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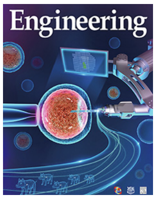

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Theory and Practice of Hydrodynamic Reconstruction in Plain River Networks

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ABSTRACT

The river networks in the plains of China are in low-lying terrain with mild bed slopes and weak hydrodynamics conditions. Filled with intense human activities, these areas are characterized by serious water security problems, for example, frequent floods, poor water self-purification capabilities, and fragile water ecosystems. In this paper, it's found that all these problems are related to hydrodynamics, and the spatiotemporal imbalance of river network hydrodynamics is identified as the common cause of these water-related problems. From this, a theory for the hydrodynamic reconstruction of plain river networks is proposed. In addition to the importance of the flow volume, this theory highlights the role of hydrodynamics and limited energy in improving the ecological water environment. The layout of water conservancy project systems (e.g., sluices and pumping stations) is optimized to fully tapping the potential integrative benefit of projects. The optimal temporal and spatial distributions of hydrodynamic patterns are reconstructed in order to meet the needs of the integrated management of complex water-related problems in river networks. On this basis, a complete theoretical method and technical system for multiscale hydrodynamic reconstruction and multi-objective hydraulic regulation in plain river networks with weak hydrodynamics is established. The principles of the integrated management of water problems in river network areas are put forward. The practical application and efficacy of the theory are demonstrated through a case study aiming to improve the water quality of the river network in the main urban area of Yangzhou City.

1. Introduction

The plains of river networks are densely populated and economically developed; therefore, water security problems in river network areas are important. Affected by typhoons, rainstorms, floods, and storm surges, these areas are subject to frequent disasters. Given today's rapid economic development and urbanization, the adverse impacts of human activities are increasing. The plain river networks have various emerging problems, such as an imbalance of water supply and demand, deterioration of the water environment, and degradation of water ecology. Disasters related to water resources, the water environment, water ecology, and other water problems coexist and are intertwined, making it difficult to manage and attain sustainable development of the social economy in these regions. The water governance concept of "prioritizing water conservation, balancing spatial distribution, using a systematic approach, and allowing full play to the roles of both the government and the market" imposes higher standards for the environmental protection of water ecology and for river basin/regional multi-target system governance. It is difficult to manage water-related problems in plains solely based on conventional water resource allocation theory.

Large river basins around the world usually suffer from water security issues. For example, due to intensive river improvement projects in the Mississippi River Basin in the United States, a large amount of sediment has been intercepted, the water and sediment balance of the downstream rivers has been disrupted, estuary and coastal wetlands have been eroded, and the ecology of the estuary has been destroyed despite better flood protection [1–3]. For the Rhine Basin in Europe, the Netherlands and neighboring countries have implemented a flood prevention plan called "Room for the River," which eventually reduced flood occurrences. Since the Industrial Revolution, the rivers in the Rhine Basin have become

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increasingly polluted. Although centralized treatment has been conducted for nearly 70 years, the river sediment still contains a large amount of pollutants. Flooding in the river basin causes sediment erosion and resuspension, and thus introduces the risk of water pollution. The relevant countries are still trying to explore how to achieve comprehensive management of flooding and preservation of the ecological water environment [1,3]. At the beginning of this century, the European Union issued the Water Framework Directive [4] to guide the comprehensive management of river basin water problems. China has also progressed from the initial stage of flood control to the current stage of comprehensive management of river basins. The Water Law of the People's Republic of China which was revised in 2002, clarifies that river basins are the basic unit of water resource management. However, at present, there is still no complete theory or technique for the integrated management of water problems. Additional research on theory, techniques, and systems is needed to balance both the quantity and quality of water resources [5].

A plain river network area generally has weak hydrodynamics due to its gentle terrain and mild bottom slope. Anthropogenic disturbances, such as dense engineering projects that disrupt the connection of the water systems, result in flow retardation and weakening. However, the complex water-related problems that occur in a plain river network area are closely related to its hydrodynamic characteristics. For example, the low flow rate of the water body in such areas—which is usually accompanied by poor re-oxygenation capacity and poor self-purification ability—causes the deterioration of the water body; that is, the water easily becomes black and odorous.

Studies have shown that a low dissolved oxygen content of river water directly affects the degradation rate of organic pollutants by microorganisms [6]. When the dissolved oxygen concentration is less than 2.0 $\mathrm{mg{\cdot}L^{-1}}$, the degradation of pollutants may also produce toxic substances and harmful gases (e.g., methane and hydrogen sulfide), causing the water body to turn black and odorous. When the dissolved oxygen concentration exceeds 7.5 $\mathrm{mg{\cdot}L^{-1}}$, the water quality is considered to be good. Flow conveyance is an important factor that influences the dissolved oxygen content of a water body, and improvements in the hydrodynamics of a river network can enhance the re-oxygenation process [7]. Moreover, increases in the water flow rate improve the river's ability to purify carbon, nitrogen, and phosphorus pollutants to a certain extent, especially in terms of lowering the biochemical oxygen demand (BOD) [8]. Proper flow of a water body enhances the water's turbulence intensity, promotes diffusion of pollutants, and helps pollutants to be completely degraded by microorganisms faster, thus reducing the pollution concentration of the water body.

Flow velocity, water depth, and turbulence characteristics are also important parameters that affect the water ecology. The flow velocity can affect the physiological and ecological behaviors of aquatic organisms, such as fish and benthic animals [9–12]. Increasing the flow velocity within a certain range can restrain the growth of algae [13]. For the precise allocation of water resources, it is unscientific to implement traditional water scheduling ideas (e.g., diluting a polluted water body with clean water) without considering the important role of hydrodynamics in improving the ecological environment. Doing so does not conform to the idea of "prioritizing water conservation" in the new water management era. All of these adverse water problems are closely related to temporal and spatial imbalances of the hydrodynamics, which can be improved by the setting up of sluices, pumping stations, dams, spurs, and other water conservancy devices. These in turn result in suitable spatiotemporal distribution of hydrodynamics that are conducive to solving these water problems.

