays, propelled by swift advancements in computer technology and the Internet, there is a surge in data related to regional water cycles and basin runoff yield and flow concentration, gathered through sophisticated observational techniques. This data-intensive paradigm-based hydrological forecasting holds extensive potential for development and application in CUBWR.

(4) Meteorological and hydrological forecasting technologies rely heavily on data accuracy. Moving forward, there should be an increased focus on data collection efforts. This could involve deepening the integration of satellite technology with meteorological and hydrological forecasting to harness satellite remote sensing for gathering more comprehensive hydrological and underlying surface data.

3 BASIN-WIDE WATER RESOURCE SCHEDULING MANAGEMENT

3.1 Overview

3.1.1 Development status of basin-wide water resource scheduling management

The traditional approach to water resource scheduling typically revolves around a single goal, such as maximizing water supply volume or minimizing costs. However, the comprehensive utilization of a cascade reservoir system pursues multiple service objectives, including flood control, power generation, navigation, and water supply. As such, the cascade reservoir system serves as a large-scale hydro-complex system, addressing a variety of objectives. In the system, the interconnections between upstream and downstream reservoirs are often intricate, including both hydraulics and electricity. During the joint scheduling of cascade reservoirs, the power plants involved may have distinct scheduling objectives and requirements. Moreover, there may be conflicts in water usage during certain times of the year, depending on the specific scheduling objectives. Thus, the joint scheduling of a cascade reservoir system poses a decision-making challenge that involves multi-objective optimization with complex constraints. The conventional single-objective scheduling methods overlook other related optimization goals, such as conservation of water resources, land use, and environmental protection. Addressing this issue has led to the gradual emergence of multi-objective optimization as a significant field of study in water resource scheduling.

Currently, research on multi-objective water resource scheduling can be divided into two main approaches: 1) The use of objective function fitting, constraint methods, and weighting methods to transform multi-objective problems into single-objective ones for resolution; and 2) The application of multi-objective evolutionary algorithms grounded in Pareto theory to achieve parallel solutions[11-13]. Existing algorithms for multi-objective optimized scheduling of water resources are generally divided into two categories. The first category encompasses conventional optimization solution algorithms, including linear programming, nonlinear programming, network flow programming, dynamic programming, and large system decomposition and coordination methods. These methods often face the issue of the "Curse of Dimensionality." With advancements in computer technology and artificial intelligence (AI) theories, modern heuristic intelligent optimization algorithms that simulate the evolutionary, migratory, and foraging behaviors of organisms have increasingly garnered the attention of scholars in the field. These heuristic optimization algorithms do not impose specific requirements on the form of the objective function or problem constraints, whether they are continuous or discrete, or derivable or not. Moreover, the computational cost in terms of space and time increases linearly with the scale of the cascade. As a result, compared to conventional optimization methods, heuristic optimization algorithms exhibit superior adaptability. Consequently, in recent years, several heuristic optimization algorithms have been successfully applied to address issues related to multi-objective optimized scheduling of water resources.

The research on the application of multi-objective optimization in water resource scheduling primarily encompasses the following aspects:

1. Water Resource Allocation: Utilizing multi-objective optimization methods enables the rational allocation of water supply volumes across various regions. This approach not only satisfies the diverse regional demands but also maximizes the efficiency of water resource utilization while minimizing the costs associated with water supply.

2. Water Source and Environmental Protection: The application of multi-objective optimization methods facilitates the identification of optimal strategies for water source protection. These

strategies aim to reduce pollution and prevent the degradation of water quality, while concurrently safeguarding the ecological environment.

3. Emergency Water Sourcing: In the event of disasters or emergencies, the multi-objective optimization method can assist decision-makers in devising a rational temporary water supply plan. This ensures that emergency requirements are met while also aiming to minimize losses.

4. Water Resources Management Decision Support Systems (WRM-DSS): Utilizing multi-objective optimization methods can facilitate the development of WRM-DSS, thereby aiding decision-makers in conducting long-term planning and management of water resources.

To sum up, the application of multi-objective optimization in water resource scheduling research can effectively address the supply and demand imbalance, and promote the rational and sustainable use of water resources. As technology advances and its applications expand, the role of multi-objective optimization in water resource scheduling is anticipated to grow in significance, offering robust support for addressing water resource challenges.

3.2 Challenges and needs

3.2.1 Requirements for multi-objective optimized scheduling

Generally, natural water resources are typically stored in rivers, lakes, and other water systems. To control these water resources, people often build up reservoirs, diversion channels, sluices, and other hydraulic engineering structures to manage water resources in a segmented manner. The improvement and operational management levels of these structures directly affect the hydraulic engineering benefits as well as the comprehensive utilization efficiency of hydraulic engineering and water resources. In hydraulic engineering scheduling, the primary goal is to make rational plans for scheduling rules based on the reservoir's designated tasks. This involves sustaining the safe operation of the reservoir while also allocating its water resources in a unified and rational manner. Such allocation aims to resolve conflicts in water use among different regions and demands. To achieve this, it is essential to maximize the reservoir's capacity, ensuring the water resources are impounded and utilized wisely, minimizing unnecessary water loss and optimizing comprehensive benefits in terms of economic gain, ecological preservation, and flood control. For comprehensive reservoirs, adopting rational regulation methods is necessary to efficiently operate the reservoir and reduce unnecessary losses of water resources and energy. Over the past two decades, significant research outcomes have been achieved concerning the application of optimization theories and methods in reservoir scheduling. Nowadays, a breakthrough in reservoir management is the implementation of optimization techniques for optimized reservoir scheduling. Currently, the widely applied methods for reservoir scheduling include routine scheduling drawings and optimized reservoir scheduling rules. Both methods have their strengths and weaknesses in practice, and their theories are not always well integrated with practical applications. **As climate change intensifies and efforts to achieve carbon peaking and neutrality goals progress, hydraulic engineering scheduling has become a crucial link affecting environmental and economic sustainability. Currently, issues related to multi-objective optimization in hydraulic engineering scheduling have emerged as a hot topic in current research, and are of great importance for the sustainable development of society, economy, and environment, as well as for building a harmonious society.**

In the current context, water resource scheduling must address a multitude of issues, including economic gains, flood control benefits, environmental protection, and the potential surplus of water resources during high-water periods. As the number of factors are considered, multi-objective optimization scheduling has been both deeply studied and widely applied. However, the emergence of many new methods for multi-objective optimization scheduling presents challenges. While these methods have been tested to varying degrees in practical applications, there is still the lack of standardization across the models. Furthermore, the inherent uncertainty and complexity of water resource systems can result in significant errors when applying these models in practice. **Therefore, it is recommended to review and clarify the objectives, models, and solution approaches of multi-objective optimized scheduling. This re-evaluation aims to promote the rational allocation of water resources and to address the imbalance between water supply and demand.**

3.2.2 Requirements for sustainable development

With societal and economic progress, human exploitation of natural resources has gradually intensified, exacerbating ecological issues within river basins. Consequently, water resources utilization has become a pivotal factor constraining the sustainable and high-quality development of river basins. As industrialization and urbanization advance, the extensive discharge of industrial and domestic wastewater has led to a decrease in runoff, a loss of biodiversity, and the degradation of the ecological environment in many regions. Moreover, unsustainable land use practices, including deforestation and artificial manipulation of river flow have altered the natural structure of riverbanks and disrupted the ecological balance in the surrounding areas. These interventions have given rise to problems such as the shrinking of riverbeds and the drying up of river channels. In light of sustainable development principles, the remediation of river ecosystems, the restoration of rivers' ecological functions, and the resolution of water environment degradation have emerged as pivotal research topics globally[14-17].

Water ecology monitoring and simulation are essential forming the basis for managing, protecting, and sustainably developing and utilizing water ecosystems[18-20]. In short, they utilize the characteristics of aquatic communities to qualitatively and quantitatively assess the state of surface water ecological environments, identify interference in water ecosystems, and diagnose the root causes and key factors of deterioration. This process helps to identify interference in water ecosystems and diagnose the causes and key factors leading to their deterioration. It also aids in setting ecological restoration goals, evaluating the effectiveness of restoration efforts, and providing data to support environmental legislation and enforcement. However, current water ecology monitoring and simulation technologies are not yet fully developed, and routine water quality monitoring is insufficient to accurately reflect the complex trends in changes to water ecological environmental quality. It also cannot meet the growing demands for the evaluation, protection, and management of water ecological environments. Therefore, it is imperative to advance research in water ecology monitoring and simulation, thereby laying a solid foundation for ecosystem conservation and promoting sustainable development of the river basin's social and economic systems.

3.2.3 Requirements for reliability of hydropower station equipment

For a hydropower station, ensuring that the discharged flow can pass through the generating units for power generation is a basic requirement for the optimization of water resources scheduling. Thus, the efficient operational management and the enhancement of equipment reliability at a hydropower station are essential prerequisites for the successful implementation of reservoir scheduling strategies. They also serve as the basic guarantee for CUBWR. As the roles of reservoirs expand and the installed capacity, as well as the single unit capacity of hydroelectric generators, continues to grow, the consequences of any accidents at hydropower stations become more significant. This leads to increased expectations for the reliability of hydropower station equipment.

Managers responsible for the operational management of reservoirs and hydropower stations must have access to real-time information regarding the operation laws and the health status of equipment and facilities. This information is essential to guide their operation, maintenance, and repair. Additionally, they must formulate reasonable operation and maintenance (O&M)

plans for power generation equipment to ensure the smooth execution of reservoir scheduling strategies. The fundamental requirements for decision-makers are to comprehend the operational management modes and basic information of the relevant equipment and facilities. Moreover, it is recommended to enhance the use of new materials and technologies in the scheduling of reservoirs and the O&M of hydropower stations. This continuous improvement in the reliability of hydropower equipment is crucial for the efficient utilization of water resources.

3.3 Key technologies and modes

In this section, the focus is on addressing the challenges and needs in basin-wide water resource scheduling management through the following areas of research: 1) With regard to the reliability requirements of hydropower station equipment, this section delves into online monitoring technology and the inspection, maintenance, and repair strategies for such equipment. This detailed discussion aims to offer comprehensive technical support for the full lifecycle operational management of hydropower station equipment. 2) With regard to the demands of sustainable development, the section concentrates on water ecology monitoring and ecological environmental simulation technologies. This focus is intended to establish a robust foundation for the management, protection, and sustainable development of water ecosystems. 3) With regard to the requirements for multi-objective optimized scheduling, the section presents a thorough explanation of the tasks, schemes, strategies, and scheduling models associated with it. This in-depth analysis is designed to provide both the technical and case-based support necessary for multi-objective optimized scheduling.

3.3.1 Operation and management of basin-wide hydropower stations

Through the operational management of hydropower stations, the CUBWR is ensured, with the primary objective being to ensure the high reliability of the equipment. With the rapid advancement in technologies such as computers, sensors, PLCs, and big data, automation technology has been extensively implemented in hydropower stations, steering them towards intelligent operation.

3.3.1.1 Online monitoring technology for basin-wide hydropower station equipment and facilities

In accordance with the classification and monitoring requirements for hydropower station equipment and facilities, the primary subjects of monitoring encompass the electrometrical equipment in generating units, steel structures, dam, and hydraulic structures.

1. Online monitoring of electromechanical equipment in generating units

Online monitoring of electromechanical equipment leverages both an automatic data acquisition system and manual inspection to fully harness modern computer technologies. This approach is used to gather and analyze operational data from the electromechanical equipment of hydropower stations, aiding in decision-making and ensuring timely oversight of the safe operation of this equipment. The online monitoring system for the status of hydropower units typically consists of transducers, data acquisition units, servers, associated network equipment, and software. By monitoring parameters such as temperature, liquid levels, voltage, current, gas composition, pressure, and sound from the electromechanical equipment in generating units, and subsequently processing and analyzing this data, we can assist the O&M personnel in gaining a comprehensive understanding of equipment status. This process further enables functions such as status monitoring, trend analysis, fault early warning, fault analysis, and status evaluation for electromechanical equipment. These capabilities are specifically demonstrated as follows:

(1) Real-time monitoring and early warning and alarm

Through extended monitoring, the online system for electromechanical equipment obtains a vast array of data on the operation of generating units. Analyzing this historical data from normal operations allows us to derive the necessary performance indicators for the current status. Subsequently, we can establish alarm set values and sample data under various operating conditions, tailored to the specific operational context of the hydropower station and the modes of equipment operation. By comparing the actual operational data with the expected parameters, the system can automatically evaluate the real-time operational status of the generating units. If any deviations in operational status occur, the online monitoring system will immediately issue alarms and early warning signals. This enables shift attendants to receive notifications about abnormal operations, enabling them to take appropriate action. Such timely interventions are crucial for preventing minor faults from escalating into major incidents that could disrupt the normal operation and scheduling of both the reservoir and the hydropower station.

For example, in a case from Portugal, the O&M personnel identified an impact phenomenon from the original signal of the radial acceleration sensor positioned at the upper guide bearing. Analysis of the shaft center tracking diagram revealed two opposing impacts along the diameter of the main shaft per rotation. The maintenance personnel confirmed that these monitoring findings correlated with certain noises originating from auxiliary equipment in the vicinity of the upper guide bearing. During a short-term overhaul, some bearing pads were found loose during an inspection of the upper guide bearing. After the bearing pads were re-tightened and the tilting device of the pads was adjusted, the maintenance personnel monitored the subsequent operational status of the upper guide bearing. They confirmed that this treatment effectively resolved the impact signals and abnormal sounds in that area.

In a Chinese case, the O&M personnel detected an abnormal increase in the partial discharge data of a generator through the generator's partial monitoring system. Upon shutdown and inspection of the stator bars, they found a 10 mm diameter iron flexible tube between the upper ends of two lower stator bars, with the insulators of the stator bars showing signs of wear, as depicted in Figure 3-1. After conducting repair work on the affected stator bars, the partial discharge level of the generator returned to normal, thereby preventing an accident.

Figure 3-1 Stator bars with damaged insulation at ends

(2) Performance evaluation and condition-based maintenance

For hydropower stations, the online monitoring system for electromechanical equipment facilitates the status evaluation of equipment and guides the implementation of condition-based maintenance. The reliable operation of hydropower station equipment is closely connected to the performance of this electromechanical equipment. However, given that faults are inevitable for equipment with a finite service life, maintenance is crucial for ensuring the ongoing health and extending the service life of hydropower station equipment. The maintenance mode for hydropower stations has evolved with changing management concepts, transitioning from the original reactive breakdown maintenance to the current approach that combines preventive maintenance with breakdown maintenance. This shift has significantly enhanced the reliability of hydropower station equipment. Furthermore, with the assistance of the online monitoring system, automatic generation of status reports before and after maintenance is possible. By comparing historical data trends and curves, the effectiveness of maintenance can be evaluated, leading to an elevation in the level of maintenance quality.

For example, the monitoring and analysis system developed in Germany, equipped with intelligent monitoring and analytical capabilities, can provide effective support for a preventive maintenance strategy. To enhance the useful information within vibration signals and to illustrate the interrelationships between various vibrations, the system's statistical module offers the flexibility to supply measurements for any process variable of interest. It enables multi-dimensional comparative analysis across different measurement planes, signals, and key parameters.

In China, analysis of the online monitoring system revealed abnormal increases in the lower guide bearing runout and head cover vibration within a generating unit. To address this issue, it was recommended that Level-A maintenance be conducted on the affected generating unit. During the maintenance, once the runner of the generating unit was lifted out, it was discovered that the wearing ring of the runner was damaged, as depicted in Figure 3-2. Consequently, the maintenance prevented forced shutdowns of the generating units that could have been caused by the failure of the wearing ring, thereby ensuring the normal operation and scheduling of the hydropower station during the flood season.

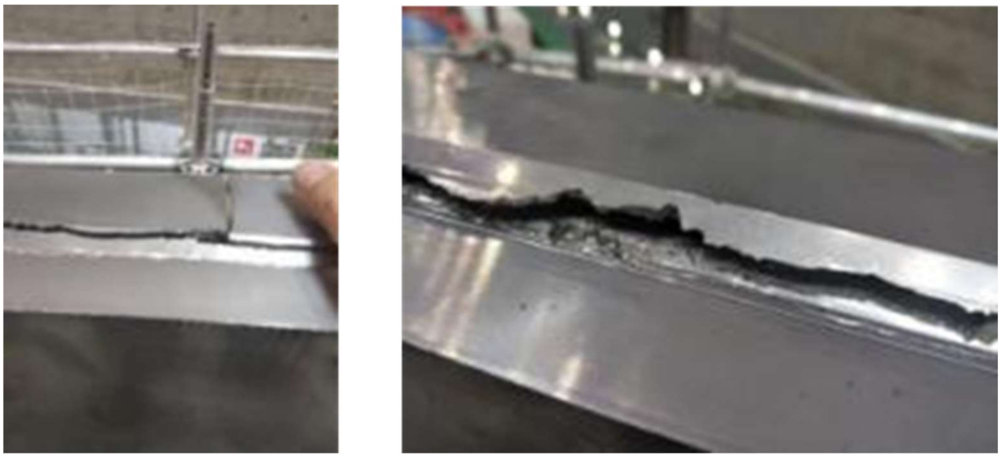


Figure 3-2 Conditions of broken wearing ring in the runner

(3) Remote analysis and diagnosis

For the electromechanical equipment at hydropower stations, online monitoring systems facilitate remote analysis and diagnosis. Many hydropower stations, due to their geographic location, size, and shift work patterns, have limited on-site technical capabilities. Consequently, when certain equipment faults occur, it can be challenging to quickly identify the root cause and resolve the issues. A local LAN (Local Area Network) can be used to establish a status monitoring network for plant units, enabling equipment management engineers to perform online monitoring and analysis, and to stay informed about the unit status at any time within the network's coverage. By diagnosing faults, they can accurately locate and identify the causes of faults in a timely manner. This approach provides precise maintenance solutions for units and reduces both the cost and the time required for troubleshooting.

For instance, in a Chinese case, a big data platform integrates production and operational data from subordinate hydropower stations, ensuring unified capabilities for data sharing and analysis on a large scale. Utilizing this big data platform, a diagnosis center system has been established, with its system structure topology graph presented in Figure 3-3. The diagnostic center system has access to all online monitoring system data from operational hydropower stations and some data from computer-based supervisory control system (CSCS). This enables the system to facilitate real-time data communication and display, perform statistical data analysis, and conduct fault diagnostics. With these functionalities, it can generate operational status reports for generating units and also conduct studies for equipment status identification and optimization of the operation of relevant generating units.

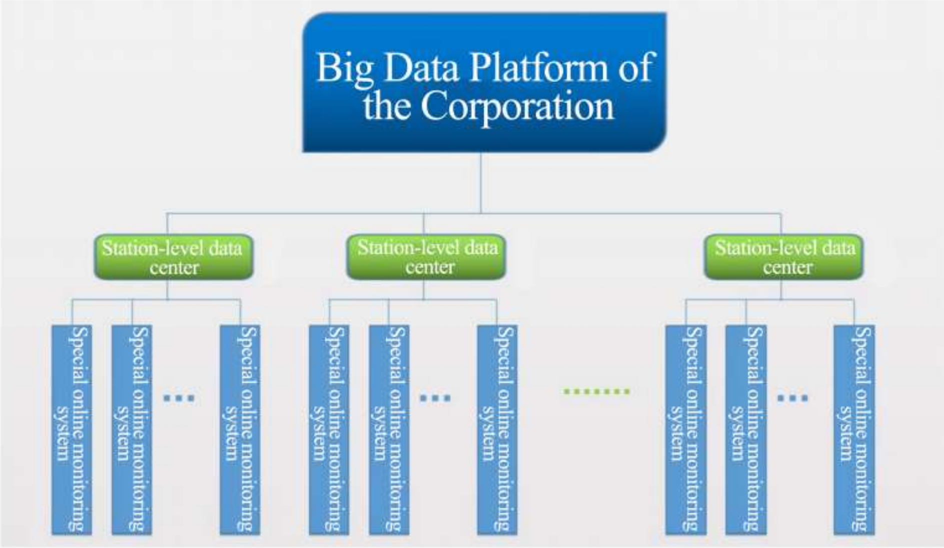


Figure 3-3 Structure topology graph for diagnosis center system
(with simplified graph indicated by schematic diagram)

The monitoring analysis and diagnosis system developed by Germany facilitates secure remote access from the central server to the online monitoring system. Analytical diagnostic experts can access the local status monitoring system through the secure access to special equipment. In the absence of equipment diagnostic experts on site, the system offers remote support, enabling rapid analysis of unit equipment incidents, conducting periodic evaluation, and performing equipment parameter configuration, commissioning, and troubleshooting analysis.

2. Online monitoring of steel structures and equipment in hydropower stations

In a hydropower station, steel structures such as gates, hoists, and penstocks are key components. Failures in these metal structures could lead to abnormal operation of the generating units and gates, potentially causing severe consequences like flooding of the power house. The online monitoring technology for these steel structures and equipment captures real-time status data. It utilizes transducer technology, information acquisition, and data processing, calculation, and analysis technologies to transmit and process this information. This enables real-time online monitoring, intelligent analysis, and auxiliary diagnosis of the status of steel structures and equipment.

In China, the online monitoring system for steel structures and equipment is widely applied in hydropower stations within the basins of the lower Jinsha River and the Dadu River. Most of these hydropower stations, characterized by high dams and large reservoirs, form an important part of the flood control system in the Yangtze River Basin, where safety management is of paramount importance. As shown in Figure 3-4, partial monitoring signals from the online monitoring system are directly integrated with the hydropower station's centralized control system. This integration enables remote operation of gates, ensures real-time monitoring and early warning of equipment status, and allows for preliminary emergency disposal through the remote monitoring system. The online monitoring system gathers data across various operating conditions, providing equipment managers with a basis for condition-based maintenance evaluation. The monitoring scope for different steel structures is tailored to the safety characteristics, operating conditions, and common damage mechanisms of the monitored objects. For example, common faults of gates include excessive stress, structural resonance, blockage of gate leaf, and failure of major components. The real-time online monitoring system for gates primarily focuses on monitoring flow-induced vibration damage, operation beyond specified standards, failure of key components (such as trunnions, fixed wheels, and chain wheels), and the quality of manufacturing and installation. The monitoring content mainly encompasses flow-induced vibration monitoring, stress monitoring, operation attitude monitoring, and the operational status of key components.

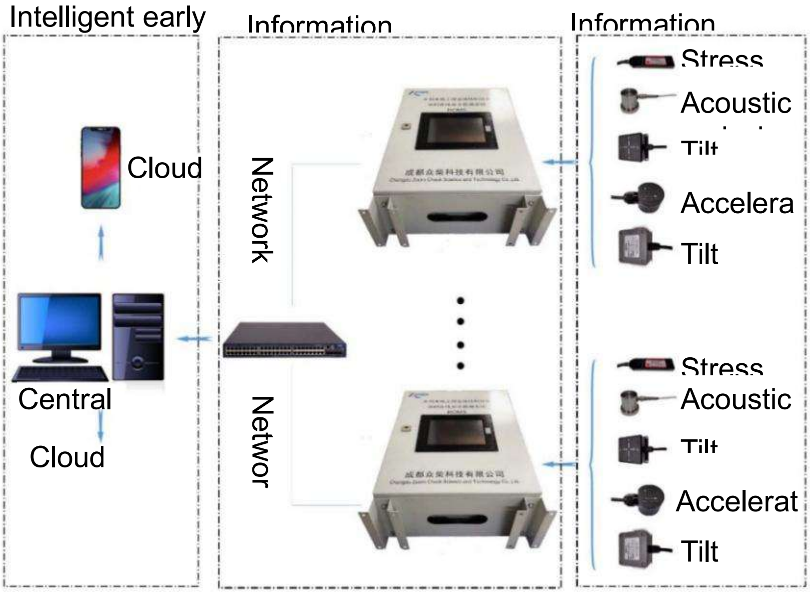


Figure 3-4 Structure of real-time online monitoring system for steel structures of hydropower stations

3. Online monitoring of dams and hydraulic structures

Dam safety monitoring involves the precise evaluation of a dam's operational status through the measurement and analysis of parameters at key safety-related locations, such as the dam body, foundation, and abutments. Currently, dam safety monitoring is primarily conducted using a dam safety monitoring system, which facilitates real-time monitoring of the dam's condition. Generally, operational changes in a dam are slow and not easily noticeable. The safety monitoring system enables us to understand the relationship between the dam's actual working conditions and various environmental influences. It helps to comprehend the fluctuation range and the laws governing changes in all observed variables. In the event of any anomalies, the system allows for the timely implementation of remedial actions. This prevents the dam's condition from worsening from a quantitative to a qualitative change, thereby maintaining the dam's health, extending its lifespan, and averting major incidents. In special circumstances, such as during floods or earthquakes, online monitoring technology can be used to evaluate the dam's safety status promptly.

In an actual case scenario, Russia has developed a dam safety monitoring system based on the High-Speed Service (HSS) module and finite element modeling. This system is designed to enhance the standards of dam safety monitoring and ensure the reliable operation of hydraulic structures. The HSS module within this system consists of three components: the Information Integration and Diagnosis System (IDS), the Computation Module (CM) and the Expert Module (EM). The IDS is capable of data collection and preprocessing, transmitting control commands to the EM, and presenting data to the users. The CM, which is composed of various mathematical models, can access the basic data in real time and send computation results to both the EM and the end-user. The EM retrieves data from the IDS and, based on the computation results provided by the CM, performs a comprehensive data evaluation to identify potential hazards and evaluate the dam's safety status. The interworking relationship among the different modules is illustrated as follows:

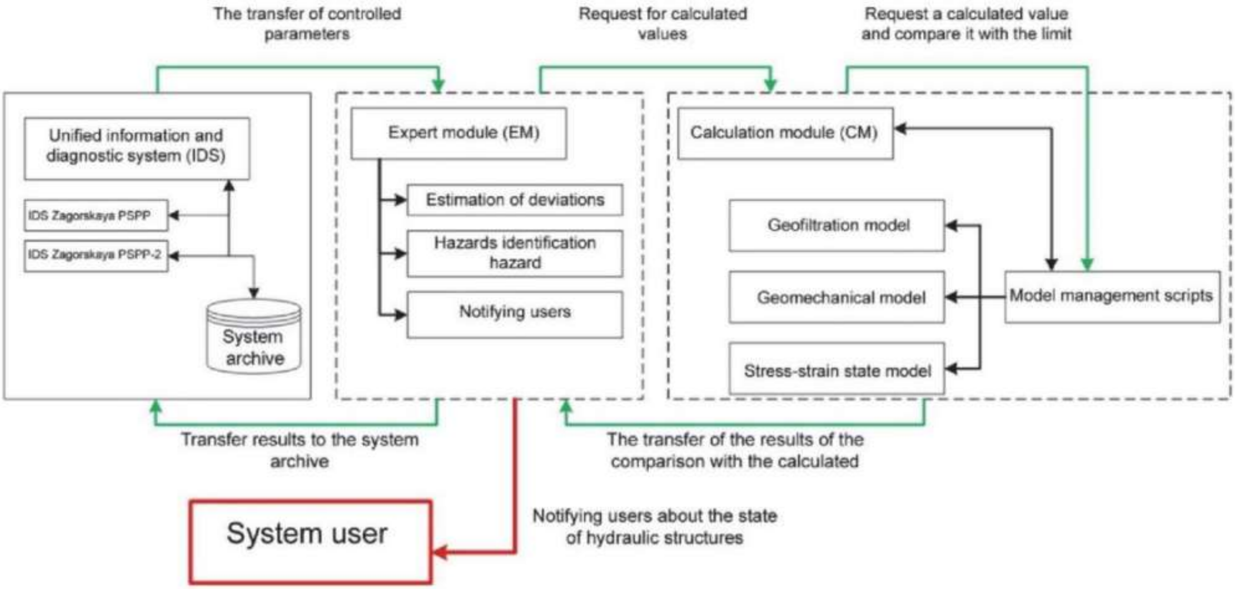


Figure 3-5 Relationship among different modules in the dam safety monitoring system of Russia

In China, the Gezhouba Dam has implemented a dam safety monitoring information management system known as iDam. This system facilitates the real-time import of data from the dam's automatic monitoring and collection system. It automatically checks and issues early warnings for monitoring data. Utilizing the expert diagnostic module within the data management system, iDam regularly evaluates the dam's safe operational status. This allows for the fundamental achievement of real-time online monitoring and control over the dam's safe operational status.

3.3.1.2 Equipment maintenance mode and technology for basin-wide hydropower stations

1. Condition-based maintenance of hydropower station equipment

During condition-based maintenance of hydropower station equipment, both the historical database and the online monitoring system are leveraged to gather data relating to equipment design, installation, and O&M. Additionally, a professional data management and analysis platform, along with advanced applications, are employed to diagnose and analyze the equipment status, ensuring that the O&M personnel have a comprehensive understanding of the equipment's condition. Based on this understanding, maintenance strategies are determined, taking into account expert experience. Throughout this series of implementation processes, it is essential to consider a variety of factors, including power grid dispatching, water resource utilization, equipment operating conditions, and power market demands. Furthermore, optimal maintenance decisions should be made to ensure the ongoing health of the hydropower station equipment while also maximizing economic benefits.

With oversight of six large-scale hydropower stations, China Three Gorges Corporation has accumulated rich experience in the condition-based maintenance of generating units. The corporation has developed a comprehensive condition-based maintenance process and a technical support system for the maintenance of hydropower station equipment, as illustrated below.

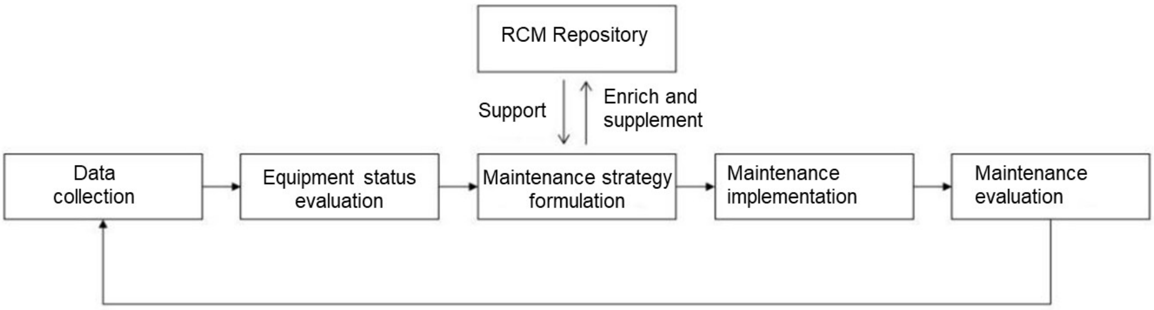


Figure 3-6 Condition-based maintenance process of hydropower station equipment

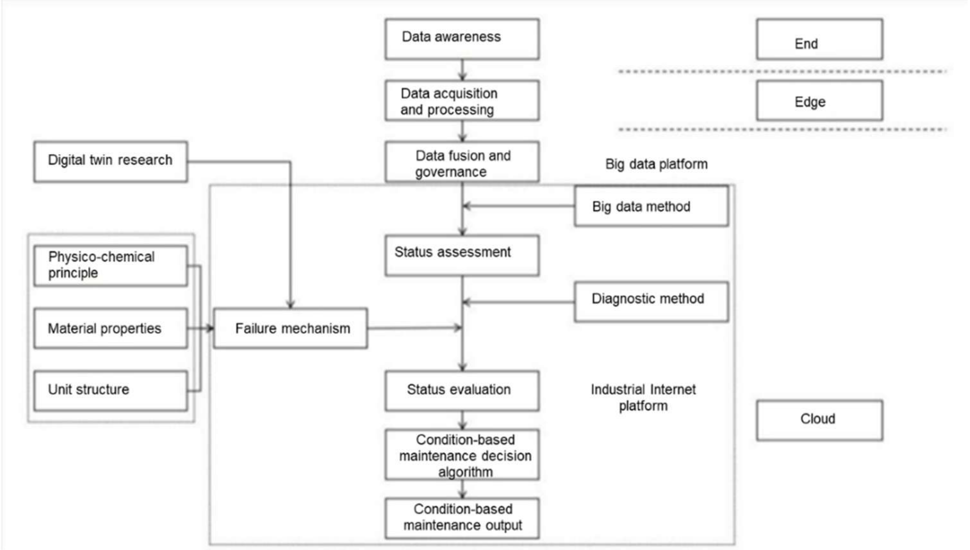


Figure 3-7 Technical support system for condition-based maintenance of hydropower station equipment

2. Digital maintenance technology

Digital maintenance is a concept where an overall digital model is built using a digital twin. This model then facilitates the optimization of maintenance activities through data analysis and utilization, leading to a continuous upgrade of the maintenance mode. Essentially, digital maintenance embodies the complete integration of an array of advanced maintenance technologies that are closely intertwined with information technology, all aimed at ensuring high reliability.

During digital maintenance, texts, graphs, voices, and other traditional maintenance information formats-relating to equipment status, diagnostic conclusions, maintenance resources, manpower allocation, spare parts services, as well as the manufacturers and technical support of suppliers-are transformed into digital data. By leveraging computer technology, digital communication, network transmission, detection and diagnosis, multimedia, and intelligent technologies comprehensively, the stakeholders in maintenance—including the maintenance company, equipment manufacturers, and other technical support personnel—are integrated into a cohesive unit. This integration ensures that various digital information can be transmitted, processed, stored, and exchanged in real time or near real time. Furthermore, it facilitates the open sharing of information resources across the entire maintenance system. Consequently, it enables the efficient convergence of multiple functions such as fault diagnosis, equipment monitoring, maintenance decision-making, communication and transmission, and logistical support.

Digital maintenance technology represents intelligent maintenance, primarily manifesting in five key areas: intelligent decision of maintenance items, intelligent planning of maintenance organization, intelligent collaboration of maintenance process, intelligent evaluation of maintenance effect, and intelligent service of maintenance knowledge.

1) Intelligent decision of maintenance items

Establishing a digital maintenance system facilitates the digitalization of maintenance decision. The core of this system is to harness data resources comprehensively, enabling automatic evaluations and judgments. It intelligently provides maintenance decision recommendations based on an analysis of equipment status, operational trends, operational risk data, fault diagnosis conditions, and the impact of maintenance-induced downtime. Additionally, it considers the estimated benefits and the availability of human resources and production means within the enterprise. This approach aims to maximize economic benefits and achieve optimal maintenance decisions.

2) Intelligent planning of maintenance organization

Establishing a digital maintenance system facilitates the digitalization of maintenance planning. The core of this system is to establish a basic information base, standardized with data that encompasses key elements such as projects, personnel, tools, materials, and technical documentation. It also clarifies the relationships and correlation rules among these elements. By leveraging data on regulations, standards, and equipment status evaluation, the system progressively achieves automated functions like "one-click planning and one-click listing" at the planning stage. This advancement enhances the efficiency of maintenance planning further.

3) Intelligent collaboration of maintenance process

Establishing a digital maintenance system facilitates the digitalization of maintenance process control. The core aspect is the comprehensive use of information, digital, and intelligent technologies to achieve digital control over the maintenance progress, digital inspection of maintenance quality, digital supervision of maintenance costs, digital visualization of the entire maintenance process, and digital management of safety risks.

4) Intelligent evaluation of maintenance effect

Establishing a digital maintenance system facilitates the digital evaluation of maintenance effect. The system's core involves leveraging big data, the industrial internet, the Internet of Things, and other technologies for long-term tracking of the equipment's maintenance effect. It achieves this by comparing and analyzing the equipment's status pre- and post-maintenance, as well as by monitoring and evaluating the equipment's operational status. This process not only enables a digital evaluation of maintenance effect but also lays a solid foundation for the advancement of maintenance technologies.

5) Intelligent service of maintenance knowledge

Establishing a digital maintenance system enables the development of a digital maintenance business model. By harnessing digital resources, knowledge, and capabilities for maintenance activities, the system can capitalize on maintenance data to create new service-oriented business types for users and stakeholders. This includes offering digital resource services such as data queries, statistical analyses, data processing, and data transactions to external users. Moreover, on the basis of knowledge digitalization, digital twin technology, and intelligent modeling, the system can provide digital knowledge services. These services encompass knowledge maps, tools and methods, and knowledge models for external users. In addition, by building digital capacity through modeling, digitization, and platform construction related to its core business, the system can offer digital capability services. These include R&D, simulation verification, production, and supply chain management services to external users.

3.3.2 Water ecology monitoring and simulation

Monitoring and simulating the water ecological environment are fundamental tasks in the management and scheduling of basin-wide water resources. These activities provide essential support for formulating ecological preservation measures, which are critical to the sustainable development of water resources. The primary focus lies in ecological environment monitoring technologies and simulation models. The global community has shown significant interest in water ecological environment simulations, leading to the development of various advanced commercial software widely used across river basins worldwide. Numerous case studies have demonstrated the efficacy of these simulation tools. However, under current climatic conditions, significant challenges remain in enhancing the frequency of water ecological environment monitoring, establishing automated and comprehensive online monitoring platforms, and improving the computational efficiency and accuracy of simulation models.

3.3.2.1 Ecological environment monitoring technology

Ecological environment monitoring involves the use of technologies such as 3S (RS, GIS, GPS), physical and chemical methods, and biological monitoring techniques to assess environmental indicators, examine the interactions between the environment and living organisms, and evaluate the structure and functionality of ecological systems. This approach is gradually leading to the development of automated online monitoring service platforms.

1. 3S environment monitoring technology

3S environment monitoring technology integrates remote sensing (RS), geographic information systems (GIS), and global positioning systems (GPS) to provide robust technical support for ecological environment monitoring.

Remote sensing, based on electromagnetic wave principles, captures and records changes in electromagnetic signals reflected and radiated from objects with varying properties, enabling the effective identification of terrestrial landscapes. GIS, leveraging computer technology, manages the collection, storage, and analysis of geographical distribution data, facilitating the monitoring of ecological phenomena such as land use, vegetation, and green spaces. In basin-wide water resource management, GIS can simulate hydrological environments, analyze ecological water consumption, and evaluate water resources. Additionally, GIS plays a crucial role in environmental monitoring by producing detailed pollution source distribution maps for river basins

2. Physical and chemical technologies

Physical monitoring technologies employ equipment to measure environmental pollution indicators such as heat, light, electromagnetic radiation, and noise within a given area. By analyzing the intensity and energy of these physical factors, it is possible to determine the proportion of various physical factors contributing to environmental pollution.

Chemical monitoring technologies focus on detecting and quantifying chemical pollutants in the environment. This approach is one of the most commonly applied methods in environmental monitoring. Traditional chemical analysis methods, such as titration, and modern instrumental techniques, including photochemical, electrochemical, and chromatographic analysis, are widely used.

3. Biological monitoring technology

Biological monitoring is a vital method for achieving ecological environment monitoring objectives. Common techniques include animal, plant, and microbial monitoring methods.

In the realm of animal monitoring method, earthworms are frequently used for soil environment monitoring. Known for their high sensitivity to soil conditions, earthworms can detect harmful substances such as lead and pesticides, thereby facilitating the monitoring of soil pollution. In the realm of plant monitoring method, the growing status of plants might be altered by environmental pollution. The distinct symptoms exhibited by plants in polluted conditions can be utilized to judge the main factors contributing to environmental pollution. Regarding the microbial monitoring method, microorganisms are sensitive indicators of environmental pollution. Changes in the microflora due to pollution can be monitored to achieve environmental monitoring.

4. Comprehensive service platform for ecological environment monitoring

The comprehensive service platform for ecological environment monitoring is centered around online automatic analytical instruments, integrating modern sensor technology, automatic measurement and control technologies, computer applications, specialized analytical software, and communication networks. This platform automates the collection and pre-processing of ecological data, enabling continuous operation of analytical instruments. The system supports real-time data collection, storage, remote transmission, and control interfaces.

By utilizing a big data management and analysis platform coupled with GIS, this comprehensive service platform manages monitoring stations and vast amounts of monitoring data. It uncovers intrinsic connections and patterns within the data, enabling regional and spatio-temporal analyses across multiple monitoring points. This system supports basin-wide ecological preservation efforts by providing real-time monitoring data simulations, statistical analysis, forecasting, and visualization.

3.3.2.2 Ecological environment simulation model

In ecological environment simulation, the principles of system analysis are utilized to build up a mathematical model for the ecological environment system. This model can then be adopted to simulate the behaviors and characteristics of the system, as well as to forecast and evaluate trends associated with changes in the system's key factors.

1. Environment simulation model

The water quality model utilizes the principle of conservation of mass to mathematically represent the water quality components within a water body involved in the hydrological cycle. It identifies and describes the physical, chemical, and biological changes in these components, providing insight into their intrinsic relationships. Since the development of the biochemical oxygen demand-dissolved oxygen (BOD-DO) model by Streeter and Phelps in 1925, water quality modeling has advanced significantly. Today, these models are widely used in water quality forecasting, environmental pollution control, and environmental protection planning, as well as in water quality early warning research.

1) Water quality model based on fuzzy mathematics

Water body quality is influenced by multiple factors. In water quality evaluations, there is inherent fuzziness and uncertainty in pollution levels, water quality types, and classification standards. Fuzzy mathematics models address these complexities by applying mathematical methods to analyze and quantify uncertainties in water quality assessments.

2) Water quality model based on artificial neural network (ANN)

Artificial neural networks (ANN) offer advantages such as high adaptability, prediction accuracy, and automated parameter adjustment. Water quality models based on ANN simulate the way the human brain processes and stores information, using artificial intelligence to handle complex data processing tasks.

3) Water quality model based on satellite remote sensing technology

Since the 1980s, researchers have increasingly applied satellite remote sensing technology to water resource monitoring and protection. This has led to the development of various water quality information platforms, diverse functional water quality models, and corresponding management systems, providing data support for regional environmental risk management. Satellite remote sensing offers comprehensive and timely data, which is quickly analyzed and processed to inform water quality management.

In recent years, water quality models have evolved from point-source to non-point-source pollution models, and from single to comprehensive models. However, these models still face limitations, such as insufficient understanding of pollutant mechanisms and the complexity of pollutant migration and transformation processes, often necessitating assumptions that lead to significant deviations from reality. Additionally, water quality modeling requires extensive and accurate data, which is essential for producing reliable simulation results. As research progresses and technological integration continues, water quality models are expected to become more accurate, with improvements in type, quantity, and prediction precision.

2. Ecological hydraulic model

Ecological hydraulics is an interdisciplinary field that integrates principles from hydraulics, biology, and ecology. Its research encompasses a variety of topics, including ecological flows, fish way, eutrophication, water blooms, wetlands, water ecological habitats, and the ecological restoration of water areas.

1) Eutrophication model

In the field of ecological hydraulics, the eutrophication model is a crucial tool for studying the occurrence of water blooms and facilitating their prediction[21-23]. When a water body's pollution exceeds certain thresholds, or it undergoes significant hydraulic disturbances (such as from a hurricane), conditions can become conducive to the proliferation of phytoplankton. This can lead to one or several types of algae gaining an absolute competitive advantage in their growth. The unchecked growth of a single algal species can suppress the development of other organisms and disrupt the system's food chain. In such instances, the ecological system may enter an unhealthy cycle and lose its balance. Under these circumstances, it is nearly impossible for the ecological system to recover autonomously. Hence, intervention through artificial restoration methods becomes necessary.

2) Fish habitat model

Constructing a fish habitat model is instrumental in aiding the protection and restoration of fish habitats. Tailored to the physical habitat requirements of the target species, the fish habitat model is primarily simulated through two approaches: the habitat suitability model and the process-based biotic population dynamics model. The habitat suitability model's core mechanism is established by identifying the relationship between indicative target species and their habitat factors. The habitat suitability curve method stands as the most classic technique within the habitat suitability model framework. Currently, the habitat suitability curve method is utilized to evaluate habitat suitability in over 80% of habitat models globally.

3. Ecological environment simulation software

1) MIKE

The MIKE model, developed by the Danish Hydraulic Institute (DHI), is adept at simulating a variety of surface water environments, including rivers, lakes, reservoirs, estuaries, and bays. It is designed for dynamic simulation and can calculate hydrodynamics and water quality under complex conditions. The MIKE model comprises several modules: a hydrodynamics module, a water quality migration module, a eutrophy module, a heavy metal module, and a sediment module. The suite includes one-dimensional MIKE 11, two-dimensional MIKE 21, and three-dimensional MIKE 31 models. These three MIKE models are efficiently interoperable, allowing for combined application and seamless integration with GIS.

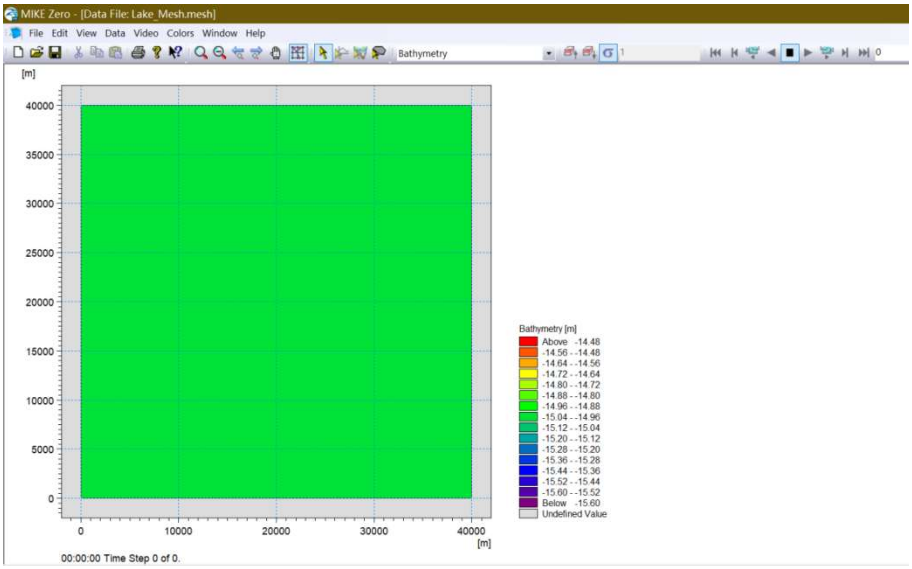


Figure 3-8 Software interface of MIKE

MIKE 11 facilitates one-dimensional simulation of rivers and water channel flows, including the behavior of sediment, pollutants, and ecological processes. With the hydrodynamics module at its core, it ensures robust connectivity between various modules. The model primarily simulates water quality factors such as dissolved oxygen (DO), biochemical oxygen demand

(BOD), nitrogen, phosphorus, heavy metals, coliform bacteria, and algae. Additionally, users have the option to tailor simulation indicators to their specific needs.