At present, a large number of sluices and pumping stations have been built in plains, forming a relatively complete water conservancy system. This provides the necessary means for controlling and enhancing the regional hydrodynamic field. The conventional water resource allocation theory and method involve the use of sluices, dams, pumps, and other appurtenances to allocate water. However, the application of these devices is usually focused on a singular objective, while secondary disasters may still occur. There are several theoretical and technical challenges in the reconstruction of favorable hydrodynamics in plain river networks. First, a flat terrain does not have the conditions necessary for the construction of large-scale water conservancy projects. Hence, a large number of small-scale projects, such as sluices and pumping stations, are usually built. Second, these plains are usually crisscrossed by rivers, and the internal water flow is disordered and complex. It is difficult to determine an appropriate hydrodynamic field for the entire large water body. Furthermore, the boundaries are complicated, and these areas are usually close to large rivers and oceans. The internal and external hydrodynamic forces interfere with each other, forming unfavorable combinations that increase the magnitude of the risks involved. Finally, problems coexist and the hydrodynamic requirements for solving different water problems are not completely exclusive and consistent. In this study, a complete theory and techniques for hydrodynamic reconstruction are presented. These are based on years of research and engineering practices related to water problem management in plains. A theory for hydrodynamic reconstruction in plain river network areas through the joint management of sluices, pumps and other water conservancy projects is proposed. The ensuing results provide theoretical and technical support for the comprehensive management of many water problems in plain river network areas.

Hydrodynamic reconstruction of a plain river network area refers to store and increase the limited water flow energy in the river network area (supplemented by sluices, pumping stations, dredging, flood storage and detention areas, and other projects) in order to regenerate the desired temporal and spatial distribution of hydrodynamic forces. In addition to the importance of the flow volume, this theory emphasizes the important role of hydrodynamics in protecting the water environment and ecology. The layout of water conservancy project systems is optimized to fully tapping the potential integrative benefit of projects. Fig. 1 shows the framework, which presents the multiscale hydrodynamic reconstruction theoretical method, the engineering technology system, and the multi-objective hydraulic regulation technology. Taking the principles of controlling energy dissipation and efficiently utilizing natural hydrodynamics as the core ideas, the engineering technology system is intended to optimize the river confluence dynamics to minimize blocking, smooth the flows near the combined sluice–pump station, prevent erosion and siltation of the riverbed, and solve other issues encountered in hydrodynamic reconstruction projects. Five previously developed technologies are used in the proposed framework: flow power reconstruction technology for channel confluences [14], rectification and energy dissipation technology for combined sluice–pump stations, anti-scouring technology for a tetrahedral permeable frame group [15], energy-saving and anti-siltation technology for coastal tidal sluices, and a new type of sluice that can intake channel water without sediments [16].

2. Theoretical method for multiscale hydrodynamic reconstruction in plain river networks

The dynamic mechanism of a river network is complex due to the river network's unique hydro-geomorphology, intense human activities, and multiscale spatiotemporal processes. In order to reconstruct the hydrodynamic field in a plain river network area

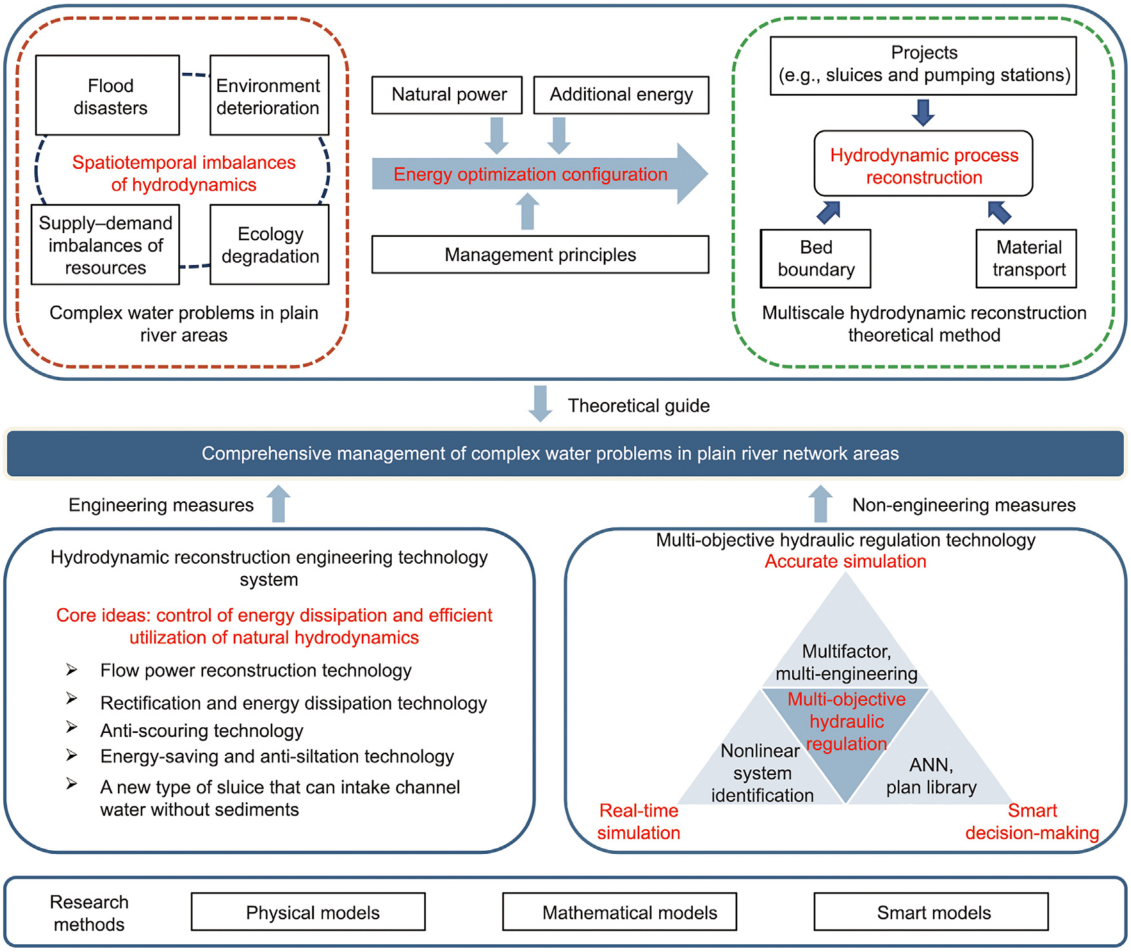

Fig. 1. Theoretical framework for the hydrodynamic reconstruction of a plain river network area. ANN: artificial neural network.

with weak hydrodynamics and to meet multi-objective management requirements, it is necessary to understand the complex dynamic processes involved. Sediment particles in plain rivers are fine and have unique physical–chemical properties; therefore, it is necessary to pay attention to both the dynamic processes and the eco-environmental responses at the microscopic level. Moreover, each river network has characteristic bed forms (e.g., sand waves and vegetation) and complex river morphologies (e.g., compound channels and river confluences), so its water–sediment movement and associated material transport processes are unique. Furthermore, the extensive dispatching and operations of sluices, pumping stations, and other activities make these processes even more complex. It is necessary to understand the interaction between water, sediment, and pollutants at the microscopic level, which will help in determining the influence of the characteristic bed forms, river morphology, and hydraulic devices on coupled transport processes involving water, sediment, and pollutants at the macroscopic level (Fig. 2). Here, the key is to establish quantitative relationships between energy allocation and water management objectives in order to achieve water security. The three relationships between the hydrodynamics and the material transport, bed boundaries, and hydraulic project regulation, respectively, are the crux of the multiscale hydrodynamic reconstruction theoretical method for plain river network areas.