MIKE 21 enables two-dimensional simulation of free surface flow, suitable for areas such as lakes, reservoirs, wetlands, estuaries, and seas where stratification can be ignored. The water quality module in MIKE 21 is capable of simulating conservative substances, first-order decay substances, and eutrophication processes. It covers key water quality factors including salinity, DO, BOD, nitrogen, phosphorus, heavy metals, coliform bacteria, algae, and zooplankton. Moreover, users have the flexibility to customize simulation indicators.

MIKE 31 is a specialized engineering software package designed for three-dimensional simulation of free surface flows. It is versatile, capable of modeling the hydraulics, water quality, and sediment transport in various water bodies, including rivers, lakes, estuaries, offshore regions, coastal areas, and seas. When it comes to the computation of free surface and turbulent flows, MIKE 31 offers a variety of methods for users to select based on their specific needs. In terms of simulating water quality and ecological processes, the factors considered by MIKE 31 are similar to those utilized in MIKE 21.

2) EFDC

The Environmental fluid dynamics code (EFDC) model, a three-dimensional water quality mathematical model for surface waters, has been developed by the Virginia Institute of Marine Science at the College of William and Mary (VIMS). It's able to simulate the hydrodynamics and water quality across a range of water bodies, including rivers, lakes, reservoirs, wetland systems, estuaries, and seas. Essentially, EFDC is characterized by its multi-parameter approach and the use of finite difference methods. Having undergone nearly two decades of development and refinement, EFDC has been widely adopted by academic institutions, government agencies, environmental consulting firms, and other organizations. Moreover, it has been successfully applied in studies of over 100 water bodies in both American and European countries. In China, EFDC has been utilized in various water-related simulations, such as the water quality simulation for Dianchi Lake in Yunnan Province, the hydrodynamics simulation at the confluence of the Yangtze River and Jialing River in Chongqing, the nutrient simulation for Miyun Reservoir in Beijing, and the eutrophication simulation of Wuliangsuhai Lake in the Inner Mongolia Autonomous Region.

EFDC comprises several key modules, including the hydrodynamics, sediment, toxic substance, water quality, substrate, and wave modules. Initially, during simulation calculations, it completes the computation of the flow field to determine the spatio-temporal distribution characteristics of the three-dimensional flow field. Subsequently, it calculates the sediment's migration, erosion, and deposition effects, simulating the dynamic changes of various water quality variables influenced by the adsorption of cohesive sediments. EFDC's hydrodynamics module is designed to calculate river flow velocities, tracers, temperatures, and salinities. The output variables from this module can be directly integrated with the water quality, sediment transport, and toxic substance modules, providing the necessary driving conditions for substance migration. The sediment module of EFDC simulates sediments with multiple components, and categorizes the sediment into suspended load and bed load according to the sediment transport characteristics within the water body. The suspended load is further divided into cohesive and non-cohesive sediments based on particle size, with the potential for additional subdivisions. This module can simulate sediment settling, deposition, erosion, and resuspension using relevant physical or empirical models. The toxic pollutant module of EFDC is capable of simulating the transport and transformation processes of various pollutants within the water body. Researchers must provide specific reaction processes and set reaction parameters for the simulation of specific toxic pollutants. The water quality module of EFDC primarily focuses on simulating the interrelationship among different variables, centered around algal growth within the water body. Meanwhile, the substrate module is designed to simulate the exchange of materials between the sediment and the water body.

3) SWAT

SWAT (Soil and Water Assessment Tool) was developed by Dr. Jeff Arnold of the Agricultural Research Service, part of the United States Department of Agriculture (USDA), in 1994. The model, grounded in GIS technology, leverages digital elevation models (DEM), and other spatial data to construct a comprehensive database that covers topographical, soil, land use, meteorological, hydrological, and nutrient substance specific to the research area. This enables SWAT to simulate and forecast runoff, sediment, and non-point source pollution loads across various watersheds or regions. Initially, the model was designed to forecast the long-term effects of land management practices on moisture, sediment, and chemical substances under the diverse and fluctuating conditions of soil types, land uses, and management measures within large watersheds. In recent years, the SWAT model has experienced rapid development and application, primarily focusing on the simulation of a range of hydrological, physical, and chemical processes. This includes water volume and quality, as well as the transport and transformation of pesticides, facilitated by the spatial information provided by RS and GIS.

From the creation to the calibration of the SWAT model, the necessary data can be divided into two primary categories: 1) initial modeling data, and 2) subsequent calibration data. Additionally, the SWAT model's data requirements may be supplemented by information needed for various specific modules within the research scope. The initial modeling data is further divided into two types: basic geographic information and meteorological and hydrological data. On the other hand, the subsequent calibration data is primarily derived from monitoring station data. The raster data are provided with different accuracy. Researchers should select and utilize the appropriate level of raster data accuracy based on the scale of the research area, the required accuracy of the research, and the computational capacity of the available hardware.

3.3.2.3 Application cases

1. Water temperature simulation of the Xiangxi River, a tributary of the Yangtze River in China

A two-dimensional hydrodynamics-water temperature model for the elevation of Xiangxi River was built by adopting the CE-QUAL-W2 model. Relevant simulation results are shown as follows:

1) In the initial stage, the simulation area's water temperature exhibits weak stratification; the mainstream is present in both the bottom and surface layers. The bottom layer is characterized by a downslope flow with a maximum velocity of 0.06 m/s, while the surface layer has a reverse flow with a maximum velocity of 0.06 m/s, and the reverse flow area extends to a length of 3.25 km.

2) After a three-day increase in the upstream water level behind the dam, there is no obvious change in the water temperature distribution within the simulation area. The flow velocity in the middle surface layer experiences minor changes. The reverse flow velocity at the estuaries decreases from 0.05 m/s to 0.04 m/s, and the surface layer's reverse flow area slightly expands downward. Consequently, the length of the reverse flow area in the middle and lower layers extends to 12 km.

3) Following a three-day drop in the upstream water level behind the dam, there is a slight increase in the water temperature above the bottom layer in the backwater area. The reverse flow velocity at the estuaries and in the middle surface layer experiences minor changes. The surface layer's reverse flow area slightly shrinks upward, and the reverse flow area in the

middle and lower layers recedes longitudinally towards the center, reducing its length to 8.0 km.

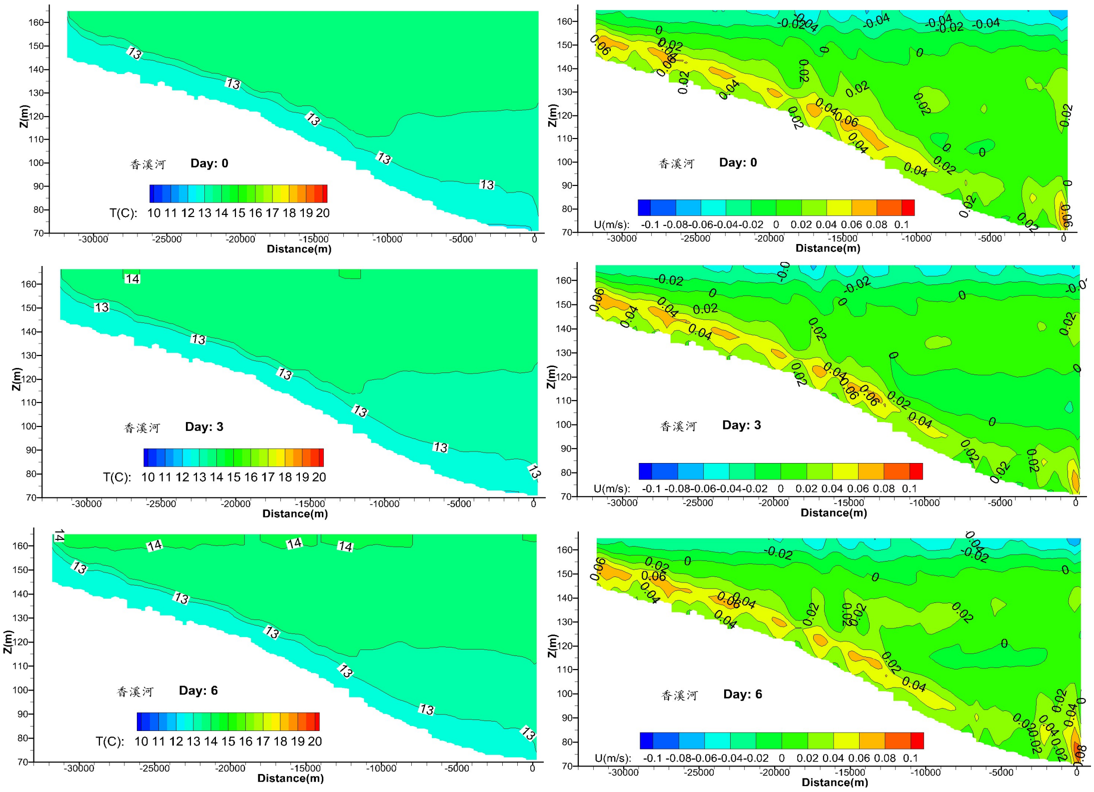


Figure 3-9 Changes of water temperature and flow velocity distribution in the Xiangxi River (Z_0=165m, +0.5 m/d[3d] ~ -0.5 m/d[3d])

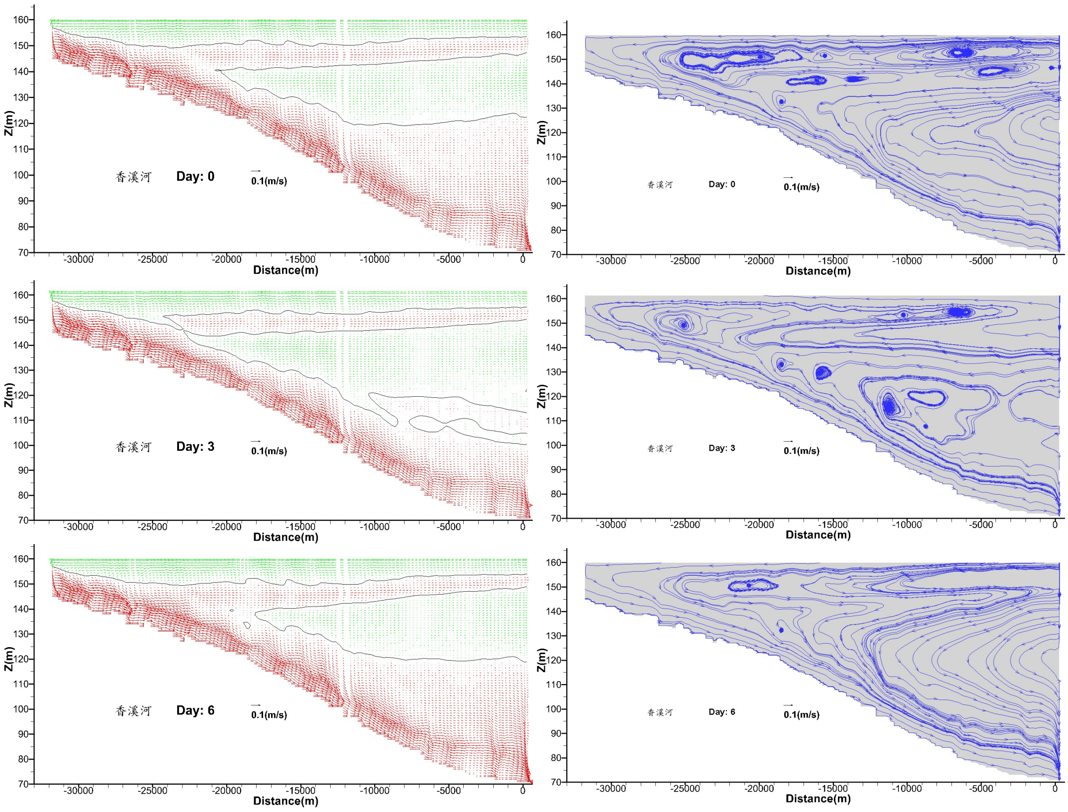
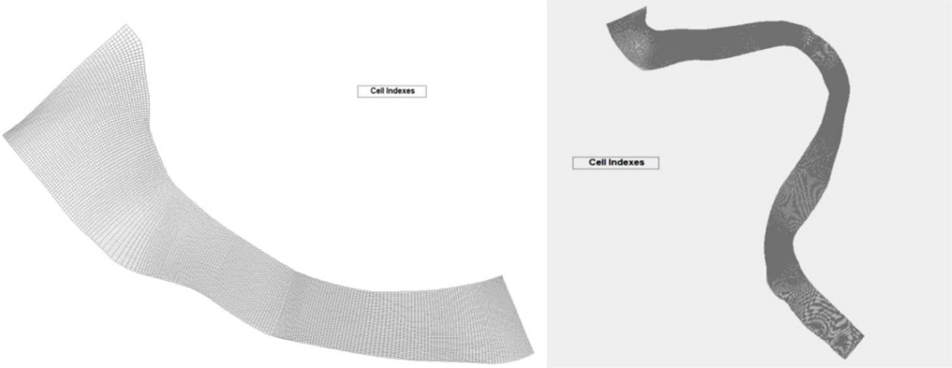


Figure 3-10 Changes of flow field in the Xiangxi River (Z0=165m, +0.5 m/d[3d] ~ -0.5 m/d[3d])

2. Application case in the lower reaches of Gezhouba Dam in the Yangtze River and Zhicheng

The EFDC model is utilized to simulate the water depth and flow velocity within the flow field at the Chinese sturgeon spawning site in the lower reaches of the Gezhouba Dam and at the spawning site for the four major Chinese carps in Zhicheng, under the following assumptions: the water body's density remains constant regardless of pressure; the hydrostatic pressure is uniform, and the horizontal dimension far exceeds the vertical one; and the quasi-three-dimensional conditions are met. For these spawning sites, the corresponding structured grids are illustrated in the figure provided below.

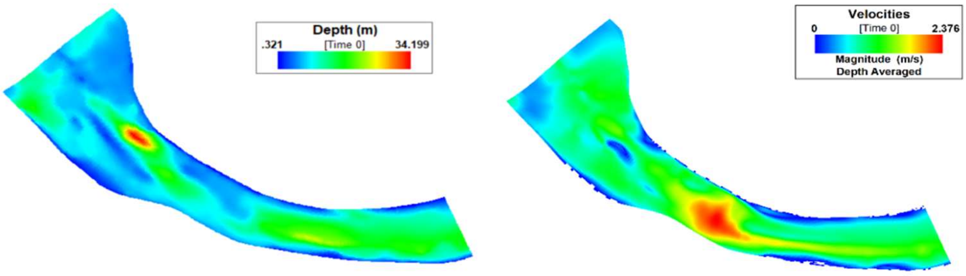


(a) Chinese sturgeon spawning site (11,000 grids)

(b) Spawning site of four major Chinese carps (52,800 grids)

Figure 3-11 Structured grids for the Chinese sturgeon spawning site in the lower reaches of Gezhouba dam and the spawning site of four major Chinese carps in Zhicheng

When the outflow of Gezhouba Dam reaches 6,000 m^3/s, the simulation results for the water depth and flow velocity of flow field in the Chinese sturgeon spawning site in the downstream of dam are shown in Figure 3-12.

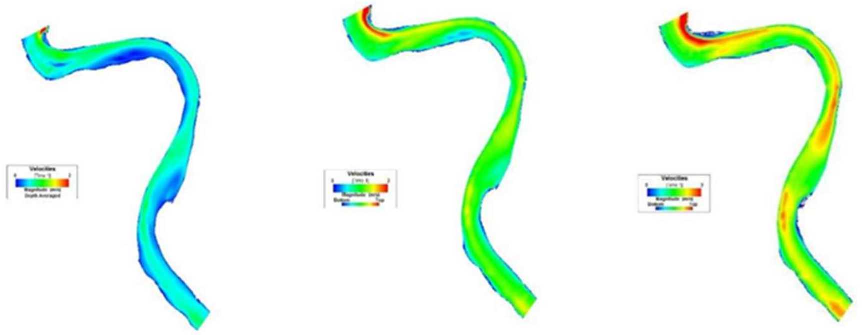


(a) Water depth (m)

(b) Flow velocity

Figure 3-12 Simulation results for Chinese sturgeon spawning site in the lower reaches of Gezhouba dam

When the outflow of Gezhouba Dam reaches 8,000 m^3/s, 20,000 m^3/s or 30,000 m^3/s, the simulation results for the flow field in the spawning site of four major Chinese carps in Zhicheng are shown in Figure 3-13.



(a) Q = 8 000 m^3/s (b) Q = 20 000 m^3/s (c) Q = 30 000 m^3/s

Figure 3-13 Simulation results for the flow field in the spawning site of four major Chinese carps in Zhicheng

3.3.3 Multi-objective optimized scheduling technology

3.3.3.1 Tasks and scheduling modes for multi-objective comprehensive utilization

In reservoir scheduling, the reservoir's regulation and storage capacity is utilized to manage the natural runoff entering the reservoir, based on the priority of the water conservancy tasks and the scheduling principles required. This should be done with the safety of the dam as a precondition, to eliminate adverse effects, enhance beneficial outcomes, fully utilize water resources, and meet the needs of the national economy to the utmost extent. Based on the scheduling mode, reservoir scheduling can be categorized into three types: flood control scheduling, beneficial use scheduling, and comprehensive utilization scheduling. Based on the implementation object, the scheduling can be divided into three categories: single reservoir scheduling, basin-wide cascade reservoir scheduling, and basin-wide cascade reservoir system scheduling. In terms of the scheduling calculation cycle, the scheduling can be classified into: medium and long-term scheduling, short-term scheduling, real-time scheduling, and multi-period nested scheduling.

When a reservoir is tasked with multiple functions, including power generation, flood control, irrigation, water supply, ecological protection, and navigation, it is essential to follow the principle of comprehensive utilization. This approach ensures a coordinated and comprehensive satisfaction of various sectors' needs within the national economy, thereby effectively improving the reservoir's comprehensive utilization efficiency. Ever since the principles for multi-purpose river development were proposed in the 1930s, comprehensive utilization has emerged as a fundamental guiding principle for river development in nearly all countries globally. As basin-wide water resource development progresses and the demands of regional economic development evolve, the primary objectives of river development may occasionally shift. Nonetheless, adherence to the principle of comprehensive utilization remains a constant requirement. The key objectives of river development and comprehensive utilization in various countries are outlined in Table 3.1.

Table 3-1 Objectives for comprehensive utilization of typical rivers in the world

Name of river	Geographical location	Comprehensive objective
Columbia River	North America	Power generation, flood control, irrigation, navigation, fishing, and log transportation
Tennessee River	Southeast, United States	Power generation, navigation, flood control, agriculture, fishing, and tourism
Colorado River	Southwest, United	Irrigation, power generation, water supply, and

	States; northwest, Mexico	flood control
Volga River	Southwest, Russia	Navigation, power generation, irrigation, and tourism
Yenisei River	North Asia	Power generation and navigation
Parana River	Between Uruguay and Argentina	Power generation, flood control and navigation
The Danube	Europe	Navigation, power generation, flood control, and irrigation
Rhone River	Switzerland and France	Power generation, navigation, irrigation, and tourism
Tone River	Japan	Flood control, power generation and irrigation
Yangtze River	China	Flood control, power generation, navigation, water supply, and fishing
Yellow River	China	Flood control, power generation, irrigation, fishing, and ice flood prevention

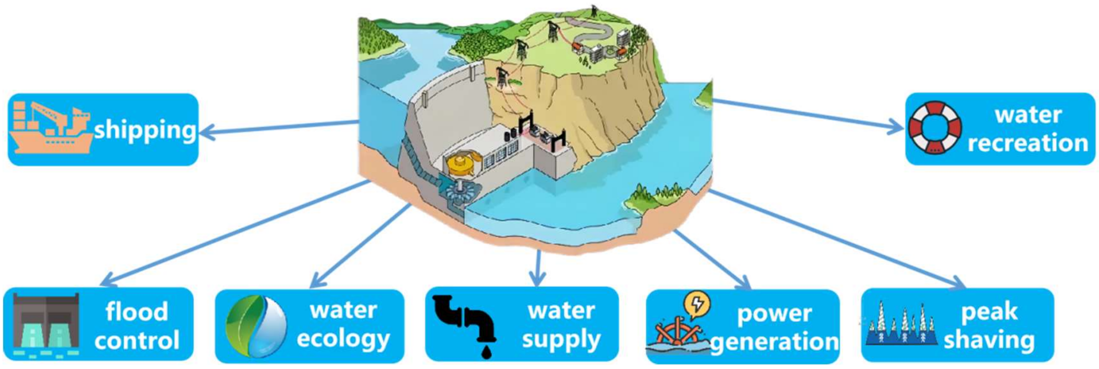


Figure 3-14 Multi-objective scheduling modes of cascade reservoirs

1. Flood control scheduling mode

For cascade hydropower stations, the overall principle for flood control scheduling of the reservoir systems is to ensure the safety of the power stations while maximizing the overall flood control capacity within the basin, with the aim of keeping the water level of downstream flood control objects below the flood control level, thereby guaranteeing the safety of the river basin during flood periods. Generally, basin-wide reservoirs with superior regulation capabilities are utilized to assist those with relatively weaker regulation capacities. By employing a compensatory scheduling method, the overall flood control capacity of the river basin can be enhanced. Specifically, the process involves upstream reservoirs in a river basin, or those situated farther from the flood control protection area, taking the lead in intercepting and storing floodwaters. Subsequently, the final discharge of floodwaters is managed by the reservoir that has a higher proportion of floodwater interception and storage, greater regulation capacity, and is closer to the downstream flood control protection area.

For river basins that are at high risk of flooding, have large populations along their banks, and contain critical flood protection infrastructure—such as the Yangtze River Basin, Yellow River Basin, and Huai River Basin—it is recommended to establish flood storage and detention basins. These basins should include flood flow areas, diversion areas, storage areas, and detention areas to enhance the flood protection level for key targets. In the case of an extraordinary flood, a coordinated effort is made to utilize both the cascade reservoir system and the flood storage and detention basins. This collaboration is essential to ensure the safety of the most important flood control objects and to reduce the overall impact of flooding.