2.1. Relationship between hydrodynamics and material transport

The sediment particles in plain rivers are fine and experience strong adsorption/desorption of pollutants. The coupled water–sediment–pollutant transport process plays an important role in changing the water environment of a plain river network. Under weak hydrodynamic conditions, suspended sediment is prone to adsorbing dissolved pollutants, which reduces the concentration of pollutants in the water. On the other hand, under strong hydrodynamic conditions, the pollutants in the bed sediments are prone to desorption (Fig. 2(c)). The sediment adsorbing pollutants undergoes resuspension, which can cause secondary pollution downstream. Therefore, it is necessary to construct a conducive hydrodynamic field during flow regulation in order to ensure that the sediment plays its desired environmental role. This measure can conserve water resources and flow energy to a certain extent.

At the particle scale, the adsorption or desorption of phosphorus and other major pollutants by the sediments in a plain river network is affected by various factors such as water flow movement, the dissolved phosphorus concentration, sediment grain size, organic matter and iron–aluminum oxides, and cation exchange capacity [17,18]. Water flow causes the suspension and settling of sediment particles and the accompanying pollutant adsorption and desorption by sediments [19]. The higher the turbulence intensity of the water flow or the more the sediment resuspended from the riverbed, the larger the amount of pollutants released from the sediments [20]. At the riverbed interface scale, there are relatively strong flows in the hyporheic zone (i.e., the interaction zone between the surface water and groundwater), where material exchange between the surface water and groundwater is significant [21–23]. The hyporheic exchange has prolonged effects on pollutant transport resulting from the density

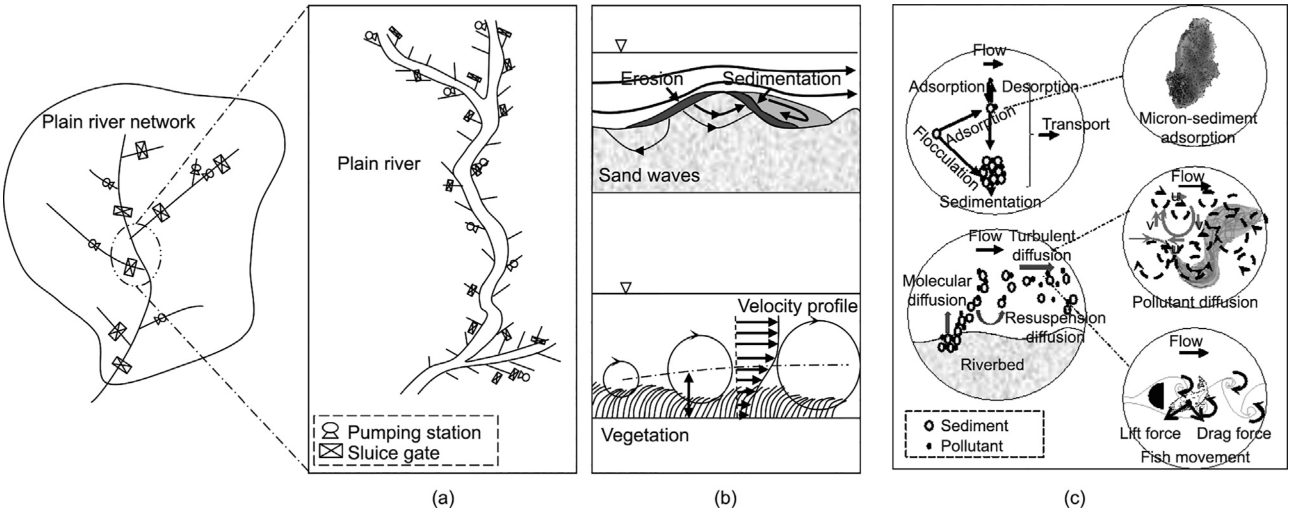

Fig. 2. Schematics of the coupling transport processes of hydrodynamics and material in plain river network areas with a fixed geometrical and topological structure at the (a) river channel scale, (b) riverbed interface scale, and (c) microscopic scale.

effects. The density gradients, due to variations of solute concentrations, can accelerate the exchange of pollutants into the hyporheic zone and decelerate the release of pollutants from the hyporheic zone into the surface water. Thus, the hyporheic exchange process is closely related to secondary pollution [24]. At the river channel scale, different river morphologies (e.g., river bends, river confluences/difluences, and compound rivers) have distinguishable material transport processes and environmental and ecological responses [25]. For example, the presence of secondary circulation and helical flow in bends can enhance the lateral sediment transport and the convection and diffusion of pollutants [26]. Moreover, certain special flow structures (e.g., spiral flow, shear vertical vortex, and backflow) near the channel confluence affect the material mixing and riverbed erosion processes [27]. For compound river channels, the riverbed pressure difference between the main channel and the floodplain can also induce hyporheic exchange. Steeper bank slopes result in greater hyporheic exchange. This process can reduce the downward transport rate of the solute in the riverbed and the total amount of net exchange [28]. Therefore, in order to determine the hydrodynamic field that can effectively and accurately accomplish the water management objectives, it is necessary to understand the interactions/coupling between the transport processes of water, sediment, and pollutants at all of these scales. Considering the effects of the sediment concentration, flow velocity, and pollutant adsorption/desorption capacity of the sediments, we propose a term reflecting the interaction between sediment and pollutants:

$$\begin{cases} F_C = k_\mathrm{a} \cdot C \cdot (A_\mathrm{m} - N) - k_\mathrm{d} \cdot N \\ k_\mathrm{a} = f\left(\dfrac{C}{C_0}, \dfrac{U}{u_*}, \dfrac{D_{50}}{H}\right) \\ \dfrac{k_\mathrm{a}}{k_\mathrm{d}} = g\left(\dfrac{C}{C_0}, \dfrac{U}{u_*}, \dfrac{S}{S_0}, \dfrac{D_{50}}{H}\right) \end{cases} \tag{1}$$

where F_C represents the source term of the pollutant adsorbed from the water onto the sediment surfaces; N is the mass of pollutant adsorbed per unit sediment; A_m is the maximum adsorption capacity of the sediments; k_a and k_d are the adsorption and desorption coefficients, respectively, with their values related to the concentration of dissolved pollutant C, flow velocity U, median sediment diameter D_{50}, and suspended sediment concentration S; C_0 is the initial concentration of the dissolved pollutant; u_* is the friction velocity; S_0 is the sediment transport capacity; H is the depth of the river channel; and $f(\cdot)$ and $g(\cdot)$ are the functions. Eq. (1) provides important theoretical support for the determination of the appropriate hydrodynamic thresholds in plain river networks.