2. Water supply and irrigation scheduling mode

For reservoir systems prioritized for irrigation and water supply, the principal scheduling objectives are to store and retain water resources, allocate water based on irrigation and supply demands, and simultaneously consider the roles of flood control and power generation. Moreover, the goal for these systems is to minimize the total volume of discarded water and determine the sequence of water storage and release for each reservoir. Generally, in a cascade of reservoirs, those located upstream are tasked with storing water prior to distribution. Within such a system, the reservoir with greater regulation capacity and an earlier conclusion to the flood season should initiate water storage. This reservoir then performs compensatory regulation based on the overall water supply requirements during the distribution period.

For example, the Mead Reservoir on the Colorado River in the United States, also known as Hoover Dam, prioritizes the following three developmental objectives: river flow regulation, navigation improvement, and flood control; domestic, commercial, and irrigation water supply; and hydroelectric power generation. It ensures irrigation for an area of 7,000 km^2 of desert land in California and Arizona. The southern part of California, being semi-arid, receives only 380 mm of rainfall annually. Via the aqueduct on the right bank downstream of the Parker Reservoir, water can be provided to cities like Los Angeles. Additionally, through a diversion channel, the Mead Reservoir is capable of irrigating the Imperial Valley and other semi-arid areas..

3. Power generation scheduling mode

For basin-wide cascade hydropower stations, ensuring the safety of the hydro projects and power grid is paramount. The primary goal of the reservoir system is to maximize the total power generation capacity of these stations. Through joint scheduling, it is essential to optimize the water storage and release schedules for downstream reservoirs. This strategy aims to manage water levels effectively, minimize surplus water volume, and optimize the power generation benefits of cascade hydropower stations. Usually, cascade hydropower stations feed into the main power grid, taking on the bulk of the tasks for peak load regulation and frequency modulation within the power system. Consequently, during the optimized scheduling, the peak load regulation demands of the power system must be fully considered. This approach not only enhances the system's ability to manage peak loads but also bolsters the operational safety and stability of the power grid.

During the flood season, reservoir systems primarily focused on power generation often take on flood control responsibilities. The scheduling for power generation must often yield to the demands of flood control scheduling. Moreover, the optimization of this scheduling directly impacts the effectiveness of flood management and is pivotal in determining the flood control safety across the entire basin. Consequently, large reservoirs within a cascade that possess superior regulation capabilities are crucial for the compensatory regulation of hydropower for both the cascade and the broader river basin. By analyzing the flood characteristics of the river, the flood control objectives, and the scheduling rules of the cascade reservoirs, it is essential to develop the optimal scheduling and operation strategies for the basin's cascade hydropower stations, with the aim of maximizing their power generation capacity.

4. Ecological scheduling mode

Ecological scheduling involves ensuring the ecological preservation needs downstream of the dam and the water environment of the reservoir area are met. It aims to maximizing the reservoir's multifaceted roles to keep the negative impacts on the water ecological environment both upstream and downstream of the dam, as well as within the reservoir area, within tolerable limits. Gradually, this approach aims to restore the ecosystem and environmental systems. During the scheduling process, it is crucial to thoroughly examine the relationship between the river flow regime and the ecological responses of the river. It involves evaluating the stress levels that society and the economy can endure. Moreover, it is recommended to preserve, as much as possible, the flow components that significantly affect the river ecosystem and to shape a flow regime that closely mimics natural flows, thereby restoring the river's ecological integrity. Simultaneously, ecological scheduling objectives should be tailored to specific times, locations, and species. It involves identifying the specific ecological flow components and simulating the natural hydrological regime by recognizing various flow incidents and their ecological effects. This strategy is designed to foster suitable hydrologic and hydraulic conditions for the spawning, breeding, and growth of key aquatic organisms in the river. It also sustains the basic ecological water levels for the downstream river channels of the reservoir. Furthermore, ecological scheduling can prevent eutrophication and address emergent water environmental incidents in the reservoir area while restoring and enhancing the connectivity among rivers and lakes.

5. Navigation scheduling mode

In large river basins, the scheduling of cascade hydropower stations often need to satisfy the navigation requirements for both upstream and downstream areas. For example, along the Yangtze River's main channel, the operation of these hydropower stations promotes navigation within the Yangtze River Basin and improves conditions in the reservoir areas. This plays a vital role in increasing the waterway's navigation capacity, boosting the navigation guarantee rate, and fostering the shipping industry of the Yangtze River. For navigation scheduling, it is recommended to first conduct a compensatory scheduling of navigation flows to satisfy the requirements for navigation water depth and to effectively enhance downstream navigation conditions. Additionally, when actually scheduling the hydropower stations, it is advisable to implement strategies that accommodate fluctuations in navigation water levels, thereby reducing tensions between navigation and power generation needs. Moreover, in the event of a navigational incident within the river basin, it is crucial to promptly initiate emergency navigation scheduling. This response is intended to avoid or mitigate the adverse impacts of such incidents on navigation.

6. Emergency scheduling mode

In emergency scheduling, the process should be as follows: initially, monitor the operation of the reservoir; subsequently, establish the relevant outflow constraints based on varying scenarios such as emergencies, levee breaches, or normal operations; then, ascertain the discharge capacity and status of the reservoir, the inflow conditions, and the incoming flood discharge for each period; ultimately, employ a trial-and-error approach to resolve the water balance equation. This involves a forward calculation of the outflow condition variables for each period to ascertain the flood discharge and the corresponding reservoir storage volume for each time frame.

3.3.3.2. Scheduling management mode for multi-objective comprehensive utilization

Reservoir scheduling and management represents a scientific approach that serves as the central component of reservoir governance, focusing on rational utilization while ensuring reservoir safety to maximize overall benefits.. As the economy grows rapidly, the demand for water resources across various sectors becomes increasingly stringent. Reservoir scheduling is crucial not only for determining the efficiency of the reservoir and the interests of water users but also for safeguarding the reservoir's security and the safety of life and property for residents living upstream and downstream. Therefore, in managing reservoir scheduling, it is essential to effectively reconcile the relationship between flood control and benefit generation.

Additionally, it is necessary to harmonize the water requirements of different sectors and strike a proper balance between water storage and release, thereby optimizing the allocation of water resources.

1. French reservoir management mode

The reservoir management mode in France is widely acknowledged as a successful approach globally. The country is delineated into six river basins based on its water systems. For each basin, France has established a river basin committee and a river basin water resource management bureau, sometimes referred to as the water management bureau. These entities are tasked with the unified planning and management of water resources. They ensure environmental protection while also striving for the efficient development and utilization of basin-wide water resources. In terms of reservoir management organizations, France categorizes them into national, basin, regional, and local levels. In addition, there are specialized international bodies in place to address matters concerning international rivers or watercourses.

(1) National level - the Ministry of Environment

In France, the Ministry of Environment is primarily responsible for managing reservoirs. Within this ministry, the Department of Water Resources is set up to supervise the implementation of water regulations and policies, to analyze and monitor water pollution, and to formulate national standards for water resources. The Ministry of the Environment has also established local branches, known as the Environment Division, in each of the designated regions. These divisions are tasked with enforcing French regulations and European Community directives on water resources. They supervise reservoir management and public utilities, collaborate with local water authorities to formulate plans for water resource management and development, and provide expert advice on matters related to the water environment.

(2) Basin level

In the French *Water Law* of 1964, the nation was divided into six major basin regions, each with an established basin water authority. Despite the original system remaining unreformed, these basin water authorities, though lacking administrative powers—such as the issuance of permits for water intake and discharge—and not being involved in the construction, management, or operation of hydraulic engineering, serve as the executive body of the river basin committee. Known as the "Water Parliament," this committee is composed of representatives from water users, local governments, and relevant central government departments that partake in the utilization of basin-wide water resources. The water authorities primarily fulfill three roles: 1) formulating the river basin planning; 2) levying fees within the basin to provide financial support for organizations involved in the development, use, protection, and management of basin-wide water resources; and 3) collecting and issuing relevant water information. Branches under the water authority include: the offices dedicated to comprehensive management, fees and charges, water quality, water resource development, planning, financial management, information and documentation, and foreign affairs.

(3) River basin committee

In France, the river basin committee operates as a "water parliament" at the river basin level, symbolizing a democratic approach to the management of water resources. It is designed to allow all stakeholders to participate in the decision-making process regarding the development and utilization of water resources, thereby reinforcing the democratic nature and legitimacy of such decisions. The committee's role is to offer authoritative advice on the long-term planning, development, and utilization policies for the river basin, as well as the fee schedules formulated by the water authorities. As a non-permanent body, the river basin committee adopts an organizational structure based on the "three-thirds system," comprising over 100 members. This includes one third representing users and professional associations, another third representing local authorities (elected by mayors and other senior officials), and the remaining third appointed by relevant government departments. The committee is tasked with providing consultations on the planning, fee schedules, and water regulations developed by the water authorities.

(4) Regional level

At the regional level—where each region encompasses 2 to 5 provinces—the water management agencies primarily consist of regional governors, regional water technical committees, and regional boards of directors. Their responsibilities include participating in the development and implementation of development plans for smaller river basins within their jurisdiction, fostering and harmonizing related research initiatives, and supervising and sanctioning the implementation of pertinent projects.

2. Chinese reservoir management mode

In recent years, China has witnessed some progress in reservoir scheduling and associated technologies. Notably, with the advanced development of basin-wide cascade reservoirs, dedicated cascade scheduling organizations have been established. These organizations aim to enhance the control and regulation of power generation in hydropower stations, ensuring the safe operation of both the stations and the power grids. In terms of flood control scheduling, the State Flood Control and Drought Relief Headquarters is tasked with the overall responsibility for organizing, coordinating, guiding, and supervising flood and drought mitigation efforts nationwide. Within the Ministry of Water Resources, a State Flood Control and Drought Relief Command Office has been established by the same headquarters. This office is charged with executing flood control and drought relief scheduling, as well as emergency water scheduling for key rivers, lakes, and hydraulic engineering works. It also develops and implements the national emergency plans for flood and drought relief. At the local level, local governments (including provinces, cities, and counties) have established their own flood control and drought relief command offices within local water resource departments or bureaus. These offices are responsible for flood control and drought relief within their respective administrative regions. Moreover, the flood control and drought relief scheduling is governed by an executive chief responsibility system. The procedural flow of reservoir scheduling management is depicted in Figure 3-15.

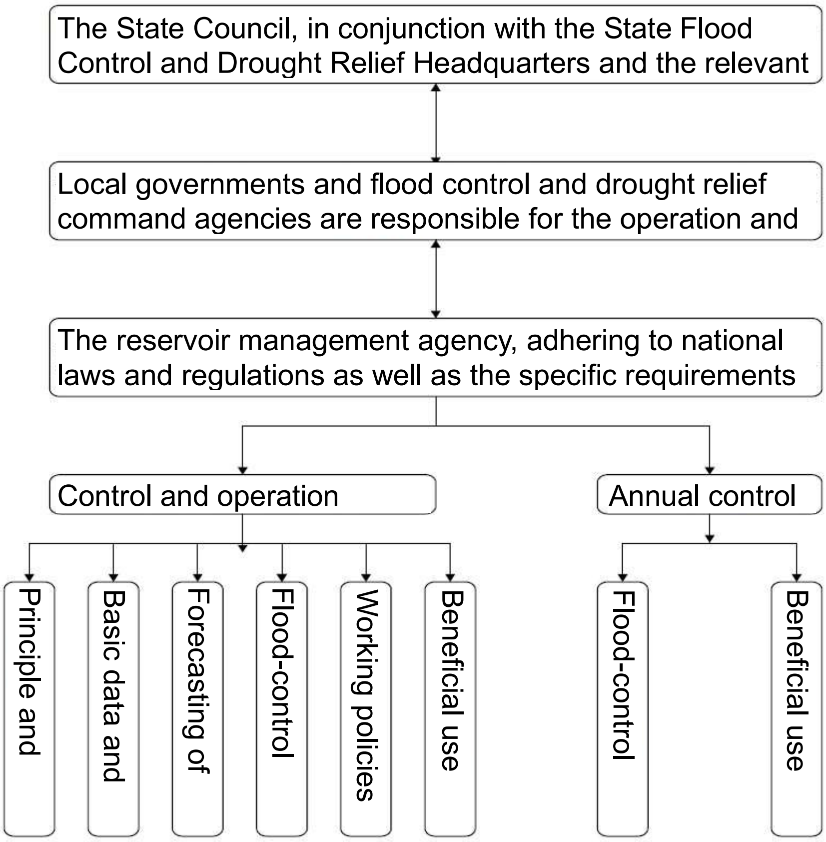


Figure 3-15 Flow diagram for reservoir scheduling management

3.3.3.3 Optimized scheduling model and solution algorithm

In multi-objective optimized scheduling, the approach is to utilize optimization algorithms based on the reservoir's regulation and storage capabilities, while ensuring the dam's safety and downstream flood control. The goal is to solve the optimized scheduling model to derive the optimal scheduling and operation schemes for the reservoir system, thereby enhancing its overall efficiency. This is done with the aim of meeting the specific demands of the national economy and societal development, which may include flood control, power generation, irrigation, water supply, and ecological considerations. The core challenges involve the development and solution of mathematical model for optimized scheduling. It is also necessary to quantify the objectives of optimized scheduling into explicit mathematical formulas. Moreover, when there are multiple goals, it is important to distinguish between primary and secondary objectives. For example, in a reservoir system primarily focused on power generation, the main goal is typically to maximize power generation capacity or benefits. However, the reservoir often has additional social responsibilities, such as flood control, water supply, and ecological considerations, which are deemed to be secondary objectives in optimized scheduling. These secondary objectives are usually incorporated as constraints within the optimization model. Therefore, multi-objective optimized scheduling essentially involves dealing with constraints and boundary conditions. The solution process is designed to identify a set of schemes that closely approximate the optimal solution.

1. Mathematical model of optimized scheduling focusing on flood control

For scheduling that prioritizes flood control, this task is the reservoir's primary objective during the flood season. When the river basin experiences a small or medium flood, it is essential to utilize the limited flood control capacity of the reservoir system within the basin reasonably. Additionally, while ensuring the safety requirements for downstream areas are met, the application sequence of the reservoirs and the rate of flood control capacity occupation should be sensibly organized, taking into account the regulation performance of the reservoirs within the flood control system. Typically, the more robust a reservoir's flood control and regulation capabilities are within the overall system, the less it occupies of the flood control capacity during the optimized scheduling. This approach is intended to keep sufficient flood control capacity in reserve for subsequent scheduling, ensuring the full effectiveness of flood control scheduling once the current task is completed. Therefore, the aim of such an optimized scheduling model is to minimize the total sum of the occupied flood control capacity.

During flood control scheduling, it is crucial for the reservoir to maintain sufficient flood control capacity to handle larger floods. Consequently, the objective function designed for this purpose is particularly well-suited for the scheduling of small to medium floods, with the detailed formulation provided as follows:

$$V = \min\left[\sum_{i=1}^{N_1}\sum_{t=0}^{T}\max(V_i(t))\right] \tag{3.1}$$

Where, "N_1" denotes the number of hydropower stations; "T" is the duration of flood process, and; "$V_i(t)$" denotes the flood control capacity being utilized by "level-i" reservoir at time "t".

When faced with an extraordinary basin-wide flood, the primary goal of flood control scheduling shifts to executing reservoir scheduling that maximize the utilization of flood control capacity to mitigate the flood peak as effectively as possible. In such cases, the objective of minimizing the occupied flood control capacity is no longer the focus. Instead, the focus should be on achieving the maximum reduction in peak flood levels to minimize the overall flood damage to the river basin. The functional expression for this strategy would be as follows:

$$F = \min\sum_{t=1}^{T}\left(\sum_{j=1}^{N_2} q_t{}^j + \Delta q_t{}^j\right)^2 \tag{3.2}$$

Where, q_t^j denotes the outflow from the "level-j" reservoir at time "t"; Δq_t^j denotes the upstream local inflow to the "level-j" reservoir at time "t"; "T" is the duration of flood process; "N_2" denotes the number of hydropower stations, and; "F" is the total amount of peak shaving.

The reservoir system is tasked with ensuring the safety of the dam and the protection of upstream and downstream areas. Specifically, during flood regulation, the maximum water levels both upstream and downstream must not surpass the limits established by the flood control authorities. Ideally, the lower the peak water level during flood regulation, the more advantageous it is for the reservoir's scheduling and operation. The corresponding objective function to reflect this priority would be expressed as follows:

$$H_1 = \min(\max H_t) \quad t = 1, 2, 3, ..., T \tag{3.3}$$

Where, "H_t" denotes the upstream or downstream water level at the dam site at time "t", and "T" is the duration of flood.

2. Mathematical model of optimized scheduling focusing on power generation

Currently, for reservoir systems that prioritize power generation, the prevailing approach is to primarily employ the "water-driven power generation" mode. Typically, the optimization model is designed to maximize either the power generation capacity or the benefits derived from power generation. This is achieved while considering the water balance within the reservoir and the hydraulic connectivity upstream and downstream as constraints. The goal is to identify the optimal scheduling scheme for the reservoir system under these conditions. For its objective function, the specific expression is as follows:

$$E = Max\sum_{i=1}^{N}\sum_{t=1}^{T}C_tK_iQ_{(i,t)}H_{(i,t)}\Delta t \qquad (3.4)$$

Where, "E" denotes the total electricity of the cascade; "N" is the count of cascade hydropower stations; "T" is the number of scheduling time period; "C_t" is the tariff of time period "t"; "K_i" denotes the output coefficient of hydropower station "i"; "$H_{(i,t)}$" denotes the average water head of hydropower station "i" in time period "t"; "$Q_{(i,t)}$" denotes the quotative discharge of power generation for hydropower station "i" in time period "t", and; "△t" denotes the length of time period.

During the scheduling for cascade hydropower stations, the peak regulation task effectively encompasses two dimensions [8]: 1) The scheduling of average output and reservoir outflow, as well as the water level at the end of the time period. The associated peak regulation goal is to minimize the maximum discrepancy between the average load of the power grid and the overall average output of the hydropower. 2) The distribution of daily load across each time period. Given that long-term scheduling spans numerous days, it is generally recommended to select a typical day for evaluating the balance of electric quantity. The corresponding peak regulation target is to minimize the maximum difference between the power grid's load and the total output of hydropower. In other words, the cascade hydropower stations should accommodate the peak load on the typical day. Furthermore, reducing the maximum instantaneous residual load is beneficial to improve the daily electric quantity and increase the average output of hydropower stations over the long term. The objective function for this purpose is as follows:

$$F = \min\sum_{i=1}^{N}\sum_{t=1}^{T}max(C_{t,i} - P_{t,i}) \qquad (3.5)$$

Where, "F" denotes the objective function for the maximum peak regulation amount of cascade hydropower stations, applicable to both the typical daily load process and the long-term average load process; "t" and " i" respectively denote the scheduling time period and the serial number of hydropower stations in the cascade; "N" is the count of cascade hydropower stations, and; "T" denotes the number of scheduling time period. When "$C_{t,i}$" and "$P_{t,i}$" denote the power grid load and the output of cascade hydropower station, respectively, in the typical day load process, "F" will denote the maximum objective function for peak regulation in the typical day load process. When "$C_{t,i}$" and "$P_{t,i}$" denote the average load of power grid and the average output of the cascade hydropower stations, respectively, in the long-term scheduling process, "F" will denote the maximum objective function for peak regulation in the long-term average load process.

3. Mathematical model of optimized scheduling focusing on comprehensive objectives

During reservoir operations, it is essential to comprehensively considers environmental impacts, ecological preservation, the rational allocation of water resources, and the harmonious development of society and economy. By engaging in beneficial use scheduling, the cascade reservoir system can effectively manage a variety of functions, such as irrigation, water supply, navigation, sediment control, prevention of ice floods, ecological water replenishment, etc.

For reservoir systems that emphasize irrigation and water supply, it is advisable to conduct scheduling with a comprehensive view of the natural growth patterns of crops, while also considering the variations in water resource distribution and agricultural practices. Typically, the objective of the model is to minimize the occurrence of water scarcity for crops. The functional expression of this objective is presented as follows:

$$W = \min \sum_{t=1}^{T} \sum_{i=1}^{N} \left| G_t^i - X_t^i \right| \quad (3.6)$$

Where, *"t"* denotes the duration of water supply; "i" is "level-i" reservoir in the cascade; "G_t^i" is the water demand of crops in the water supply area of "level-i" reservoir in time period "t"; "X_t^i" is the amount of water supplied by "level-i" reservoir in time period "t", and; "W" is the difference between the water demand of crops and the water supplied by the cascade reservoirs in the water supply area.

To maximize the comprehensive benefits of a reservoir, while ensuring the requirements for flood control, power generation, and water supply of the cascade hydropower stations are met, it is recommended to minimize sedimentation accumulation within the reservoir. This approach aims to prolong the reservoir's service life, enhance its flood control capacity and usable storage, and reduce the loss of reservoir capacity due to siltation. The mathematical expression for this objective function is as follows:

$$F = \min \sum_{t=1}^{T} \sum_{i=1}^{N} VS_{t,i} \quad (3.7)$$

Where, *"t"* denotes the calculation time; "i" is "level-i" reservoir in the cascade; "$VS_{t,i}$" is the amount of sedimentation accumulation (unit: 100 million m^3) in the reservoir area of "level-i" reservoir in time period "t", and; "F" is the total amount (unit: 100 million m^3) of sedimentation accumulation in cascade reservoirs.

The scheduling must adhere to the requirements of water balance equation, constraints on discharge, outflow, reservoir capacity, and the hydraulic connection between cascade reservoirs, as detailed in the preceding section. Moreover, to minimize sedimentation accumulation during the optimization of reservoir system scheduling, it is essential to consider the sediment transport between upstream and downstream reservoirs. Specifically, the amount of sediment entering a downstream reservoir should equal the sum of the sediment outflow from the upstream reservoir and the sediment released into the river, within the defined limits. The corresponding expression for this relationship is as follows:

$$QS_{i+1}^{in}(t) = QS_{il}(t - t') + QS_{i+1}^{qj}(t) \quad (3.8)$$

Where, *"$QS_{il}(t)$"* denotes the sediment outflow ($QS_i(t)$) from the "i-th" level reservoir, which is transformed into the sediment amount in the downstream reservoir over time t'. t' is the time for evolving the outflow of reservoir "i" to the inflow section of downstream reservoir, and; "QS_{i+1}^{qj}" denotes the amount of sediment discharged into river in the area between reservoir "i" and downstream reservoir "i+1" at time "t". Usually, the objectives for navigation, ecological preservation, and emergency response are translated into specific constraints of water level, flow, and reservoir control methods.