2.2. Relationship between hydrodynamics and bed boundaries

In plains, the riverbed slope is mild and the hydrodynamics are weak, so the usage of water energy needs to be subtle. To achieve this goal, the key is to identify the process of water energy consumption in a river network. Vegetation and wavy sand bed forms are common in plain rivers (Fig. 2(b)). They consume flow energy by agitating the flow and strengthening turbulence. The traditional method of determining the resistance of the stream bed is purely based on experience; it is difficult to accurately determine the energy consumption by the flow due to vegetation and sand waves.

Vegetation on the bed disturbs the water body and induces many vortex structures, such as wake vortices within the canopy zone, turbulent bursting structures around the canopy, and Kelvin–Helmholtz (KH) vortices between the upper canopy zone and the free water surface [29–32]. The existence of a canopy shear layer tends to transfer a considerable amount of momentum from the free stream toward the canopy interior, which eventually promotes kinetic energy loss of the flow. The extent to which the vegetation affects the water flow depends on many factors, such as the relative degree of submergence, canopy density (i.e., solid volume fraction of stems), nonuniformity of spatial distributions, rigidity of the vegetation, and the flow Reynolds number [30,33,34]. Similarly, sand waves cause the separation of flow and a subsequent pressure difference between the stoss face and lee face, resulting in form resistances that consume the free stream energy [35,36]. The geometric forms of the sand waves (including shapes, length, and height) are critical in determining the form resistance [36]. The form of a sand wave is mainly related to parameters such as the particle Reynolds number, flow intensity, and Froude number [37–39]. A quantitative relationship has been established between the geometric eigenvalues of sand waves (wave length and wave height) and the particle Reynolds number [40,41]. The coherent structure of the turbulent flow near the sand dunes and its response to different bed morphologies have also been determined [40,41]. Given all this, we propose an equivalent roughness element theory, in which vegetation, sand waves, and other riverbed forms are equivalent to "additional particles"—that is, equivalent roughness elements. Assuming that the hydraulic slope after equivalence is unchanged, the calculation formula for equivalent comprehensive roughness is obtained by balancing the forces:

$$n_{\mathrm{e}} = \frac{1}{U}\left(\frac{B\alpha^{5/2}}{2\alpha + B/H}\right)^{2/3} i_{\mathrm{hg}}^{1/2} \tag{2}$$

where n_{e} is the equivalent comprehensive Manning roughness coefficient; i_{hg} is the hydraulic gradient; α is the porosity; and B is the width of the river channel. With this, the energy loss in a river channel containing vegetation and/or sand waves can be appropriately determined.

2.3. Relationship between hydrodynamics and hydraulic project regulation

There are usually a large number of water conservancy projects in plain river network areas, which use sluices, pumping stations, flood retention areas, and flood bypasses (Fig. 2(a)). These projects provide engineering measures for the allocation of water energy in river networks. However, the flow energy of a plain river network is limited. In order to adopt a system of hydraulic devices to allocate the energy well, the premise is to clarify the relationship between the hydrodynamics and the operation of a single project and to reduce the loss of flow energy. A combined sluice–pumping station—a common feature of projects in plain river networks—is considered as an example here. The outflows of the sluices and the pumps interfere with each other, and the resulting flow regime (e.g., unsmooth streamlines) reduces the discharge capacity of the sluices and affects the efficiency of the pumps. In order to mitigate the loss of energy, it is necessary to avoid the occurrence of local swirls and strong turbulent flow. In addition, retrofitting can be used to smooth the streamlines and improve the local flow regime of the project.

Plain rivers mostly have gentle slopes, and the influence of water conservancy projects on the hydrodynamics will be transmitted upstream and downstream [42]. Hydrodynamic interactions between these small, numerous, and dense water conservancy projects take place during the projects' joint operation; that is, the interaction between the hydrodynamics and multiple projects (i.e., the energy loss under the joint operation of multiple projects) is complex. There is a nonlinear relationship between the hydrodynamics and the operation of multiple projects. Hence, a superposition method cannot be used. Therefore, the first step is to clearly understand the response of the hydrodynamics to the project disturbances. Then, according to the degree of energy consumption and project effectiveness, a suitable and efficient project system can be selected from the large number of projects. Next, the flow system identification method (described in Section 3.2) is used to identify the response of the hydrodynamics to the prevailing regulations of the group of selected projects. In addition, the energy field is preferentially configured using these selected projects, supplemented by energy supply through pumping stations. The expression is as follows:

$$\begin{cases} W = \sum_{i,j}\left(P_{\mathrm{s}i} + \tilde{P}_{\mathrm{s}i}\right)\Delta t_{ij} + \sum_{i,j}\left(P_{\mathrm{p}i} + \tilde{P}_{\mathrm{p}i}\right)\Delta t_{ij} - E(\varphi) \\ W > W_{\min}(\varphi) \\ \sum_{i,j} P_{\mathrm{p}i}\Delta t_{ij} \to \min \end{cases} \tag{3}$$

where W is the kinetic energy of the river network flow; P_{s} is the power that converts potential energy into kinetic energy by sluices, P_{p} is the power that supplies kinetic energy by means of pumping stations, the subscript "i" represents the water conservancy project number, and the superscript "~" represents the influence of other engineering disturbances; Δt_{ij} is the operation time of each project, and the subscript "ij" represents the jth operation of the ith project; φ represents the flow characteristics (e.g., the flow velocity, water depth, and turbulence intensity), and $E(\varphi)$ is the energy loss of the river network flow under a constructed hydrodynamic field φ; and $W_{\min}(\varphi)$ is the minimum kinetic energy of the river network flow for constructing hydrodynamic field φ. The relationship between the hydrodynamics and the project regulation provides theoretical support for the optimal layout and joint operation of the projects in plains.