4. Mathematical model considering multi-objective optimized scheduling

For an extended period, the constraints of optimization theory and technology have often led to the optimization of a single objective during optimized scheduling research (such as maximizing power generation capacity or peak shaving rates). Even when a multi-objective optimization model for cascade reservoirs is established, it is common to use constraint methods, weighting methods, and other techniques to transform the multi-objective model into a single-objective model for solution. This is because the comprehensive utilization demands of cascade reservoirs are highly complex, involving aspects like power generation, navigation, flood control, ecology, and the environment, making it challenging to select objectives for cascade reservoirs. As hydropower energy continues to expand on a large scale and socio-economic development accelerates, the scheduling of cascade hydropower stations requires more sophisticated multi-objective management. The conventional single-objective optimization models can no longer satisfy the CUBWR needs. The multi-objective optimization model encompasses various objective functions related to power generation, flood control, navigation, and ecology.

$$\begin{cases} F_1 = Max\sum_{i=1}^{N}\sum_{t=1}^{T}C_t K_i Q_{(i,t)} H_{(i,t)}\Delta t \\ F_2 = \min\sum_{i=1}^{N}\sum_{t=0}^{T}\max(V_i(t)) \\ F_3 = \min\sum_{i=1}^{N}\sum_{t=1}^{T}| G_t^i - X_t^i | \\ F_4 = \min\sum_{i=1}^{N}\sum_{t=1}^{T}VS_{t,i} \end{cases} \tag{3.9}$$

Where, "F_1" denotes maximizing the total electricity of the cascade; "N" is the count of cascade hydropower stations; "T" is the number of scheduling time period; "C_t" is the tariff of time period "t"; "K_i" is the output coefficient of hydropower station "i"; "$H_{(i,t)}$" is the average water head of hydropower station "i" in time period "t"; "$Q_{(i,t)}$" is the quotative discharge of power generation for hydropower station "i" in time period "t", and; "△t" is the length of time period. "F2" is intended to realize sufficient flood control capacity, and "$V_i(t)$" denotes the flood control capacity occupied by "level-i" reservoir at time "t". "F_3" is intended to realize the minimum downstream water scarcity; "G_t^i" denotes the downstream water demand at time period "t" in the water supply area of "level-i" reservoir, and; "X_t^i" is the water supply volume at time period "t" in "level-i" reservoir. "F_4" is intended to minimize the total amount of sedimentation accumulation in the cascade reservoirs, and "$VS_{t,i}$" denotes the amount of sedimentation accumulation in the reservoir area of "level-i" reservoir for the duration of "t".

5. Optimized scheduling model and solution algorithm

Research on multi-objective optimized scheduling for water resources can be divided into two main approaches: 1) The use of objective function fitting, constraint methods, and weighting methods to transform multi-objective problems into single-objective ones for resolution; and 2) The application of multi-objective evolutionary algorithms grounded in Pareto theory to achieve parallel solutions. Existing algorithms for optimized hydropower station scheduling are generally divided into two categories. The first category encompasses conventional optimization solution algorithms, including linear programming, nonlinear programming, network flow programming, dynamic programming, and large system decomposition and coordination methods. These methods often face the issue of the "Curse of Dimensionality." Along with the progress of computer technology and the evolution of artificial intelligence theory, contemporary heuristic and intelligent optimization algorithms that simulate the biological evolution, migration, and foraging have captured the widespread interest of scholars globally. These algorithms include, but are not limited to, the Genetic Algorithm (GA), Simulated Annealing (SA), Particle Swarm Optimization (PSO), Chaos Optimization Algorithm (COA), Differential Evolution, Ant Colony Optimization (ACO), Artificial Neural Networks (ANN), Tabu Search (TS), and the Artificial Fish Swarm Algorithm. These intelligent optimization methods are mostly based on the evolutionary mechanisms of biological species and possess inherent parallel search capabilities. This allows them to avoid the "Curse of Dimensionality" faced by many mathematical programming methods, ensuring high solution efficiency. When the heuristic intelligent optimization algorithm is used to solve the optimized scheduling problem of basin-wide cascade hydropower stations, these heuristic intelligent optimization algorithms do not impose specific requirements on the form of the objective function or problem constraints, whether they are continuous or discrete, or derivable or not. Moreover, the computational cost in terms of space and time increases linearly with the scale of the cascade. As a result, compared to conventional optimization methods, heuristic intelligent optimization algorithms exhibit superior adaptability. Consequently, in recent years, several intelligent optimization algorithms have been successfully applied to address issues related to optimized scheduling of hydropower station(s).

(1) Solution method based on single objective

This approach is an extension of the traditional single-objective optimization method. It employs technical means such as the constraint method, weighting method, and fuzzy fitting, along with the experience and preference information of the scheduling decision-makers, to condense the multi-objective problem into a single-objective one. Subsequently, mathematical programming or intelligent optimization methods are used to iteratively solve the model and produce a set of multi-objective scheduling schemes. Essentially, this still represents a single-objective optimization problem. For example, based on the simulation set theory, different fuzzy subsets are used to describe the multiple scheduling objectives for a reservoir. By ensuring the optimized scheduling of reservoirs on the basis of maximizing the sum of the weighted membership degrees of these fuzzy subsets, a fuzzy nonlinear programming model for comprehensive reservoir scheduling can be constructed. However, a drawback is that it requires the identification of primary and secondary objectives using empirical knowledge, with other objectives being transformed into constraints. For the weighting method and fuzzy function method, the decision-maker's preference coefficients need continuous adjustment to derive the non-dominated solution set for multi-objective scheduling. Moreover, it is challenging to represent the constraints and competitive relationships between scheduling objectives using manually set weight vectors or fuzzy memberships. When the multi-objective frontiers of the problem are non-convex and non-continuous, the non-dominated scheduling scheme set obtained by these methods may fail to reflect the true characteristics of the actual objective frontier. Furthermore, the optimization mechanism used in such dimensionality reduction methods does not meet the "vector comparison" demands of multi-objective optimization. It can provide limited scheduling information to decision-makers. Additionally, a single solution yields only one scheduling scheme. To obtain multiple scheduling schemes, multiple iterations are necessary, leading to reduced computational efficiency.

(2) Multi-objective evolutionary algorithm

There is a competitive and constraint relationship among the benefit functions of multiple scheduling objectives for hydropower stations. Striking a balance in the joint scheduling optimization of these objectives constitutes a type of multi-objective optimization problem (MOP). The ultimate goal is to acquire a set of non-dominated scheduling schemes that offer comprehensive decision-making information for the schedulers. Since the mid-1980s, multi-objective evolutionary algorithms (MOEAs), which leverage swarm intelligence, have been increasingly applied within the domain of multi-objective optimization.

When applying multi-objective evolutionary algorithms, which are based on the framework of evolutionary algorithms, to practical engineering problems, it is necessary to address the prevalent issues of "premature convergence" and the potential entrapment by local non-dominated frontiers. This is particularly challenging when these algorithms are used to tackle the multi-objective optimized scheduling of cascade hydropower stations—a class of practical engineering optimization problems characterized by complex, interrelated constraints that require further enhancement of the algorithm. The scheduling problems related to reservoir systems are large-scale and present several challenges, including the difficulty of managing highly nonlinear and intricate multi-constraints, the extended duration of computations, and the disorderly spread of non-dominated solutions. Addressing these problems is crucial for improving the efficacy and applicability of multi-objective evolutionary algorithms in the context of cascade hydropower station scheduling.

3.3.3.4 Cases for multi-objective optimized scheduling

1. Scheduling case in France

In France, several key reservoirs exist within the Seine river basin, including those on the Yonne, Seine, Marne, and Aube Rivers. These reservoirs fall under the management of the Interprovincial Reservoir Authority of the Seine River Basin. Established in 1969, this financially autonomous public agency operates under the direct supervision of the French International Water Affairs Authority. The Interprovincial Reservoir Authority's jurisdiction extends over areas including Paris, Hauts-de-Seine, Seine-Saint-Denis, and Val-de-Marne, Its primary mission is to mitigate the impact of floods from the Seine and Marne Rivers on Paris by managing these reservoirs. The specific scheduling method is as follows: During periods of high water levels in the Seine and Marne Rivers, the reservoirs are employed to capture and store water, thereby reducing peak flood levels. Conversely, in times of low water levels, water is released from the reservoirs to maintain the rivers' water levels within a normal range. The Interprovincial Reservoir Authority of the Seine River Basin also makes rational arrangements for the reservoirs' storage and water supply scheduling. It adheres to the principle of ensuring unity and mutual support among the provinces within the river basin while safeguarding the natural ecological environment of the reservoir areas. The specifics of water supply and ecological scheduling are as follows:

1) Water supply scheduling

Paris faces challenges due to a scarcity of groundwater resources. To address this issue, the water from reservoirs along the Seine and Marne Rivers is processed by local water treatment plants, supplying up to 2/3 of the region's drinking water. The city of Paris experiences a water shortage for about one month each year. During the period from September to October, the reservoirs contribute to half, and sometimes up to 3/4, of the Seine River's flow. Annually, from July to October or June to December, the reservoirs along the Seine and Marne Rivers release water into these rivers to enhance the water environment and ensure the availability of drinking water. The four reservoirs collectively supply over 1 billion cubic meters of water to Paris each year. This supply ensures that the water level in the Seine River around central Paris remains within the normal range throughout the year and guarantees an adequate domestic water supply for the residents of the Parisian area within the Seine River basin.

(2) Tourism in the reservoir area

The reservoirs within the Seine River basin have not only been free of negative impacts on the ecosystem, but they have also significantly stimulated economic development across various sectors in Paris. Moreover, they have generated substantial revenue for the tourism industry.

Currently, the four reservoir areas under the management of the Interprovincial Reservoir Authority of the Seine River Basin are recognized as significant scenic spots in France and across Europe. They have also been listed as vital international wetlands conducive to the habitat of waterfowl. The reservoir authorities have implemented a range of measures to foster favorable conditions for the survival and breeding of waterfowls. Moreover, these authorities work in tandem with local forestry departments to enhance green initiatives in the upper Seine River region. This approach exemplifies the reservoir authorities' commitment to sustainable development policies, which prioritize ecological balance and seamlessly integrate reservoir construction and management with environmental protection. Each of the four reservoirs in the Seine River basin can proudly be called a national nature reserve. Within these reservoir areas, vegetation, including grasses and trees, is maintained in a purely natural state, coexisting harmoniously with hydraulic engineering works without any adverse environmental impact from construction and management activities. The local government is pivotal in preserving the natural harmony of the reservoir areas, diligently overseeing the influence of project management on the natural environment.

2. Scheduling case in China

Taking China's Yangtze River Basin as an example, there are currently 40 reservoirs in the upper and middle reaches that engage in joint scheduling. These reservoirs have a combined total capacity of about 100 billion m^3, a regulation capacity of 57.5 billion m^3, a flood control capacity of 41.5 billion m^3, and an installed capacity of 83.8 GW. Through joint scheduling, these reservoirs maximize their comprehensive benefits, including flood control, power generation, navigation, water supply, and ecology, thereby yielding significant social and economic benefits. During the 2022 flood season, the Yangtze River Basin encountered the most severe drought since 1961, based on complete meteorological records. In July and August of that year, the region experienced continuous high temperatures in many areas, setting new records for the longest observed period. Additionally, the entire basin faced an extreme water scarcity, and the power distribution areas in East China and Central China were hit by a severe power deficit. Confronted with these unparalleled challenges, the six power stations operated by China Three Gorges Corporation successfully met the objectives of drought relief, water supply, power supply during the peak summer consumption period, and water retention in cascade hydropower stations. They achieved this through rolling forecasts, scientific scheduling (as illustrated in Figures 3-16 and 3-17), and efficient coordination, thereby fully leveraging the social and economic benefits of the cascade reservoirs.

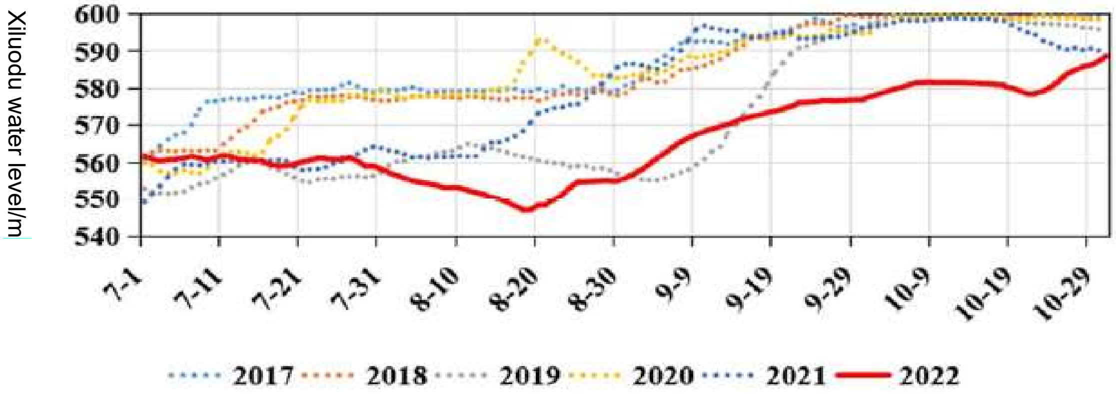


Figure 3-16 Water level results of multi-objective optimized scheduling of Hydropower Station X in the flood season of 2022

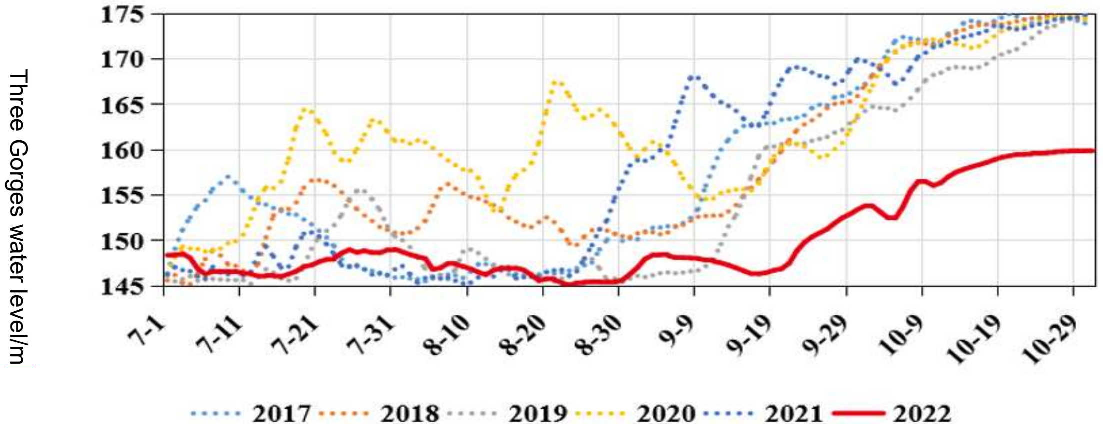


Figure 3-17 Water level results during multi-objective optimized scheduling of Hydropower Station T in the flood season of 2022

The results achieved by joint scheduling are shown as follows:

1. Guaranteed the water supply for people's livelihood

Domestic and production water supplies for the middle and lower reaches of the river basin were ensured by enhancing inflow forecasting, optimizing reservoir scheduling, strengthening close coordination with external entities, and promptly adjusting power generation plans. Moreover, the reservoirs contributed to the replenishment of 1.51 billion m^3 of water to the middle and lower reaches of the Yangtze River, which represents 24.5% of the total water replenishment volume for the basin. This water provision met the irrigation needs for 43.16 million mu (about 2,877,000 hectares) of autumn grain crops and provided for the water supply of 13.85 million residents.

2. Guaranteed the supply of electric power

By optimizing and adjusting the power delivery mode and power generation curve, an additional 257 GWh of electric power was delivered to the power grid.

3. Increased the power generation benefits

During the flood season, the cumulative increase in power generation reached 5.511 TWh through the promotion of scientific joint scheduling, the strategic use of small to medium floods to raise operational water levels, and the coordination of hydropower stations' outgoing power delivery channels.

4. Completed the impoundment task

Faced with intense conflicts among water replenishment for drought relief, ensuring power supply during peak consumption periods, and reservoir impoundment, the scheduling strategies were timely adjusted to ensure the completion of impoundment tasks for all cascade reservoirs in the lower reaches of the Jinsha River. Starting from late August 2022, by breaking away from conventional scheduling modes, Reservoir T's impoundment was conducted with the principles of ensuring downstream water supply safety, ecological safety, and the minimum water volume required for navigation safety. Consequently, the cascade reservoirs achieved a maximum impoundment volume of 27.6 billion m^3, effectively securing the water supply for power generation as well as for domestic, industrial, and agricultural use in the middle and lower reaches of the river basin.

5. Situation of ecological scheduling

In 2022, a series of 16 ecological scheduling trials across six different categories were conducted at the cascade hydropower stations located in the lower reaches of the Jinsha River. The monitoring results indicated that during the initial ecological scheduling trial, 70 million fish eggs were spawned within the reservoir area of Reservoir T, and during the subsequent second ecological scheduling trial, 41 million eggs were spawned in the reservoir area.

3.4 Conclusions and prospects

This chapter elaborates on the pivotal role that basin-wide water resource scheduling management plays in the comprehensive utilization of water resources (CUBWR). It also provides a detailed analysis of the current requirements for basin-wide water resource scheduling management. Furthermore, it offers a systematic review of related technical and management modes, including the operation and management of hydropower stations, water ecology monitoring and simulation, and multi-objective optimized scheduling. The main conclusions drawn in this chapter are as follows:

(1) Developing Smart Power Stations: This initiative will allow hydropower station managers to better monitor equipment status and respond to emergencies promptly and accurately. It will

significantly enhance the operation and management of hydropower stations, providing basic technical support for CUBWR.

(2) Advancing Condition-Based Maintenance for Hydropower Station Equipment: By implementing maintenance based on the health status of equipment, this approach will boost maintenance efficiency, notably improve equipment reliability, extend service life, and offer essential equipment support for CUBWR.

(3) Optimizing Ecological Environment Monitoring Methods: Monitoring serves as the primary support for the application of ecological environment simulation technologies. To strengthen ecological preservation and optimize laboratory monitoring outcomes, strict adherence to operation specifications during monitoring will effectively minimize errors caused by interference factors and misoperations.

(4) Enhancing the Integration of the Internet of Things (IoT) with Monitoring Technologies: By integrating with IoT, it is possible to construct a network architecture with broader coverage, leveraging network information and digital technologies. The IoT, when effectively integrated with ecological environment simulation technologies—mainly according to current environmental detection requirements for monitoring water quality, atmospheric conditions, and ecological indicators—will improve the efficiency and accuracy of the monitoring process.

(5) Optimizing Heuristic Algorithms: Each heuristic algorithm has its strengths and weaknesses. For the foreseeable future, the improvement and integration of various algorithms will continue to be a research focus. On one hand, it is recommended to improve the search mechanisms of algorithms and optimize related operations to enhance computational performance. On the other hand, optimization algorithms with similar processes and structural frameworks can learn from and complement each other. Moreover, under a unified framework, it is possible to develop hybrid intelligent algorithms characterized by higher efficiency, superior performance, excellent convergence, and faster solution delivery with better quality.

4 DECISION SUPPORT SYSTEM FOR COMPREHENSIVE UTILIZATION OF WATER RESOURCES (DSS FOR CUWR)

4.1 Overview

4.1.1 Development status of WRDSS

Since the 1960s, the early prototype of WRDSS with a singular function—namely, the reservoir flood scheduling system—has been in development. By the early 1980s, the manual scheduling mode for flood forecasting in numerous reservoirs and river basins had been phased out. In its place, computer technology began to be progressively implemented, with programmable computers being utilized to develop real-time flood forecasting systems with simple functions. As computer technology advanced, a variety of outstanding development tools have emerged, enabling scholars to integrate diverse models and build more sophisticated scheduling systems with enhanced capabilities[24, 25].

Due to technical limitations, early scheduling systems required scheduling on a DOS platform and had poor visualization capabilities. However, with the ongoing emergence of new technologies, these systems have seen continuous refinement. In 1986, Brown and colleagues developed a decision-making tool for reservoir power generation scheduling in response to the operational needs of cascade hydropower stations in the Tennessee River Basin, marking it as one of the early WRDSS with relatively simple functions. With the development and application of DSS for optimized reservoir scheduling, initially based on the VC++ programming language, there followed the introduction of WRDSSs developed in various programming languages, including VB, C, Java, and Python. To cater to the diverse office requirements of companies and departments, WRDSS was created, classified according to system model types, such as those based on B/S and C/S architectures. The B/S model-based system gained popularity for its user-friendliness, as it can be easily accessed via a web browser without the need for specific computer configurations. Conversely, the C/S model-based system has become increasingly favored due to its high stability, adaptability, multifunctionality, and scalability. Although each language and model has its limitations, they have collectively contributed to significantly enhancing the efficiency of water resource scheduling[26].

Internationally, the development of WRDSS platforms commenced relatively early. Following the large-scale development and construction of hydropower in major countries, there was a shift in focus toward optimizing the scheduling of hydropower stations and enhancing their management. Companies and research institutions worldwide have undertaken extensive practical research into the development of forecasting and scheduling platforms, tailored to the specific conditions of each country, including market characteristics, basin features, and the scale of hydropower stations. Since the 1960s, the United States and Europe have been utilizing computer programs for water regime forecasting, hydrological calculations, and reservoir scheduling. Nations have crafted their respective DSS for CUWR. This includes software like the HEC series by the U.S. Army Corps of Engineers, the MIKE series by the Danish Hydraulic Institute, the Riverware system developed collaboratively by the Bureau of Reclamation, the Tennessee Valley Authority, and the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado, the Delft-FEWS system by the UK's Environment Agency, and the GTDSS (INFROM) decision-making system, refined and widely applicable, developed by the Georgia Water Resources Institute at Georgia Tech[26-29]. These WRDSSs have been effectively implemented by numerous basin management agencies and hydroelectric power companies around the world.

4.1.2 Future development direction

4.1.2.1 System integration for meeting the needs of complex multi-objective scheduling

The WRDSS is an intricate system, influenced by many factors. The basin-wide water resource management decision involves various fields, such as society, economy, hydrology, hydrodynamics, hydraulics, and ecology. As such, it represents a typical semi-structured, multi-layered, multi-stakeholder, and multi-objective decision-making challenge. At present, most existing engineering application systems function primarily on traditional scheduling models, concentrating on the execution of scheduling at the business level. These systems are designed for small spatial scales, typically applicable to single or just a few reservoirs, and have not yet advanced to integrated systems capable of joint scheduling and analysis. Meanwhile, with scheduling tasks growing more refined and the decision-making processes more complex, the use of hydraulic engineering has transitioned from singular to multiple objectives, such as flood control, power generation, ecological preservation, navigation, and water supply. Nonetheless, current WRDSS faces significant challenges in the optimized joint scheduling of regional and inter-regional reservoir systems within a multi-objective framework. Moreover, current systems display information methods are relatively single, with crucial decision-making data dispersed across fragmented and isolated interfaces. There is an absence of effective knowledge extraction and intelligent organization. Furthermore, the potential of dynamic interactive platforms that offer multi-dimensional temporal and spatial scales, leveraging 2D/3D visualization technology, remains underutilized.

To fulfill the requirements for automated, intelligent and optimized joint scheduling of basin-wide cascade reservoir systems, it is essential to develop computational and analytical tools that align with management decision-making and scheduling demands. Researches into integration technologies for the optimized joint scheduling of cross-basin reservoir systems are also necessary. Establishing a visual interactive model that leverages knowledge excavation and 2D/3D digital basin modeling is key. This approach will lead to the development of an optimized joint scheduling management system capable of satisfying the technical demands for the comprehensive operational management of reservoir systems.