3. Multi-objective hydraulic regulation technology

Based on the existing water conservancy project system of a plain river network, the idea of hydrodynamic spatiotemporal reconstruction seems to be an important measure for solving complex water problems. However, multi-objective hydrodynamic reconstruction encounters two major challenges in practice. First, the demands of different goals on the hydrodynamics are not consistent and are often contradictory. Furthermore, it is difficult to obtain the dynamic and nonlinear relationships between the goals and the hydrodynamics. Moreover, the river network area has weak hydrodynamics and limited water energy, so optimization between the goals is important. Second, water problems in plain river networks are often subject to suddenness and unpredictability (e.g., sudden pollution incidents and typhoons). Therefore, the generation of simulation results and regulation schemes needs to be in real time.

Physical and numerical models are the most commonly used research techniques for river simulation and engineering management. However, the large-area, multiscale, multi-engineering, and multifactor characteristics and lack of measured data for a plain river network area pose huge challenges in the use of these traditional research methods. These challenges set higher requirements for the accuracy of the simulation technique, which has led to the development of emerging simulation methods (e.g., intelligent and hybrid models). When solving the practical problems of a plain river network, these research methods can be used independently or in combination, as needed. This paper uses a combination of numerical modeling and intelligent modeling as an example to introduce the use of multi-objective hydraulic regulation technology in a plain river network area.

3.1. Accurate simulation of material transport in a river network under the operation of numerous projects

Numerical modeling is an important approach for studying water and sediment transport and for the engineering management of rivers. A plain river network usually connects a large river, the sea, and lakes. The huge differences in the temporal and spatial scales of these bodies of water result in numerical models that have many advantages over physical models. However, the differences in the temporal and spatial scales and the disturbances caused by the operation of numerous projects increase the difficulty of accurate simulation through numerical modeling. Wang and Li [43] generalized the flow movement on different scales in plain river networks—that is, a zero-dimensional (0D) lake (or a flood storage area), one-dimensional (1D) river flow, and a two-dimensional (2D) flood discharge area—which as a whole can better simulate the flow movement in different areas. A large-scale, fully coupled, high-precision simulation of the river–lake–project flow fields in 2D and local 3D areas can be achieved through the nesting of sparse and dense meshes and the nesting of 2D and 3D calculation areas [44]. Using a combination of the methods mentioned in Section 2, including the determination of the resistance on the bed boundary and the mutual interaction between the water, sediment, and pollutants, we established a coupled water–sediment–pollutant transport numerical model. It provides effective technical support for basin/regional project planning and the achievement of the multi-objective functions of a single project. The equation of the coupled sediment–pollutant transport model is presented below:

$$\begin{cases} \frac{\partial N}{\partial t} + u\frac{\partial N}{\partial x} + v\frac{\partial N}{\partial y} + w\frac{\partial N}{\partial z} = \varepsilon_x\frac{\partial^2 N}{\partial x^2} + \varepsilon_y\frac{\partial^2 N}{\partial y^2} + \varepsilon_z\frac{\partial^2 N}{\partial z^2} + F_C \\ \frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \varepsilon_x\frac{\partial^2 C}{\partial x^2} + \varepsilon_y\frac{\partial^2 C}{\partial y^2} + \varepsilon_z\frac{\partial^2 C}{\partial z^2} - F_C \cdot S \end{cases} \tag{4}$$

where t is time; x, y, and z are the coordinates; u, v, and w are the 3D components of the flow velocity; and ε_x, ε_y, and ε_z are the turbulent diffusion coefficients; and $-F_c{\cdot}S$ is the source term of the dissolved pollutant in the water that is desorbed from the sediment surfaces.

The above 3D model can simulate local material transport processes near sluices and pumping stations. For specific river network conditions, it can be simplified into 1D or 2D numerical models. To simulate the transportation of degradable substances (e.g., ammonia nitrogen, chemical oxygen demand, and BOD), the relationships between the change in the dissolved oxygen content of the water, the hydrodynamics, and the degradation process of substances also need to be considered.

3.2. Intelligent quantification of parameters and real-time simulation of hydrodynamics in a river network

There are hundreds and thousands of channels in a large river network, and the river flow is highly complex. A numerical model of a river network must solve large sparse matrices. Thus, it takes a long time to generate alternative proposals for hydraulic regulation. Smart models use artificial intelligence technology to simulate the hydrodynamic processes of rivers and can give real-time predictions; they can even overcome the problem of paucity of data. For example, Ghalkhani et al. [45] applied a combination of an artificial neural network (ANN) and an adaptive neuro-fuzzy inference system to achieve the real-time simulation of flood routing in the upper reaches of a river basin. The datasets used for training were generated in advance using the rainfall–runoff and flood routing models. Chen et al. [46] established a hybrid model that combines the continuity equation and fuzzy pattern-recognition concept with an ANN to predict downstream river flow subject to reservoir scheduling.

In plain river network areas, when the regulation targets are significantly higher, the material transport process becomes more complicated. A smart model can achieve real-time simulation by means of a nonlinear system identification method. The key is to quickly identify complex nonlinear mechanisms involving the project regulations and hydrodynamics. A nonlinear system identification method refers to the identification of the best model—that is, the model that is closest to the actual measured water flow pattern. The mathematical form of the flow system identification can be written as follows:

$$\min J = J\Big(\| \operatorname{mod}(T, O, Q) - \operatorname{pho}(T, Q) \|_{\text{sys}}\Big) \tag{5}$$

where J is the criterion function for the evaluation of the flow system (sys) model; pho and mod are the prototype and model of sys, respectively; Q is the state set of sys; T is the condition set of sys; O is the model parameter set of sys; and $\| \cdot \|_{\text{sys}}$ represents a norm on the flow system.

Using a series of characteristics and capabilities of an ANN (e.g., nonlinear expression, self-learning, and generalization capability), supplemented with a large amount of data, a flow system model identification method can be established. This will quickly determine a model that is closest to the actual flow characteristics. The learning materials used for the network training are from observational data, physical model test data, or numerical simulation results. The trained model is used to identify the implicit nonlinear relationship between the flow data. A general intelligent quantification model of plain river network flow field parameters based on a genetic algorithm is established. The parameter set is operated by a selection operator, crossover operator, and mutation operator. The model determines the parameters of river network hydrodynamic simulations very quickly [47].

3.3. A smart decision-making method for multi-objective hydraulic regulation

3.3.1. Objective function

In plain river network areas, the potential energy and kinetic energy of the flow are small due to the gentle terrain and mild bed slopes. Besides the efficient use of natural energy such as tidal energy and hydrological rhythm, the flow energy is supplemented by external energy generated by the pumping stations. Large energy losses occur due to the bed forms, such as vegetation and sand waves. In regard to flow energy, understanding the mechanisms of river regulation (e.g., sluices, pumping stations, and dredging) is essential in order to optimize the utilization of the small amount of water energy in plains. The plain river energy equation is as follows:

$$\frac{\partial E_{\text{e}}}{\partial x} = \rho\frac{\partial U}{\partial t} + \frac{\partial E_{\text{p}}}{\partial x} - \frac{\partial E_{\text{f}}}{\partial x} \tag{6}$$

where E_{e} is the flow energy per unit water volume, including the potential energy (ρgh) and kinetic energy ($\rho U^2/2$), ρ is the water density, and h is the water level. The second term represents the additional kinetic energy of an unsteady process. E_{p} is the external energy input per unit water volume along the way, such as the energy provided by a pump; and E_{f} is the local (e.g., local head loss of water flowing through a sluice) and frictional (e.g., additional flow resistance due to vegetation, sand waves, and other bed forms) energy loss per unit water volume in the regulation process.

In many cases, conversion between kinetic energy and potential energy can produce desired economic, social, and eco-environmental benefits. For example, the use of sluices creates a water level difference, converts potential energy into kinetic energy, and reasonably distributes the temporal and spatial power changes to meet daily ecological flow needs. The optimal model function for the comprehensive treatment of complex water problems can be expressed as follows:

$$\begin{aligned} &\max\{M(\varphi), I(\varphi), L(\varphi), t\}, \varphi \in \Omega \\ &\qquad \text{st.} \quad G(\varphi) \le 0 \end{aligned} \tag{7}$$

where M, I, and L are the economic benefit function (e.g., irrigation benefit), social benefit function (e.g., regional flood control benefit), and ecological benefit function (e.g., biological adaptability), respectively; Ω is the feasible region; and G is a constraint set.

3.3.2. A smart decision-making method

A smart model can be integrated into the simulation–optimization model for the delicate multi-objective management of a river flow system. For example, Shokri et al. [48] integrated a multi-objective non-dominated sorting genetic algorithm, an adaptive learning ANN (NSGAII-ALANN) algorithm, and a water quality model. This combined model optimized the quantity–quality of the reservoir operation in the case of an emergent water pollution event. Skardi et al. [49] integrated a multi-objective non-dominated archiving ant colony optimization (NA-ACO) algorithm with a hydrological model to optimize the management of river basin pollution loading.

A plain river network generally has many devices, such as sluices and pumps. It is difficult to optimize and control a group of sluices and pumps to meet multi-objective requirements. A traditional sluice and pumping group regulation scheme is obtained through enumeration, comparison, and stepwise recursion. The scheme contains many subjective components, involves a large amount of manual participation, has a low degree of optimization and poor timeliness, and cannot realize automatic decision-making. Therefore, we construct a combination of a high-precision numerical model with artificial intelligence theory and a multi-objective smart decision-making method with intelligent characteristics for the hydraulic regulation of a plain river network (Fig. 3). The main ideas are as follows. First, the numerical model is used to simulate a number of hypothetical regulation schemes in order to generate a plan library. Second, the generated plan library data is applied to train the hydraulic regulation decision-making model based on an ANN. Third, according to the regulation objectives and real-time water quality data, a preliminary river network hydraulic regulation scheme is generated by the decision-making model. Fourth, the numerical model is used to predetermine the regulation scheme. If the objectives are met, this is taken as the final regulation scheme. Otherwise, manual and/or automatic adjustments of the regulation scheme will be required until the desired objectives are met. Fifth, the finalized regulation scheme can be added as a new plan to the existing plan library for training the hydraulic regulation decision-making model.

4. Principles of integrated management of water problems in plain river networks

Water problems in a river network area are complicated and intertwined, and the management objectives can also change with time and location. Thus, we propose a series of integrated management principles for complex water problems in plains.

4.1. Increase the hydraulic gradient to regularly improve flow conveyance

Low-lying terrain, gentle bed slopes, and oscillatory flow are the main causes of flooding and deterioration of water bodies in plains. During the flood season, sluices, pumping stations, overflow weirs, and other artificial structures can be used to increase the hydraulic gradient. This results in the fast passage of floodwater discharge, reducing the retention time of floodwater in low-lying areas and flood storage areas. In daily scheduling, enhancing the flow conveyance regularly as a directional flow can reduce the retention time of oscillatory polluted water. The provision of directional flow ensures good pollution-carrying capacity of the water body. In addition, sediment resuspension and the release of pollutants can be avoided.

4.2. Adjustment of flood control water level and resource utilization

Although the water problems mentioned earlier may not arise at the same time, they are interrelated and affect each other. For example, the extremely uneven distribution of the runoff throughout the year can lead to a large amount of water in the flood season, resulting in flood hazards, while the small amount of water in the dry season can lead to an imbalance in the supply and demand of water, causing insufficient ecological flow in the river. Through accurate prediction of flood processes, it is possible to achieve a reasonable balance between these two situations by limiting the flood water level/flow and storing the excess flood water at the end of the flood season for use during the dry season.

4.3. Daily flow regulation to prevent the co-occurrence of floods and pollution

In the dry season, sluices are often closed to store water. However, due to the influx of various point-source and non-point-source pollutants, stagnant water bodies have poor self-purification capabilities. Thus, the water quality deteriorates over time. During the flood season, when the sluices are opened, the flood discharge peaks and the water pollution may peak concurrently, which can cause the death of downstream aquatic organisms. By focusing on the environmental dispatch of sluice groups, it should be possible to construct a dynamic field that can ensure the self-purification of the water body.

4.4. Efficient use of tidal and other natural energy sources

Plain river network areas are often located near large rivers and the sea. The water levels of large rivers and the sea fluctuate greatly due to tidal interference. As a clean and environmentally friendly source of energy, tidal energy should be fully utilized for hydrodynamic reconstruction in plain river network areas. A group of sluices can be jointly controlled by opening sluices in the upper reaches during the flood tide and opening sluices in the lower reaches during the ebb tide. The tidal range can be used to create a hydraulic gradient and enhance the kinetic energy of the water body. In this way, the daily self-purification needs of the water body can be met.