4.1.2.2 In-depth application of artificial intelligence and deep learning in the field of water resources decision support

As science and technology advance, computer performance has seen an exponential increase, with remarkable strides in areas such as big data and deep learning. These technological leaps have facilitated the integration of deep learning techniques within artificial intelligence, particularly in the domain of water resource decision-making, owing to their proficiency in feature extraction and simulation optimization. The evolution of water resource informatization is progressively moving from traditional automation and digitization towards a contemporary era of intelligence. In recent years, the ongoing development of cascade hydropower stations, coupled with increasingly complex scheduling objectives and the input of multi-source heterogeneous big data, has led to the application of deep learning technology in the scheduling of these hydropower stations.

Within the deep learning framework, scholars globally have conducted extensive research, leading to notable advancements in the development of hydropower station scheduling modes and DSS for scheduling. However, the following issues still exist: (1) The parameters for deep learning models are often determined empirically or through a trial-and-error approach, which is somewhat stochastic. (2) The neural network models predominantly utilize a globally updated structure, demanding longer training periods. (3) The overall deep learning process, encompassing modeling, data preprocessing, model training, and application, is relatively intricate and requires extensive experience and expertise, representing a bottleneck in its broader application. (4) Most traditional WRMDSS operates on monolithic architectures, which are not conducive to large-scale model training and computation. These challenges have significantly hindered the application of deep learning technology in the scheduling of cascade hydropower stations. Thus, under the new circumstances, accelerating the integration of artificial intelligence and deep learning into water resource decision support—offering decision-makers efficient, swift, rational, and viable scheduling solutions—has become an urgent issue to be tackled in the domain of DSS.

4.1.2.3 Nested modeling and solving of multiple time scale scheduling under complex constraints

From the perspective of a spatial scale, the hydropower system encompasses the scheduling and coordination across various regions, basins, cascades, power stations, and even individual power houses. From the perspective of hydraulic connections alone, in cascade hydropower stations, the inflow to downstream stations may be affected by the cascade scheduling decisions of multiple upstream basins. The unpredictability of future scheduling schemes for upstream reservoir systems can pose considerable challenges in formulating the downstream cascade reservoir scheduling scheme. The uncertainty surrounding the hydraulic characteristics of runoff propagation through river channels may also lead to significant errors in the reservoir scheduling schemes for downstream cascade hydropower stations. Moreover, considering the power grid conditions, coordinating power generation plans across different regions and even among various hydropower stations is an issue that must be addressed in the scheduling and operation of reservoir systems. It is also a scheduling challenge that urgently needs to be solved in the new situation.

From the perspective of time scale, the operation of decision support for hydropower systems must integrate multiple time scales-encompassing annual, monthly, decadal, daily, intra-day, and real-time scales-while also meeting the complex requirements of spatial scales. It is necessary to change the previous situation where plans across different time scales were disconnected from each other. Large-scale plans should provide boundary constraints and end-to-end objectives for small-scale plans. Small-scale plans, in turn, should offer continuous feedback to large-scale plans as the scheduling is executed, allowing for the ongoing refinement of future small-scale plans while ensuring the completion of large-scale scheduling objectives. From the perspective of power generation scheduling alone, there is an urgent need for research on the coupling and nesting of long-term, medium-term, and short-term scheduling schemes[30-32].

4.2 Key technologies

This chapter offers a comprehensive guide to support water resource managers in basin management and decision-making, detailing the construction methods and key functionalities of DSS for CUWR. It covers aspects such as: information collection and storage, the development of system architecture, visual display, and the integration of system functionalities.

4.2.1 Information collection and storage

4.2.1.1 Information collection

Generally, for basin information collection, an integrated monitoring approach is utilized that encompasses satellite remote sensing, aerial surveys via drones, automatic ground station monitoring, and real-time conditions of equipment operating conditions at the sites.

For example, China has developed an extensive, comprehensive, all-weather, and precise automatic monitoring network for meteorological, hydrological, and operational conditions in the upper reaches of the Yangtze River basin. In this network, the ground observation system comprises 633 hydrological telemetry stations, 327 hydrological (water level) reporting stations, 7,182 automatic weather stations, 442 shared water regime monitoring stations, and more than 100,000 operational condition sensors. Utilizing the vast and multi-source heterogeneous edge computing dataset collected from the full-coverage, all-weather automatic monitoring system in the upper reaches of the Yangtze River-encompassing water levels, rainfall, and operational conditions-a multi-channel, real-time online monitoring and automatic forecasting system for "water, units, and electricity" has been established. This system is built on a hybrid big data framework of Hadoop and Spark, supported by various communication methods including VHF, GSM/GPRS, Beidou satellite, CDMA, PSTN, and Inmarsat. The system ensures stable operation over 99.00% of the time and is capable of collecting, transmitting, and processing comprehensive water, rainfall, and operational condition data across the entire basin within a mere 10 minutes.

4.2.1.2 Data storage

The system centrally manages a variety of data assets through a big data middle platform, enabling the collection, storage, cleaning, and analysis of multi-source heterogeneous data. It offers capabilities for data classification, resource management, data querying, sharing and visualization. The system's data storage generally encompasses three parts: data storage framework, data resource management, and data resource services.

(1) Data storage framework

The data storage framework delivers the core functionality for data storage, accommodating both structured and unstructured data types, and provides diverse storage solutions tailored to different data categories. Additionally, to satisfy data access demands, the framework also provides functions such as caching, read-write separation, and database partitioning and table sharding, all aimed at enhancing data response speeds. For structured data storage, the framework mainly relies on mainstream storage databases, including Oracle and MySQL. In contrast, unstructured data storage mainly utilizes databases such as MinIO, MongoDB, and Neo4j for graph storage.

(2) Data resource management

The data resource management functionality facilitates the collection, cleaning, storage, and management of data categorized by business type. It integrates discrete data from various systems into a unified big data middle platform. Concurrently, it offers data integration capabilities to further process and restructure data into a thematic data warehouse, encompassing a range of data types including basic data, monitoring data, and operational data. Specifically, data resource management includes the following modules:

1) Data source management

This module provides access to a wide range of database types, encompassing both mainstream relational databases and distributed databases. It enables the connection of business system data to the platform for subsequent modeling and analysis. These types of databases include: Oracle, MySQL, SQL Server, DM, PostgreSQL, etc.

2) Data integration

This module presents visually defined ETL (Extract, Transform, Load) task configurations and a variety of components that aid users in accomplishing ETL data processing and data preview tasks. The component library includes types that facilitate data analysis, data mining, and machine learning. It is capable of conducting research and computations in fields such as meteorology, hydrology, scheduling, flood control, power generation, ecology, and shipping in a process-oriented manner.

3) Dataset management

This module manages datasets within the data model's warehouse by organizing related subject tables into cohesive subject sets. Users can streamline the categorization and management of datasets by simply creating subject domains and grouping subject tables accordingly.

4) Data security management

- Data access security:

Service authentication: ensuring the legitimacy of various roles and effectively preventing identity spoofing.

Authorization management: the permissions for administrator's operations.

- Data desensitization security:

a security solution for data content.

- Data audit security:

Data auditing is the process where the system facilitates access to data and audit logs, enabling the tracking of data provenance, and monitoring the flow and transformation of data.

(3) Data resource service

The data resource management function offers a platform for data management that interfaces with both structured and unstructured data sources from various systems, including the reservoir dispatching automation system, meteorological services, sediment management, documentation systems, hydraulic engineering systems, and external internet sources. It enables the realization of data collection, cleaning, storage, and management tailored to the type of data services. It integrates discrete data from various systems into a unified big data middleware platform. At the same time, it can realize data integration, reprocess the data, and provide corresponding data services through its interfaces.

4.2.1.3 Database design

The distributed system generally uses the Spring Data framework to provide data services. This open-source framework facilitates database access and is compatible with cloud services. It builds upon the Spring framework for data access technologies, encompassing the MapReduce framework, NoSQL databases, cloud data services, and relational databases. Within the Spring Data item, there are several sub-items, including Spring Data JPA. The system uses the Spring Data JPA framework technology to implement data services for the basic data platform, offering a unified data access interface. A variety of model algorithms perform data interactions by accessing this data service interface.

The JPA includes the technologies in the following three aspects:

(1) Java Persistence API (JPA)

It enables the manipulation of entity objects for CRUD (Create, Read, Update, Delete) operations, liberating developers from intricate JDBC and SQL code complexities and allowing them to concentrate more on the system's business requirements.

(2) JPQL (Java Persistence Query Language)

JPQL is an integral component of persistence operations. It uses an object-oriented language to data querying, thereby avoiding the issue of tight coupling with SQL statements that is characteristic of database-oriented languages.

(3) ORM (object/relational metadata)

JPA supports two forms of metadata: XML files and JDK 5.0 annotations. These metadata are utilized to delineate the mapping relationships between objects and relational database tables. Based on this, the JPA framework can store entity objects into corresponding database tables. The ORM framework dynamically generates SQL statements for object persistence, eliminating the need to write database-specific SQL statements. Moreover, it can incorporate SQL statements that have been optimized by developers, according to the particular characteristics of the database. In contrast to utilizing JDBC directly, the ORM framework significantly reduces the data access workload for application developers.

4.2.2 System architecture

4.2.2.1 Distributed system architecture

A distributed system architecture integrates dispersed computing resources into a cohesive entity, offering users consistent functions for invocation, monitoring, and management. It dynamically assigns the system's various general-purpose physical and logical resources according to task demands and enables the exchange of information between these resources via a computer network.

Internationally, the Service-Oriented Architecture (SOA) is a widely adopted mainstream technology. It unifies multi-disciplinary model services for water resource management into a cohesive framework, operating as small-scale service clusters and offering them to application developers via service interfaces. Additionally, it uses collaborative software for task tracking and manages the software development process from coding to software engineering. Adhering to a service-oriented approach in service development is essential. This involves dividing software into as many distinct components as possible. These components are then encapsulated as services and made reusable through their respective APIs, achieving decoupling of software modules and facilitating continuous integration during the testing process.

4.2.2.2 Front-end frame

The front-end framework constitutes a reusable system for human-computer interaction design, outlining the application's architecture, dependencies, responsibility distribution, and control flow. It lays the contextual foundation for component reuse and provides technical support for the reuse of extensive component libraries. Internationally, the leading front-end frameworks include React, Angular, and Vue.

Take Vue as an example. Vue.js is a progressive framework designed for crafting data-driven web interfaces. It aims to facilitate data binding and the composition of view components through a simple API, offering a wide array of display functions for system interfaces. Vue.js adopts a bottom-up incremental development design, making it lightweight and user-friendly. It is well-suited for developing sophisticated single-page applications. The interaction between Vue.js and the backend is depicted in Figure 4-1.

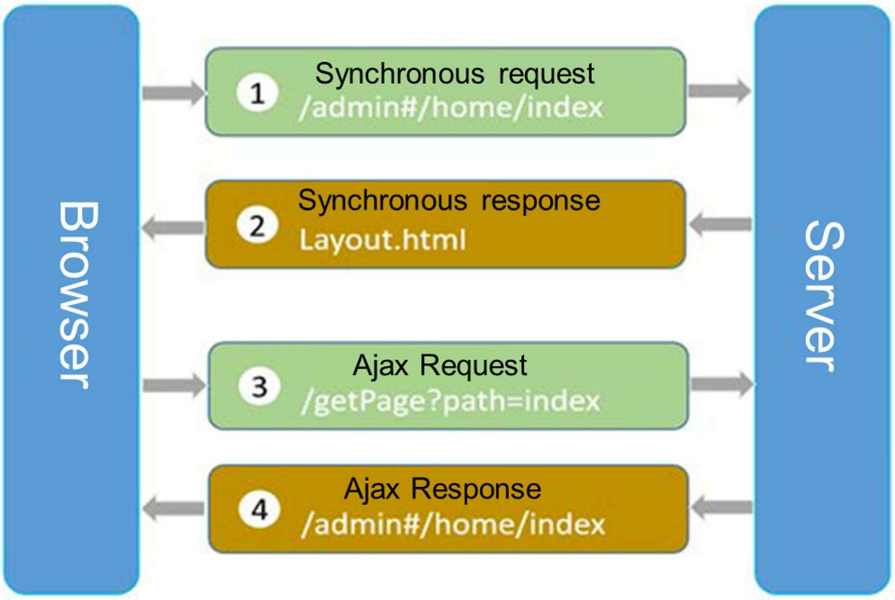


Figure 4-1 Vue.js front-end and back-end interaction flow

4.2.2.3 Back-end microservice architecture

Microservice architecture facilitates the development of a single application as a set of small services. Each service operates independently within its process and communicates through lightweight mechanisms, commonly utilizing HTTP resources. Constructed around their respective functionalities, these services are capable of being deployed independently. This approach has become a standard for crafting models that are highly reusable, scalable, and maintainable.

(1) Monolithic architecture

A typical example of monolithic architecture only includes a single application, database, and web container. This architecture is relatively simple and flexible, ensuring the swift deployment of services. With a monolithic architecture, the service access load is relatively light, and the technical demands are not stringent, simplifying the development handover for developers across skill levels. Thus, it suffices for simple business needs. The diagram of the monolithic architecture is illustrated in Figure 4-2.

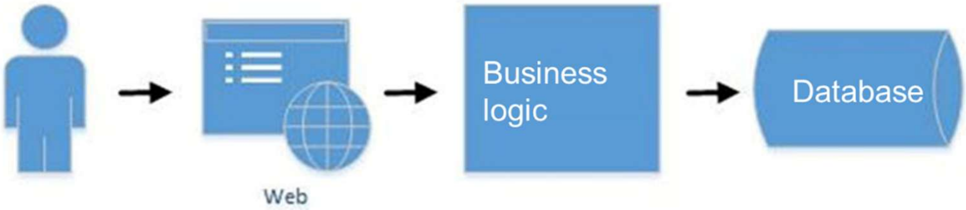


Figure 4-2 Monolithic architecture diagram

(2) Vertical architecture

As business models become more complex and the demands for system interactions increase, the existing business system can be divided into the backend system, front-end system, monitoring system, etc.

Vertical architecture divides the system into different layers, each with distinct responsibilities. The UI layer handles user interactions, the business logic layer manages the execution of specific business functions, and the database layer is responsible for data interaction and storage. Within vertical architecture, the SSH (Struts + Spring + Hibernate) is a key technology for projects. Struts facilitates logic control at the web layer, Spring manages Bean within the business layer, and Hibernate encapsulates database operations for persistent data storage. The structure of vertical architecture is shown in Figure 4-3.

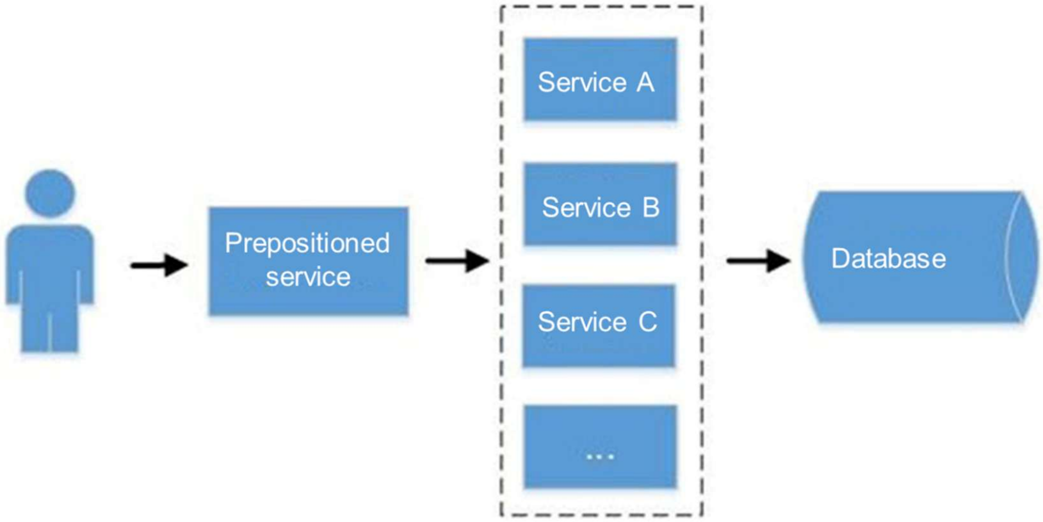


Figure 4-3 Structure of vertical architecture

(3) Microservice architecture

With the increase of vertical subsystems, the inter-system invocation relationship grows exponentially. SOA for subsystems is an ideal solution to the complex inter-system interaction demands. SOA divides applications into distinct modules based on their specific responsibilities, allowing each module to interact directly with others via defined interfaces and protocols. This architecture decouples the system into multiple single-component services to handle the requests. These components can be extended horizontally to manage high flows. Moreover, they interact with one another through mutual invocation to fulfill the overall business needs of the system.

The SOA is a loosely-coupled design structure. It operates on the principle that while each service should exhibit high internal cohesion, there should be minimal coupling between services. The SOA is shown in Figure 4-4.

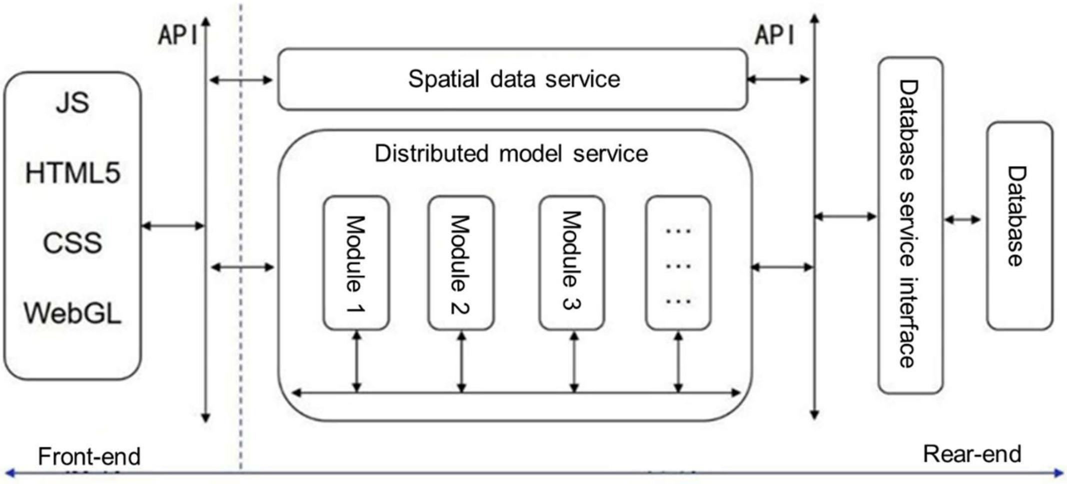


Figure 4-4 Diagram of SOA

4.2.3 Visual display

4.2.3.1 3D visualization framework

The spatial data visualization functions of the system mainly include: 1) Display of basic data layers: Each layer uses symbols, colors, and texts to depict important descriptive information about diverse geographical elements. 2) Display of model calculation results: It visualizes the results of all models to improve the system's human-computer interaction performance.

For example, Cesium is a world-class JavaScript open-source product for 3D globes and maps. It provides a JavaScript-based development package, that enables users to quickly build virtual globe web applications without plugins. Cesium offers high quality in terms of performance, accuracy, rendering quality, multi-platform support, and user-friendliness. Its main effect is shown in Figure 4-5. Figure 4-5 Example of Cesium's functions

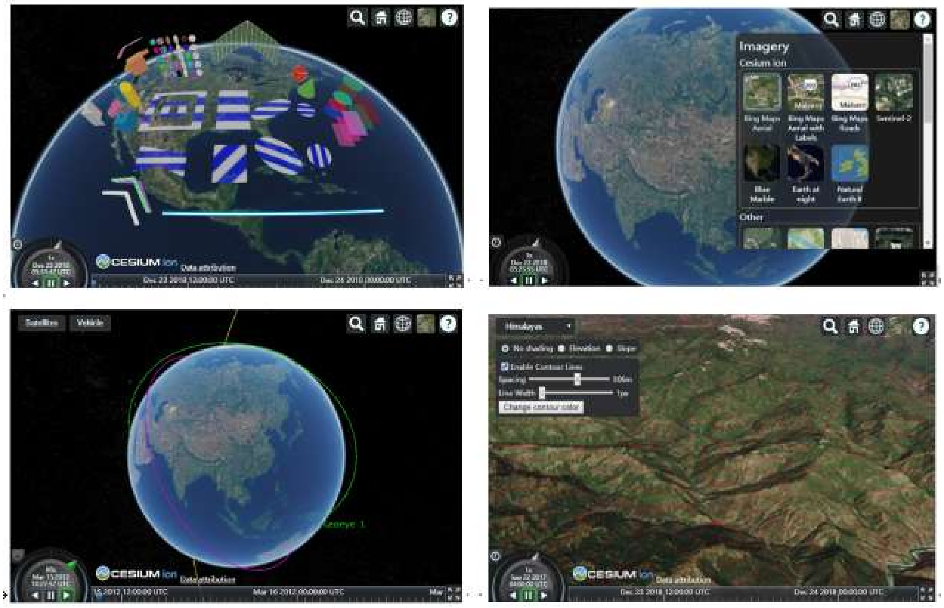


Figure 4-5 Example of Cesium's functions

4.2.3.2 Human-computer interaction design of the system

The DSS for CUWR is an intricate system, influenced by many factors. The basin water resource management decisions involve various fields, such as society, economy, hydrology, hydrodynamics, hydraulics, and ecology. As such, it represents a typical semi-structured, multi-layered, multi-stakeholder, and multi-objective decision-making challenge. The mainstream frameworks commonly used for the front-end of the system include Vue.js, Cesium, HTML5, CSS3, and Element UI.

For example, China has developed an optimized joint scheduling management system tailored to the comprehensive operational management needs of the controlling reservoir system within the main and tributary streams of the upper reaches of the Yangtze River. The system's human-computer interaction design mainly includes the following components:

(1) System's Home page display

The system's Home page can be used to query basic information and basin's overview information (as shown in Figure 4-6). It offers selections for real-time, weekly, and monthly statistical data. The real-time information encompasses comparisons of current sub-basin total storage volumes, previous day's total storage volumes, total available reservoir capacity, previous day's available reservoir capacity, total energy storage value, and previous day's energy storage value, all relative to the same period of the last year. Weekly statistics detail this week's and last week's average available water volume, average available reservoir capacity, and average energy storage value, with comparisons to the same period of the last year. Monthly statistics detail this month's and last month's average available water volume, average available reservoir capacity, and average energy storage value, with comparisons to the same period of the last year. Sub-basin labels allow users to access detailed station statistics within each sub-basin, including the data on water levels, instreamflow, outstreamflow, and year-on-year comparisons. By clicking on the left-side labels, users can further view annual operational process comparisons, unit start-stop status, rainfall forecasts, site water level warnings, and power transmission line connection information.

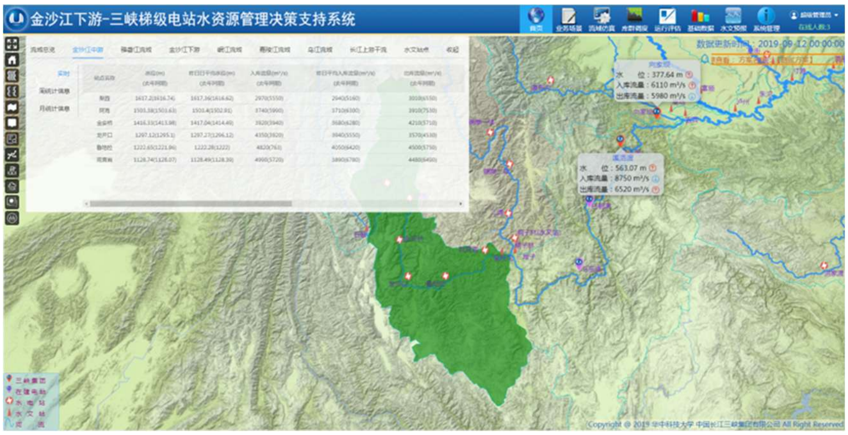


Figure 4-6 Query of basin's overview information

The annual operation level process chart presents a comparative analysis, featuring the planned versus actual data for the current year, as well as the actual data from the previous year and the year before that for the hydropower stations. This information is displayed within a dynamic chart window, enabling users to toggle between views to visualize the inflow and power generation processes. The comparative chart is depicted in Figure 4-7.

Figure 4-7 Query of annual operation level process1

The sub-basin layer automatically navigates the map view to the selected sub-basin and highlights its borders, as depicted in Figure 4-8. Concurrently, this layer presents data for each station within the sub-basin, including the upstream water level, reservoir inflow, outflow, and comparative figures from the same period of the last year.

站点名称	上游水位(m)(去年同期)	入库流量(m³/s)(去年同期)	出库流量(m³/s)(去年同期)
三峡	147.91(152.77)	18600(14600)	14400(14200)
葛洲坝	63.93(64.72)	14800(14600)	14900(14500)

Figure 4-8 Query of detailed information about the sub-basin

Furthermore, the Home page can remind users to updates within the system's model module schemes. An icon notification will appear when new module schemes are integrated into the system, presenting the names of the updated modules and schemes, as illustrated in Figure 4-9.

Figure 4-9 Prompt of updates to model module schemes

(2) Analog simulation

The flood event display mainly simulates the propagation of a specific flood event within the Yangtze River basin's main channel, in tandem with both the reservoir and river channel simulation models. It dynamically illustrates the operation processes of each reservoir, as well as the water levels along the river channel and the flow processes at key cross-sections. This interface is shown in Figure 4-10.

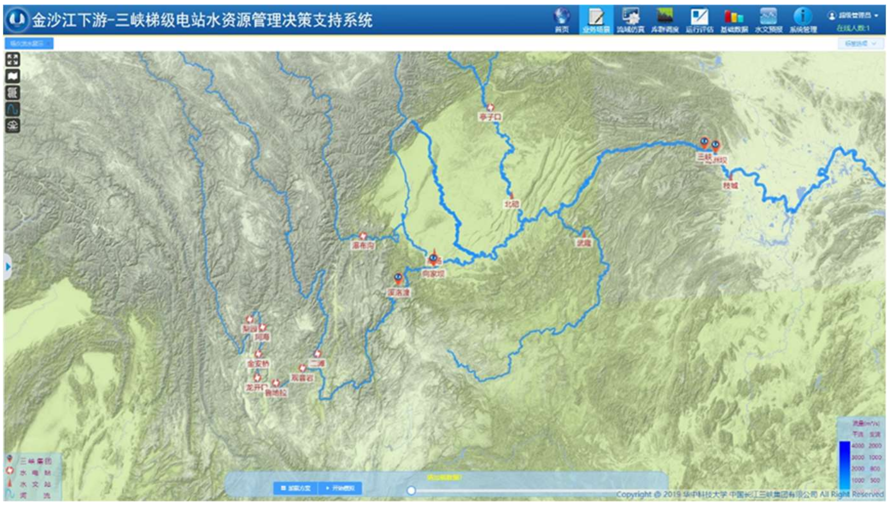


Figure 4-10 Main interface of flood event display

The page displays related simulation schemes in a tabular list. Upon loading a scheme, users are able to observe the flow processes of both the main river and its tributaries throughout the entire river section for that particular scheme. Varied colors correspond to different streamflow, as shown in Figure 4-11.

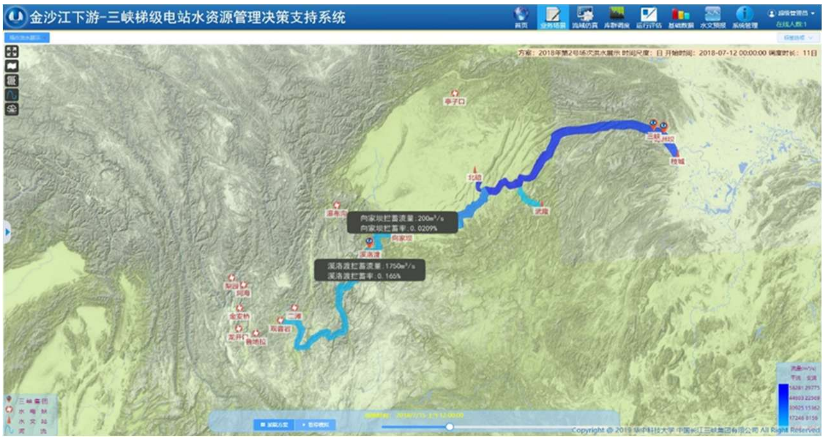


Figure 4-11 Display of a flood event scheduling scheme

The system offers an overall display of a two-dimensional dynamic map of the river channels in the basin, animating the water level, inflow, and outflow processes for each reservoir. Users can view the scheduling process for each station via the label, which includes details on water levels, inflows, and outflows, as shown in Figure 4-12.

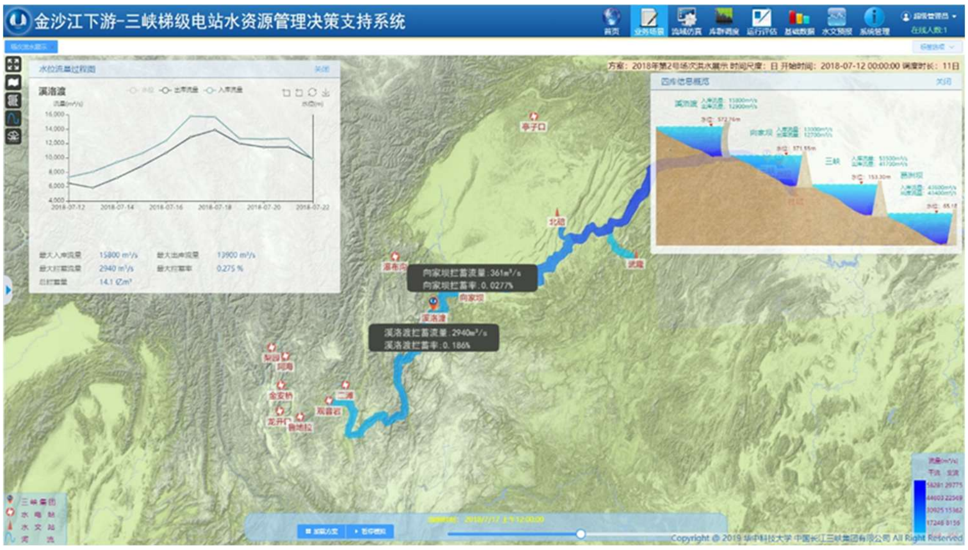


Figure 4-12 Reservoir information overview and scheduling process display

4.2.4 System integration

The comprehensive water resource management function is supported by a suite of interconnected service modules. These modules engage in frequent data exchanges and demand high stability. By employing mainstream distributed system integration and interface technologies, such as REST-based service invocation, load balancing, and fuse, the system can improve compatibility across heterogeneous platforms. These technologies ensure stability in high-concurrency scenarios and provide technical support for building a robust system architecture framework.

4.2.4.1 REST-based service invocation

Traditional Web services, centered around the SOAP protocol, encapsulate each model into a connectable component that adheres to specific interface standards for simulation computing services. These services are published on UDDI or other directory servers to provide simulation computing capabilities for client-requested model integration applications. However, as the number of standards grows and their integration becomes more common, the SOAP protocol has become increasingly cumbersome and complex to use. The REST technology has mitigated these shortcomings of SOAP. Web services built on the REST architecture offer benefits such as addressability, standard versatility, and connectivity. Besides, CRUD operations—Create, Read, Update, and Delete—are the most commonly used operations, each with a corresponding method in the HTTP protocol. REST-based Web services represent a lightweight implementation of Web services. Compared to traditional monolithic software architectures, they provide superior compatibility with various heterogeneous platforms.

4.2.4.2 Load balance and fuse

Load balance is a critical consideration in the design of distributed system architectures. It is particularly important for the performance of P2P system application servers, where imbalances can significantly impact system health. There are generally two approaches to achieving load balance. One is to distribute requests based on network flow, which entails accessing a list of registered microservice information and allocating requests accordingly. The second approach allows users to define their own load balance algorithms to connect to the necessary services.

A fuse is an isolation mechanism that improves the stability of a distributed system. It manages the number of threads in a thread pool, rejecting access when necessary, and sets timeouts for invocations to avoid prolonged waiting periods. When numerous requests are congested at a single microservice, it can disrupt the inter-service communication within the system. If microservices are highly granular and the interactions between requests are intricate, the blockage of one microservice can negatively affect the overall system performance. Therefore, in high-concurrency environments, a fuse is needed to ensure that the entire system's functionality is not compromised by the failure of a single service.

4.2.4.3 API gateway

The service gateway is a unified access control layer in a distributed system. Its main functions include access control, security control, and protecting the service registration information of the nodes within a distributed setting. It is a vital security measure for a microservice architecture. In addition to incorporating robust load balance and service discovery mechanisms, the service gateway also has functions such as access control and validation. Figure 4-13 illustrates the lifecycle and sequence of execution for various standard and user-defined filters.

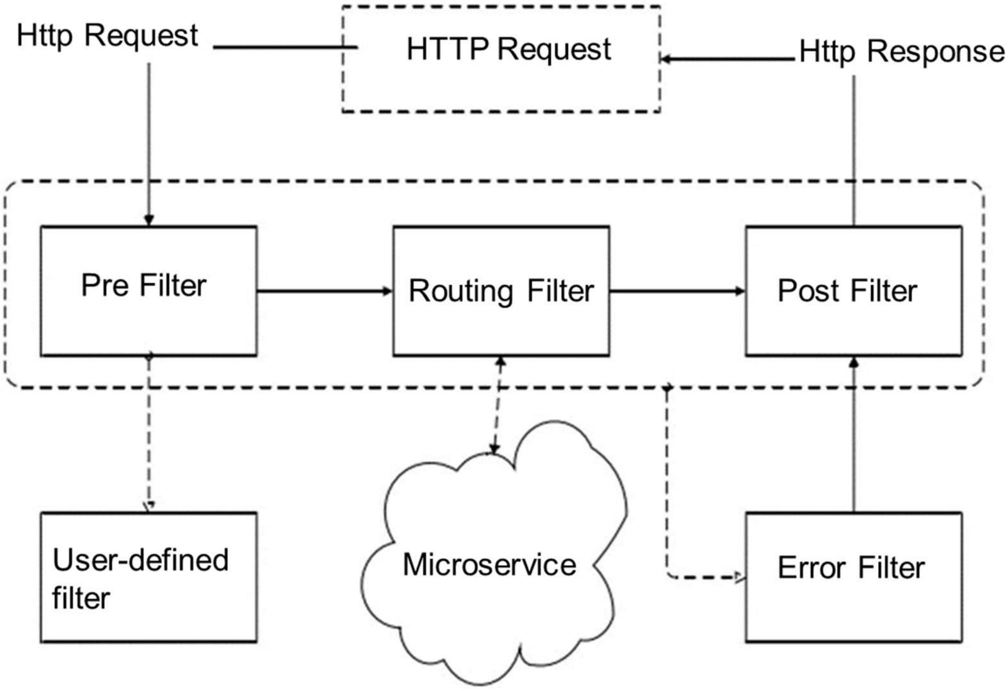


Figure 4-13 Lifecycle of filters

4.2.4.4 *Integrated functional modules*

(1) Integration of reservoir and river channel simulation modules

Focusing on large-scale controlling reservoirs within a river basin as the subjects of study, the task is to establish a library of scheduling rules for reservoirs. This involves simulating potential future scheduling scenarios for upstream reservoirs and analyzing the effects of their scheduling and storage on downstream power stations. A key aspect is to develop a runoff simulation calculation method and a river channel calculation model that support joint scheduling. These models must satisfy the consistency requirements for inflow into cascade hydropower stations across various time scales and integrate corresponding functional modules.

(2) Integration of optimized scheduling modules for cascade reservoir systems

The task is to: 1) Construct hierarchical scheduling models and nested coupling models, and explore multiple fast and efficient optimization algorithms; 2) Investigate the comprehensive scheduling integration technology for rolling optimizations, aiming to develop optimized scheduling models for reservoir systems that cater to actual production conditions across long, medium, and short terms; 3) Formulate a conventional scheduling model that aligns with production and scheduling requirements, and integrating the relevant functional modules.

(3) Integration of hydrological forecast research modules

This involves: 1) Coupling hydrodynamic models to improve the accuracy of river channel evolution, leveraging long-term series data on rainfall-runoff along with hydrological and forecasting theories; 2) Extending the hydrological forecasting periods by utilizing numerical weather forecasting models, thereby enhancing the hydrological model's capacity for long-, medium-, and short-term runoff forecasting; 3) Delivering land-atmosphere coupled runoff forecasts that are characterized by high accuracy, extended forecasting periods, and a sound physical mechanism for the basin, thereby offering decision-making support for the rational allocation and scheduling of water resources and integrating the relevant functional modules.

(4) Integration of forecasting and scheduling evaluation modules

This involves: 1) evaluating the results of long-, medium-, and short-term forecasts and the scheduling of cascade reservoirs using long-term series data; 2) recommending appropriate forecasting models and scheduling schemes for future time frames or specific scenarios based on the evaluation results; 3) offering optimization recommendations and integrating the relevant functional modules.

4.2.5 Application practice

4.2.5.1 Water resource decision support software system of Georgia Tech

The Georgia Water Resources Institute (GWRI), based at Georgia Tech in the United States, has developed a DSS for WRDSS after extensive research. This system, known as the "Georgia Tech Water Resource Decision Support System (GTDSS)," integrates long- and medium-term river runoff forecasting with optimized reservoir system scheduling and water resource management. GTDSS is designed to improve the typically weak link between medium- and long-term planning entities and short-term operational control departments within reservoir management. It enables long-term plans to be practically guide short-term operations. This integration enhances the connection between different management tiers, making the decision-making process more transparent, coordinated, and effective in maximizing the capabilities of hydropower stations. In recent years, GTDSS has become a leading system in the field of optimized joint scheduling for reservoir systems, with notable successes in the United States and Africa. It is a system that integrates forecasting with medium-, long-, and short-term scheduling models, featuring automatic rolling updates. GTDSS is utilized by more than twenty hydropower generation companies and basin management agencies globally. The system's framework and interactive interfaces are depicted in Figures 4-14 and 4-15. Notable successful applications of GTDSS include the Aswan High Dam Reservoir in Egypt, the Apalachicola-Chattahoochee-Flint (ACF) basin-wide cascade reservoirs in the southeastern United States, and the Sacramento Basin in California.

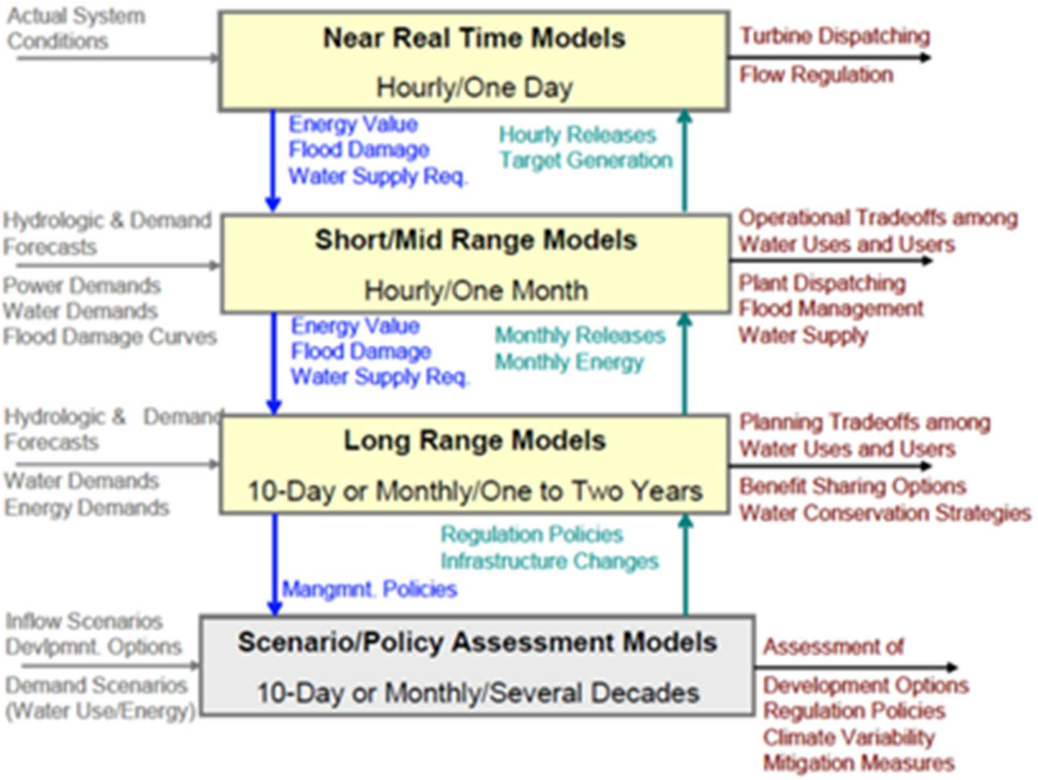


Figure 4-14 System modeling framework

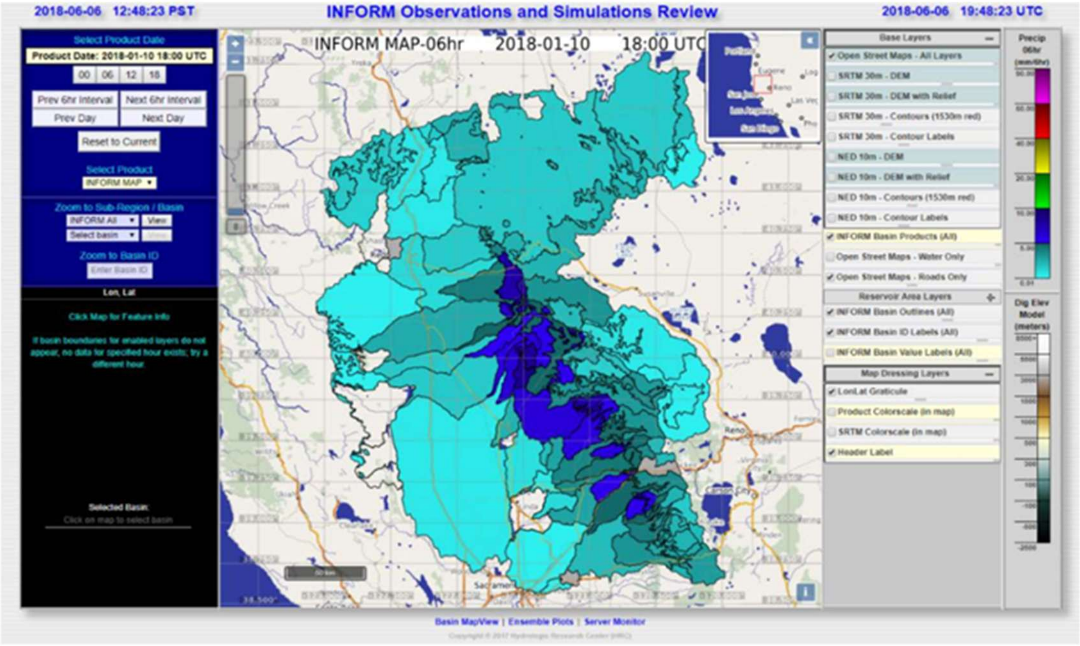


Figure 4-15 System interface of GTDSS

The operational management of the Aswan High Dam in Egypt is extremely complex. The reservoir's primary focus is on irrigation, which often takes precedence over power generation. However, decisions prioritizing irrigation can sometimes result in avoidable losses of hydroenergy and electricity or even acute water scarcity. Therefore, the development of scheduling schemes requires the concurrent consideration of multiple objectives and constraints. To meet the requirements for scheme formulation and improve the efficiency of water resource utilization, the Aswan High Dam Decision Support System (HAD-DSS) was developed by the Lake Nasser Flood and Drought Control (LNFDC) Project, based on leveraging the GTDSS. This pioneering system integrates medium-, long-, and short-term forecasting with scheduling control models for reservoir scheduling. The framework for the system's decision-making function in scheduling is depicted in Figure 4-16.

Initially, there is the unit power load distribution module, designed to maximize the hydropower station's power output by calculating the optimal output for each unit under a fixed total water consumption, thus enhancing the efficiency of hydropower generation. The second tier consists of the short- to medium-term scheduling module, which is tasked with dynamically optimizing the hourly power output for the Aswan High Dam and the Aswan No. 1 and No. 2 hydropower stations over a one-month period. This module is designed to maximize energy utilization efficiency—assessed by savings in fuel costs for thermal power plants—while satisfying the irrigation water needs and operational constraints of the hydropower stations, considering both short- and medium-term aspects. The scheduling is conducted on an hourly basis, with a maximum planning period of 30 days. The third is the long-term scheduling module, which aims to (1) quantify the trade-offs between the operations of the Aswan High Dam and the Aswan Low Dam, and (2) determine the long-term outflow sequence to meet the selected scheduling objectives. To meet the needs of two potential user groups—the water irrigation department and the power generation department—this module offers a selectable timescale of weeks, ten-day periods, or months.