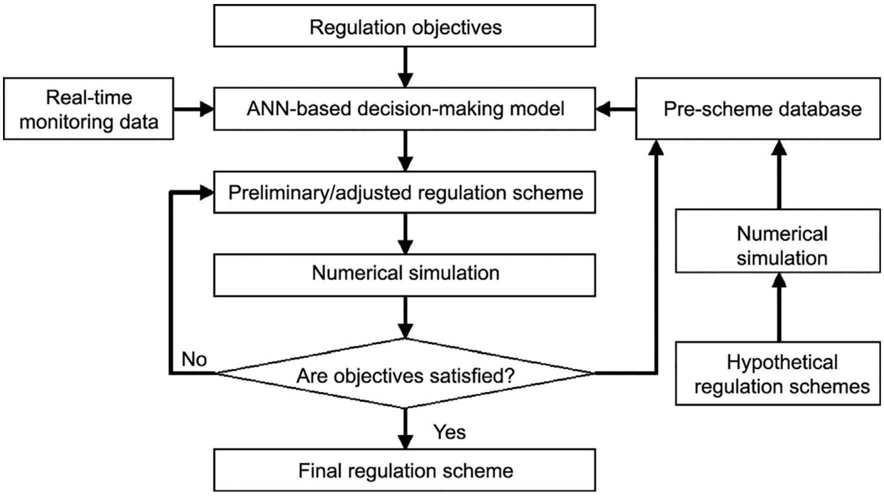

Fig. 3. Smart decision-making framework diagram of the multi-objective hydraulic regulation of a river network.

4.5. Optimal allocation of flow energy within a river network

The flow energy in the river network also needs to be optimized as a whole, following the reconstruction principles of flow loss suppression, flow threshold control, and targeted decision-making. The roughness of the river channel must be minimized to reduce energy loss. This helps to maintain the overall flow energy in a plain river, even with weak dynamics. The flow energy should be maintained within a reasonable range, as flow energy that is too high or too low is not conducive to flood control and ecological environmental protection. Finally, it is necessary to optimize the decision-making according to the multi-objective requirements and to construct the most suitable hydrodynamic field.

5. Practical application

5.1. Study area

Yangzhou City is located in an area where the Yangtze River and the Huai River converge. This typical plain river network area is formed by the crisscrossing of many other rivers and lakes. The western part of the city is hilly and mountainous with relatively higher terrain, while the eastern part is low-lying along the Yangtze River, Huai River, and Lixia River. More than 70% of the ground elevation is lower than the historical flood levels of the Yangtze River and the Huai River, resulting in a flood-prone area. Since the 1970s, in order to overcome the floods of the Huai River, 69 sluices and 64 pumping stations have been built in the main urban area (including the Guazhou and Yangzhou sluices), forming a closed and internally divided flood control and drainage system.

5.2. Problem statement

In recent years, with the rapid development of the social economy in Yangzhou City, the discharge of wastewater from industrial and domestic activities has increased many times over. The total phosphorus pollution, total nitrogen pollution, and levels of other organic pollutants have exceeded the specified standards. The water quality of the main urban area and the core scenic area of the Slender West Lake is mostly in Category V, which is the second lowest level according to China's water classification system, or sometimes worse; the water transparency is low, and some of the river sections are black and odorous. As a result, the area is facing severe water problems (e.g., flood security problems, water supply issues, a need for improvement of the scenic water environment, and a need for aquatic ecosystem protection), which require a comprehensive management strategy. To enhance the supply of water to the Slender West Lake system and the western water system, Yangzhou City has successively built two water supply routes (i.e., pipelines and river courses) into the lake. The system in the urban area forms drainage lines with the surrounding Beijing–Hangzhou Grand Canal, the ancient canal, and the Yiyang River. The river channel supply route interconnects the central and western water systems. The Slender West Lake acts as a flow carrier connecting the central and western water systems of the city. The amount of water entering the Slender West Lake–Baozhang Lake water system is about 700 000 $m^3 \cdot d^{-1}$. Nonetheless, the effect of this scheme on the water quality improvement in the scenic area is limited. The main reasons for this are as follows.

First, the main urban area of Yangzhou is dominated by plains and polder areas; along with the operation of sluice stations, the water system in the area is relatively independent and experiences little change in water level. For example, the long-term water level of the river in the Slender West Lake water system area is 4.8–5.0 m. The water level differences in the entire river network are small, resulting in poor flow conveyance. The flow of water in the area is slow and sometimes stagnant. In addition, the local rivers are often stagnant, resulting in black and odorous water. Therefore, it is necessary to enhance the energy of the pumping station for proper drainage. Alternatively, sluices can be operated to store water and create a head difference. The stored potential energy can be utilized to divert and discharge the flow via water diversion projects. However, the natural drainage conditions of these channels are relatively poor. For example, the source water of the Slender West Lake system experiences a sharp expansion in channel cross-sectional area when entering the Baozhang Lake from the Han River, causing considerable local head losses. The Slender West Lake scenic river meanders, and the head loss intensifies along the river reach. This consumes a great deal of energy and does not effectively improve the hydrodynamic state of the river. Therefore, proper application of external kinetic energy and stored potential energy is needed.

Second, the relationships between hydrodynamics and the materials in the river network, such as sediments and pollutants, remain unclear. Hence, it is very difficult to determine reasonable criteria for hydraulic regulation. For example, the scale of water diversion is too large, which causes the water body to be in a state of turbulent flow for a long time and prevents necessary sediment settling. Moreover, due to the frequent water exchange, it is difficult to establish a stable habitat inside the lake. Under such hydrodynamic effects, the pollutants that have accumulated onto the sediment are released into the river flow. According to the monitored results of sediment in July 2018, the total phosphorus concentration in the sediment organic matter was 2000–2500 $mg \cdot kg^{-1}$, with a release rate of 3000–8000 $mg \cdot m^{-2} \cdot d^{-1}$. After the closure of the Pingshantang pumping station in March 2020, the lake water transparency was improved by an average of 15%–80%. An improvement of as high as 150% at some individual locations was also noticed.

Finally, there are several problems regarding the layout and operation of the sluice and pumping group system. Under the existing project layout and operating rules, the internal flow direction in the Slender West Lake is generally from north to south, whereas the water diversion direction at Pingshantang pumping station is from east to west. These two streams interfere, and only about 25% of the water enters the core scenic area of the Slender West Lake. Even though the upstream diversion flow is large (reaching 10 $m^3 \cdot s^{-1}$), the flow velocity of the core scenic area of the Slender West Lake is only 0.01–0.02 $m \cdot s^{-1}$, and there is local oscillatory flow. Especially at night, the water diversion ratio of the Pingshantang pumping station increases, and the backflow from south to north is more prominent. The sewage entering the river channel accumulates and reverberates in the river network, causing further deterioration of the water quality of the river channel. In addition, the Gaoqiao sluice station, Bianyimen sluice station, and Chaoguan sluice station, which regulate the flow of the Cao River, Beicheng River, and Xiaoqinhuai River, respectively, are routinely closed. The resulting stagnant water bodies and the additional domestic sewage jointly contribute to the poor water quality in corresponding river segments. Water diverted by the Huangjinba sluice station carries some sewage from the Cao River and the Beicheng River into the Slender West Lake, further affecting the lake water quality.

In the above analysis, the operation of the existing water conservancy projects is relatively simple. The main cause of their failure to meet the requirements of flood control and environmental sustainability is the overemphasis on water volume itself, while the important role of hydrodynamics is generally ignored. The outcome is the unnecessary waste of water resources without satisfying conservancy effects. Based on the proposed hydrodynamic reconstruction theory, the existing water conservancy system (e.g., the sluices and pumping stations) has the potential to be synergistically utilized to achieve comprehensive management of the water-related problems in this plain river network.

5.3. Optimization procedure and implementation results

First, based on the multiscale hydrodynamic reconstruction theoretical method, the spatiotemporal distribution of the hydrodynamics was determined in order to meet the multiple objectives of flood control and water quality improvement. The roughness of all the channels in the river network was determined, accounting for the vegetation and sand wave resistance, as discussed in Section 2.1. The accuracy of the roughness parameters was validated based on hydrological data and drainage tests. Considering the adsorption of phosphorus and ammonia nitrogen by sediments, the ecological flow thresholds of the western urban area and the Slender West Lake scenic area were found to be 5 and 3 $m^3 \cdot s^{-1}$, respectively. To optimize the network-scale river flow, in order to ensure that the joint operation of the project components achieves the effect of re-oxygenation of the water body and long-term maintenance of the water quality, it was necessary to ensure that the flow is unidirectional from north to south with velocities greater than 0.1 $m \cdot s^{-1}$ during water transfer.

Second, the response of the hydrodynamic field to the operations of the 69 sluices and 64 pumping stations in the Yangzhou river network was identified systematically. A water quality model was established to simulate the spatiotemporal distributions of the hydrodynamics and the water quality indexes for a series of regulation schemes. A regulation scheme library of the operating sluices and pumping stations was created based on drainage tests. Next, a smart decision-making model for hydraulic regulation was trained using the aforementioned operational schemes. The smart decision-making model simulated the flooding process and the daily change in the water quality, greatly improved the generation rate of the optimal scheme, and provided important technical support for flood control and the prediction of water quality in this region.

Finally, based on the smart decision-making model for hydraulic regulation, hundreds of project layout and operational schemes for the water quality improvement of the Slender West Lake scenic area and the western urban area were optimized and compared. Following this, a design and regulation scheme that met the appropriate scale of water diversion and flow distribution were generated for water quality improvement in Yangzhou City quickly. The scheme dealing with water source isolation was implemented in the central and western parts of the river network. Thus, the water source of the Slender West Lake was fed separately. In the central water system, engineering measures (e.g., optimization of the operation of the sluice and pumping group system, and river dredging) were adopted to improve the flow conveyance and hydro-environment of the core scenic area of the Slender West Lake. These measures improved the hydrodynamic conditions of the rivers around the scenic area and enhanced the hydro-environment of the main urban area of Yangzhou.

In the Slender West Lake water system area, the water quality improvement scheme includes the optimization of both project layout and scheduling. Before the implementation of the planned scheme, the diversion discharge was as high as 9 $m^3 \cdot s^{-1}$, but the flow velocity was less than 0.02 $m \cdot s^{-1}$ in some areas. By implementing the above plan, the overall flow velocity was increased to 0.02–0.10 $m \cdot s^{-1}$ along with the diversion discharge was constrained at 3 $m^3 \cdot s^{-1}$, so that the river water body changed from a static to a dynamic condition and attained the threshfold requirement of ecological flow. In the core section of the scenic area, the water movement changed from to-and-fro to unidirectional flow. The quality of the water used by the residents improved significantly, the distributions of the water entering the western urban area and the eastern lake area became reasonable, and the ecological water demand of the river was secured. The ammonia nitrogen concentration in the core section of the scenic area decreased from 2.0–8.0 $mg \cdot L^{-1}$ to less than 0.5 $mg \cdot L^{-1}$. Overall, the water quality and urban water environment improved significantly.

6. Conclusions

In the present era, the management of plain river networks is undergoing a paradigm shift from simple disaster-oriented management to the integrated management of water-related disasters, water resources, the water environment, and aquatic ecosystems. The major strategies in China (e.g., the integrated regional development of the Yangtze River Delta, the Beijing–Tianjin–Hebei collaborative development, the Huai River economic belt, and the construction of the Guangdong–Hong Kong–Macao Greater Bay Area) are being implemented on plains, signifying the importance of water security issues in such areas. This paper proposes that hydrodynamics are the fundamental controlling factor in the complex water problems in plain river network areas. To deal with the problem of hydrodynamic incompatibility, we have proposed a theory and technical system for the hydrodynamic reconstruction of plain river networks that involves multiscale hydrodynamic reconstruction theoretical method, an engineering technology system, and multi-objective hydraulic regulation technology. The existing project system is used to design a reconstruction of the temporal and spatial distribution of the hydrodynamics, which provides important technical support for the transformation of the project operation from achieving a single function to achieving multiple functions. Simultaneously, balanced allocation of the limited energy in the plain river network area is achieved. While implementing the integrated management of water problems, the energy consumption and frequent use of sluices and pumping stations are minimized. The theory presented here contributes to achieving the water governance concepts of prioritizing water conservation, balancing spatial distribution, taking a systematic approach, and giving full play to the roles of both the government and the market; it also supports China's goal of reaching a peak in CO_2 emissions before 2030 and achieving carbon neutrality before 2060. In the future, this theory can be further extended and improved by considering the requirements for land and habitat protection.

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Compliance with ethics guidelines

Hongwu Tang, Saiyu Yuan, and Hao Cao declare that they have no conflict of interest or financial conflicts to disclose.

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