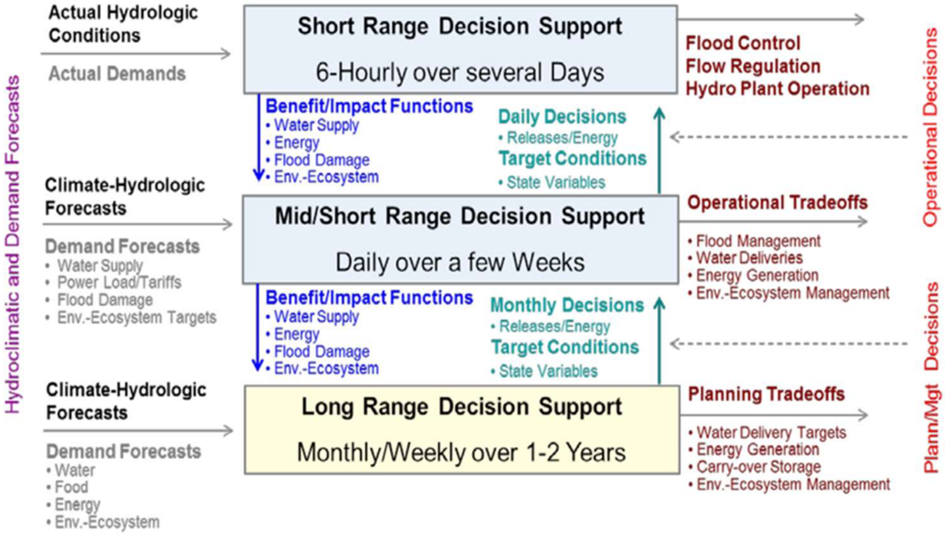


Figure 4-17 Optimal operation of Aswan high/low dam

A multi-tiered DSS is composed of various modules, and the system operation process is divided into two directions: Firstly, in an upward direction, the lower-level modules are activated to generate information on objective functions and operational boundaries for the upper-layer modules. Then, calculations are performed by the upper-layer modules to weigh long-term multiple objectives and evaluate the effects of different operational strategies. After that, the model ceases running, prompting the management department to input their most preferred scheduling strategy. Subsequently, the lower control layers are reactivated in a downward sequence to generate the optimal hourly output sequence and load distribution, ensuring consistent implementation of the scheduling decision across all relevant time scales.

After the implementation of the HAD-DSS, the annual hydropower generation benefits of the Aswan Reservoir increased by 5%, and the water supply guarantee rate achieved 100%.

In the ACF Basin in the southeastern United States, there are four cascade reservoirs that initially utilized their own software named HEC ResSim. However, the ResSim software was unable to account for ecological and environmental constraints and lacked a module for the optimized joint scheduling of the reservoir system. Consequently, the scheduling result did not satisfy the CUBWR requirements, leading to recurrent complaints from river keeper associations and other organizations. To address this, the scheduling department decided to run GTDSS and ResSim concurrently, leveraging the strengths of both systems for a comparative joint scheduling. Testing revealed that the scheduling schemes generated by the GTDSS optimization engine held significant advantages. By fully leveraging forecast information and continuously updating in real time, GTDSS could operate at high water levels during the wet season, completely avoiding water waste, and thus enhancing benefits. As a result, the ACF scheduling center discarded the original scheduling method, which primarily relied on scheduling charts, in favor of an adaptive approach that integrates forecasting with optimized decision-making. This shift had a profound impact on the industry.

The Sacramento Basin in California initially utilized a management system called CalSim, developed by the Berkeley Research and Education Center. This system was limited to medium-to-long-term planning and comparative analysis of schemes, lacking capabilities for short-term and real-time scheduling. The California basin management agency then developed a DSS known as INFORM DSS, leveraging GTDSS technology. This system encompasses forecasting and scheduling models for short-, medium-, and long-term applications. It manages four reservoirs in Northern California and the North-to-South Water Transfer System, with objectives such as power generation, flood control, water supply, and seawater intrusion control. INFORM DSS has resolved conflicts between long- and medium-term water supply and power generation, enhancing power generation benefits. Encouraged by the successful initial application, the California Energy Commission and the Department of Water Resources decided to expand the use of INFORM DSS to other basins. Currently, the project is undergoing its fourth phase of implementation.

4.2.5.2. WRMDSS in the lower reaches of the Jinsha River and the Three Gorges cascade reservoirs

The lower reaches of the Jinsha River and the Three Gorges cascade reservoirs are the largest of its kind in the Yangzi River Basin in China. It leads the world in both installed capacity and annual power generation within the hydropower sector. This system plays a crucial role in flood control, power generation, navigation, sediment management, and ecological preservation, making it the core project for the development and management of the Yangtze River.

To allocate the water resources of the lower reaches of the Jinsha River and the Three Gorges cascade reservoirs, and to efficiently utilize the upstream water resources of the Yangtze River, China has developed a DSS for CUWR (WRMDSS for the lower reaches of the Jinsha River and the Three Gorges cascade reservoirs, as depicted in Figure 4-18). This system integrates technologies such as data mining, hydrodynamics, and optimized scheduling models. It offers a range of functionalities, including: 1) Scheduling simulations for the 29 controlling reservoirs in the upper reaches of the Yangtze River; 2) Simulation and calculation of flood processes across the 1,800 km ultra-long section from Guanyinyan to Zhicheng, which includes the main and tributary streams; 3) Long-, medium-, and short-term optimized joint scheduling for the six cascade reservoir systems under the management of China Three Gorges Corporation; 4) Quantitative comprehensive evaluation of the forecasting and scheduling benefits. The system integrates information querying, simulation computation, scheme formulation, decision support, and panoramic display into a single platform. This integration optimizes the workflow of water resource scheduling management, leading to efficient and coordinated management of the cascade hydropower station.

Figure 4-18 Decision support system (DSS)

(1) River channel simulation modeling

Functions of the river channel simulation module: It cleans and organizes the shared data from the upstream reservoir system, carries out intelligent simulation of the scheduling for the upstream reservoir system (23 reservoirs), and analyzes and predicts the most probable storage and discharge scenarios of the upstream hydropower stations. This is achieved even in the context of insufficient sharing of existing forecasting and scheduling schemes among the cascade reservoir systems. The module provides valuable references for the downstream power stations' scheduling and operational decisions, as illustrated in Figure 4-19.

Technical methods for the river channel simulation module:

(1) An innovative analog simulation calculation model for the upstream reservoir system has been developed. This model leverages data mining and scheduling pattern control to explore the scheduling and operation laws of upstream power stations, enhancing the simulation calculations for long-, medium-, and short-term scheduling. By analyzing and processing the operational data of the reservoir system, various methods, including deep neural networks, are utilized to construct a model for extracting scheduling rules. This effort culminates in the establishment of a scheduling rule database for the reservoir system in the upper reaches of the Yangtze River. Building on these research findings, a simulation scheduling model for the reservoir system in the upper reaches of the Yangtze River has been successfully developed. It simulates the discharge flow process of the upstream reservoirs over a certain period, providing accurate boundary inputs and foundational data support. This contributes to the scientific and rational formulation of scheduling schemes for the lower reaches of the Jinsha River and the Three Gorges cascade reservoirs.

(2) A one-dimensional hydrodynamic model has been established for the main and tributary streams across the 1,000 km ultra-long river section in the lower reaches, from Guanyinyan Reservoir to Gezhouba Reservoir. This model has, for the first time, enabled real-time simulation and calculation of the flood process for the entire river section of the lower reaches of the Jinsha River and the Three Gorges cascade reservoirs. To tackle the issue of low computational efficiency in existing hydrodynamic models, the conservative Euler-Lagrange Equation is used to derive the discrete equation for the unsteady propagation of interval flows, delineating the movement trajectory of river flow along the channel. Simulation results show that the average water level error is less than 20 cm. This advancement has effectively addressed several challenges, including the inaccurate depiction of hydrodynamic processes

in the reservoir area, the imprecise simulation of water surface lines, and difficulties in synchronous forecasting. Consequently, it provides robust support for flood control and regulation within the basin.

(3) Utilizing the established hydrodynamic model, research has been conducted on the characteristics of water flow variation at the dam-site river section under complex conditions, where the reservoir outflow consists of both measured runoff and natural runoff. This research clarifies the mechanism by which the establishment and operation of the upstream reservoir system influence the downstream reservoirs and river flow conditions. It determines the time required for flood waves of varying magnitudes to propagate under different water levels behind the dam. By integrating the one-dimensional hydrodynamic model into the system, an independently encapsulated simulation module has been created. This module is capable of driving forecasting, scheduling, and other models in real time.

(4) For the first time, a spatiotemporal loose coupling between reservoir simulation and river channel simulation has been realized, offering accurate and efficient technological support for river channel simulation in reservoir scheduling. Utilizing virtual globe web technology, it can display the water level/flow process for any cross-section/river section at any given moment or period during the simulation period, either statically or dynamically. This approach achieves a multi-dimensional, comprehensive, and intuitive presentation of the river channel simulation results. Furthermore, by using GIS base maps and remote sensing images, any simulated flood process can be compared with the actual inundation lines. This comparison enables the real-time dynamic display of the water surface inundation process within a 100 km river section at the reservoir's tail end, at any moment during the simulation period.

(1) Selection of upstream reservoirs of Yangtze Rive Basin

(2) Simulation of scheduling process

Figure 4-19 River channel simulation modeling

(2) Optimized scheduling

Functions of the optimized scheduling module: The primary objective is to ensure the rational operation and scheduling of cascade hydropower stations. A practical calculation function for the optimized joint scheduling of cascade reservoirs has been developed based on actual operational requirements and constraints. The solving process of the optimized scheduling model integrates various optimization algorithms, including the Progressive Optimization Algorithm (POA) coupled with the Dynamic Programming with Successive Approximation (DPSA) method, and Mixed Integer Programming (MIP) integrated with POA. The medium- and long-term optimized scheduling model can set objectives such as maximizing power generation， maximizing the power generation benefits, and minimizing water discharge. It formulates the optimal operation and scheduling schemes for power stations for the next year, ten days, or week, considering constraints such as unit operating conditions, transmission line outputs, maintenance schedules, and power market demands. The short-term optimized scheduling model uses the results of the medium- and long-term model as boundary conditions for optimization calculations, thereby formulating the optimal power generation plan for shorter periods (1 day, 3 days, 7 days). The in-plant economic operation model can automatically suggest the optimal number of units to operate, their combinations and start-stop sequence, optimal load distribution, and the establishment and execution of the optimal operational mode within the station. Based on the optimized scheduling model, the system has achieved the capability to develop corresponding scheduling strategies for different periods, such as the pre-flood falling stage, flood season, storage period, and full storage operating period. This is accomplished by considering boundary conditions like power market supply and demand, forecasted electricity prices, and signed contracts, as demonstrated in Figures 4-20 to 4-22.

Technical methods for the optimized scheduling module:

(1) The coupling and nesting integration of scheduling models across various scales for cascade hydropower stations have been analyzed. This analysis enables the creation of a long-, medium-, and short-term optimized scheduling model that operates on a hierarchical feedback mode. The model integrates optimized scheduling models of differing scales into a cohesive system, based on the interrelated water level constraints. It capitalizes on the most recent water level and runoff forecasts to compute optimized scheduling results that are more closely aligned with actual operating conditions. This process offers vital guidance for formulating plans for the remaining operational periods.

(2) Utilizing the three basic control modes—water level, water flow, and power output—a conventional scheduling model library has been established that integrates multiple control modes, including water level-output and water flow output. Various output calculation models and methods have been developed, such as the "variable K-value" and "water consumption rate," which account for the station water head effect. This development facilitates the optimized scheduling calculations across different control models and time scales, providing accurate output calculation methods essential for the creation and execution of actual power station output plans.

(3) An innovative, optimized joint scheduling model for cascade reservoirs has been established, aiming to maximize the cascade's power generation or minimize the discharged water . This model integrates the storage capacity allocation needs of cascade hydropower stations, incorporating these requirements as constraints within the optimization model. It aims to satisfy regional and overall flood control requirements while ensuring maximum cascade power generation or minimal water discharge. Considering the backwater effect of downstream reservoirs on those upstream reservoirs and the minimum discharge constraints of downstream reservoirs, the model employs the penalty function method during the initial solution process. This approach establishes a cascade linkage mechanism for determining the initial scheduling line of the cascade reservoirs. By fully leveraging the regulation capacity of the cascade hydropower reservoir system, the model achieves a more optimized initial scheduling line for the cascade hydropower reservoirs.

(4) An optimized scheduling model and a software module for cascade reservoir system, based on the initial solution, have been developed. The optimized solving process of the model is more flexible. It includes the establishment of a day-end water level optimization and peak regulation model specifically for short-term optimized scheduling and a hierarchical solving method . The short-term optimized scheduling can be coupled with in-plant economic operations, enabling the achievement of optimized reservoir water levels for cascade hydropower stations without considering peak regulation factors.

Figure 4-20 Optimized scheduling scheme set

Figure 4-21 Display of optimized scheduling results

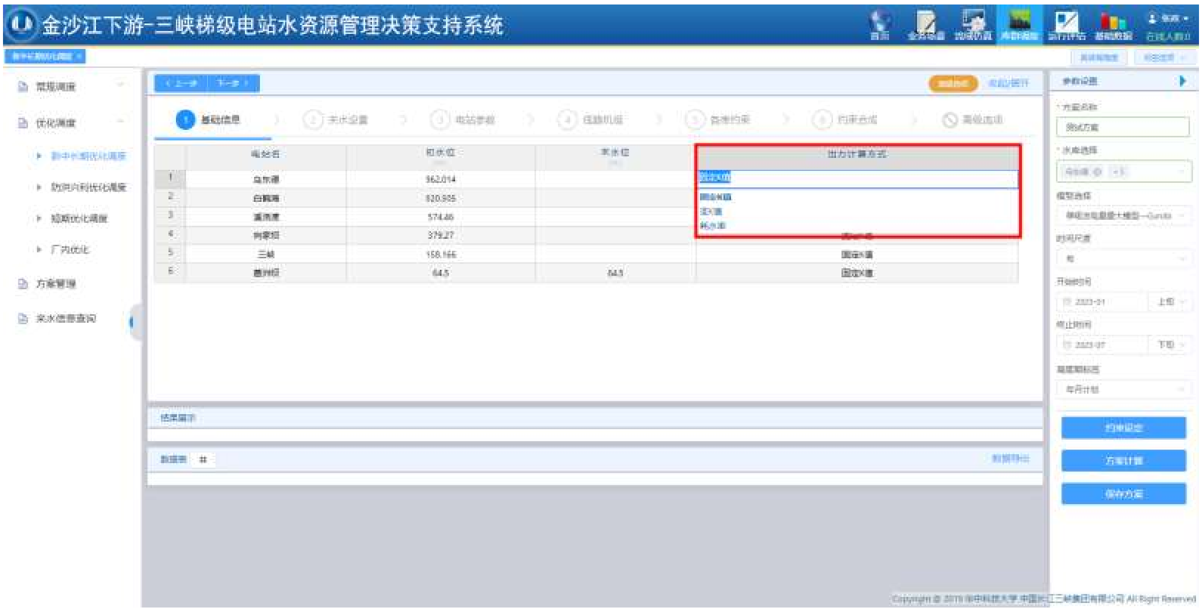


Figure 4-22 Modification of the output calculation method

(3) Scheme evaluation

Functions of the scheme evaluation module: The system employs mathematical statistical methods to quantitatively delineate the patterns of forecast errors across various forecast periods, yielding runoff ensemble forecasting results. This approach offers an intuitive representation of the probability intervals for runoff forecasts, serving as a reference for hydrological forecasting and reservoir scheduling. An evaluation indicator system for optimization schemes has been established within the system, capable of reflecting the extent of comprehensive scheduling benefits for the cascade reservoir system. It facilitates the swift evaluation of long-, medium-, and short-term scheduling schemes. Leveraging functions such as scheduling computation and operational evaluation, the system can quantitatively evaluate the impacts of human and natural factors during the scheduling process. It analyzes the relative contribution rates of each power station in joint scheduling and evaluates the effects of changes in basin structure, modifications in scheduling rules (such as flood control limit water levels and power market dynamics), and shifts in comprehensive utilization demands (including flood control, power generation, irrigation, water supply/transfer, and environmental considerations) on scheduling and operations, as depicted in Figure 4-23.

Figure 4-23 Evaluation of runoff forecasting

Technical methods for the scheme evaluation module:

(1) The accuracy of various forecasting results is appraised utilizing historical long-series runoff data. The mathematical statistics method is used to quantitatively describe the uncertainties in the hydrological forecasting process. Concurrently, ensemble forecasting results are derived from actual forecasting data, supplying more accurate hydrological forecasts for the scientific scheduling and operation of the cascade reservoir system. Evaluation indicators and criteria, including absolute error, relative error, and certainty coefficient, are utilized to quantitatively and qualitatively evaluate the accuracy of different forecasting models, thereby ascertaining the forecast scheme's suitability for application.

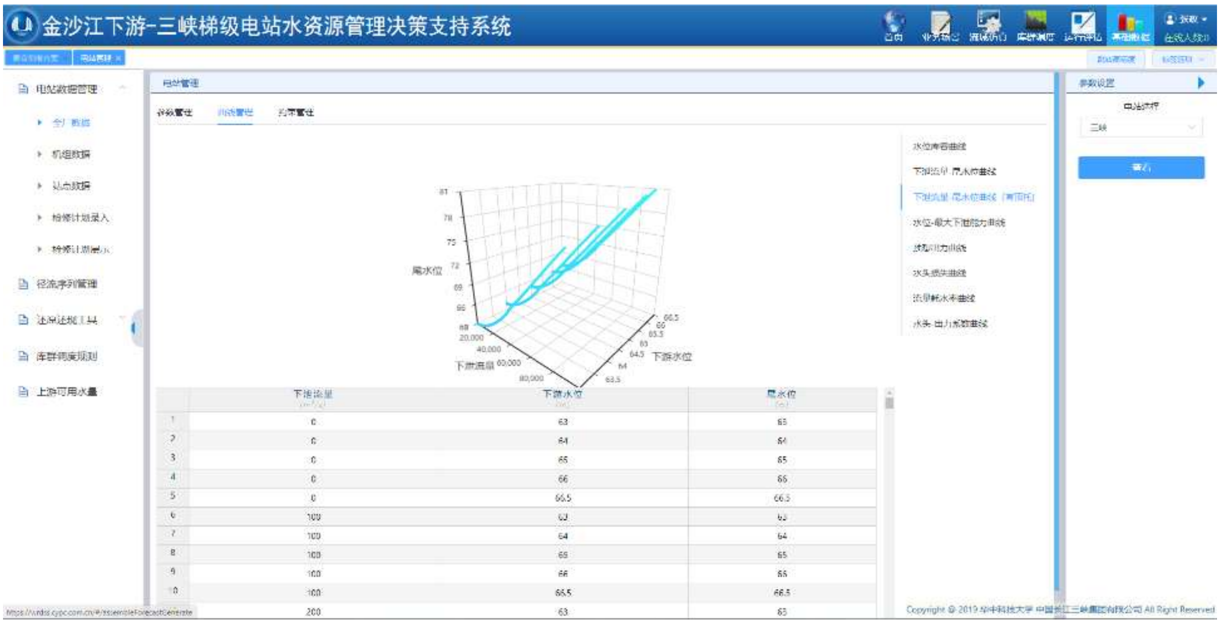
(2) The evaluation results of various forecasting schemes are analyzed, employing mathematical statistical techniques to generate ensemble forecasting results. These results are then appraised to ascertain the confidence levels associated with individual forecasts as well as ensemble forecasts. Drawing on multiple decision-making levels and expert opinions, an optimized operation strategy evaluation indicator set has been formulated. This set includes indicators such as water utilization rate and ecological assurance rate, facilitating a scientific assessment and evaluation of the devised scheduling schemes. Subsequently, techniques like linear weighting, grey relational analysis, and fuzzy optimization are deployed to evaluate the ensemble of scheduling schemes. A recommended sequence of schemes is presented in alignment with the predefined objectives, offering a basis for the refinement and improvement of the scheduling model.

(3) Indicators such as the contribution to benefits by scheduling personnel, the potential for scheduling improvements, and generation capacity are utilized to assess the influence of human factors on enhancing the power generation benefits of the reservoir system, with the goal of optimizing these benefits. The contribution coefficient method, based on compensation electricity contribution values, is used to distribute the compensation benefits among cascade reservoirs. This method also evaluates the relative contribution rate of each power station to the overall generation of the cascade reservoir system.

(4) Display and analysis

The system includes a total of six primary interfaces: Home, Business Scenarios, Basin Simulation, Reservoir System Scheduling, Operation Evaluation, and Basic Data. The Basin

Simulation, Reservoir System Scheduling, and Operation Evaluation modules are the integration and expansion of research findings from analog simulation of reservoirs and river channels, optimization of cascade reservoir system scheduling, and forecasting and scheduling operation evaluation, respectively. These modules are tailored for professional technicians. The Business Scenarios module is a specially developed functional module for core operations such as pre-flood falling time period scheduling, storage period scheduling, and flood event scheduling, designed for decision-makers. The Basic Data module comprises power station data management, unit data management, restoration and visualization tools, runoff series management, and management of reservoir system scheduling rules. Additionally, the system features multiple visual display pages created for comparing key scheduling information and schemes. It is capable of displaying the flood propagation process along the Yangtze River's main channel and the dynamic retention processes of the six cascade reservoirs. It can analyze and display the inundation conditions at the tail of reservoir during flood events. The system facilitates the analysis and display of annual scheduling, proposes optimized scheduling strategies, explores generation potentials, and guides the scheduling and operation of cascade hydropower stations, as depicted in Figure 4-24



	下泄流量	下游水位	尾水位
1	0	63	65
2	0	64	64
3	0	65	65
4	0	66	66
5	0	66.5	66.5
6	100	63	63
7	100	64	64
8	100	65	65
9	100	66	66
10	100	66.5	66.5
	200	63	63

Figure 4-24 Display of basic data

4.3 Conclusions and prospects

This chapter first introduces the definition and background of water resources decision support system (WRDSS), followed by an in-depth look at its concrete applications within the realm of water resource scheduling. It then proceeds to review the development experiences of various WRDSS globally, identifying their current shortcomings, needs, and urgent issues in light of new circumstances. The chapter summarizes several key technologies that are integral to the construction of WRDSS. These include scheduling models, information collection and storage, system architecture, visualization techniques, and system integration methodologies. Furthermore, it examines the comprehensive application of WRDSS in resource allocation and regulation. This is illustrated through practical cases, such as the decision support software system from Georgia Tech and the DSS designed for the lower reaches of the Jinsha River and the Three Gorges cascade reservoirs. The main conclusions drawn in this chapter are as follows:

(1) With the continuous improvement in international water resources development and utilization levels, the WRDSS has been progressively integrated into water resource scheduling and operational management. The robust capabilities of these systems have significantly improved the utilization efficiency and allocation accuracy of water resources.

(2) The architecture and integration methods of WRDSS have transitioned from diverse forms to a more streamlined and cohesive approach. Initially, the system was primarily designed for single-objective scheduling, but it has now evolved to address more complex needs. Today, the DSS has advanced into a multi-objective, comprehensive system. It considers a range of factors including flood control, power generation, navigation, ecology, and overall water resource utilization, thereby aiding in the improved efficiency of multi-objective CUBWR.

(3) With the rapid development of technology and computer science, the DSS for CUWR has achieved significant progress and improvement in key supporting technologies. This includes advancements in water resource information collection, system architecture, system visualization, and system integration.

(4) The WRDSS has become an indispensable and important tool for guiding the daily operations of cascade reservoir systems across various basins globally. It offers practical and viable scheduling decision solutions for CUBWR. The WRDSS plays a crucial role in achieving optimized scheduling of cascade reservoirs and improving the economic and societal benefits of reservoir systems.

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