Path for Enhancing the Climate Resilience of the Beijing–Hangzhou Grand Canal Utilizing the SEE Model and Scenario Simulation

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Abstract In the context of global climate change, the increasing frequency of extreme weather events presents significant challenges to urban water systems. This study focuses on the Beijing section of the Beijing-Hangzhou Grand Canal, introduces the SEE model, and develops an integrated "comprehensive water environment simulation model" to systematically examine the path for enhancing its climate resilience. Through the coupling of multiple models (MIKE 11, MIKE URBAN, MIKE 21) and scenario simulations, this study analyzes the response mechanisms of various governance strategies under extreme climate conditions. The research proposes four specific measures to enhance resilience: dual-scenario simulation of climate and governance, identification and reinforcement of weak points in resilience, parametric modeling of ecological restoration interventions, and the development of a "digital twin canal system". The research findings indicate that the system integration of the SEE model substantially improves the adaptability, endurance, and recovery capacity of canals in response to climate shocks, including heavy rainfall and drought. This provides a scientific foundation and a practical path for achieving long-term resilience and sustainable development of urban water systems.

Keywords Climate resilience, SEE Model, Water environment simulation, The Beijing-Hangzhou Grand Canal

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The SEE model was developed in response to the pollution and degradation of the water environment and water ecosystems in certain urban rivers amid the urbanization process in China, alongside the country's efforts to strengthen water environment management and ecological restoration of rivers and lakes. This model addresses the critical scientific issue concerning the reciprocal feedback between the improvement of urban river water quality and the enhancement of water ecosystems, with the objective of implementing governance through integrated approaches[1]. The central focus is the development of a comprehensive water environment simulation model that thoroughly incorporates three scenarios: social governance (S), environmental quality (E), and ecosystem health (E). This model is then utilized to evaluate and optimize the governance plan (Fig.1).

Historically, successful governance has rarely been attributable to a single technological achievement; rather, it has emerged from the coordinated interaction among three dimensions: society, environment, and ecology. Fig.1 clearly illustrates this interrelationship. The SEE model integrates social governance, environmental quality, and ecosystem health in a cohesive manner, thereby overcoming the limitations inherent in isolated governance approaches and enabling systematic management that spans social behavior regulation, environmental engineering, and ecological restoration objectives. By developing a comprehensive water environment simulation model, the impacts of various governance measures can be quantitatively assessed, enabling simulation-based pre-assessment and optimized selection of management strategies, thereby enhancing the scientific rigor of decision-making processes. This model facilitates the identification and collaborative mitigation of the lagging effects between water environment improvement and ecological restoration, fostering a synergistic interaction between these two aspects through integrated governance. The potential limitations of the SEE model include its considerable complexity and elevated implementation threshold. This model encompasses multiple subsystems, such as society, environment, and ecology, necessitating the integration of specialized knowledge and technologies from diverse disciplines, thereby imposing substantial demands on technical expertise and data availability. Furthermore, the development and operation of comprehensive simulation models, as well as the coordination of multiple stakeholders in social governance, may encounter challenges related to

Column introduction

The City Observer column, initiated by Yang Xin and Zhang Qi, the hosts of the RLncut research station, aims to examine the city in which we reside, to measure urban spaces, and to reveal the fundamental essence underlying superficial appearances. The SEE model has been implemented in numerous prominent river management cases worldwide. This article concentrates on the Beijing-Hangzhou Grand Canal, examining the application of the SEE model to improve its climate resilience.

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technology, management, and cost.

1 Application of the SEE model in river water environment governance

1.1 Three-dimensional composition of the SEE model

The SEE model comprises three dimensions: social governance (S), environmental quality (E), and ecosystem health (E). Social governance (S) highlights the collaborative involvement of multiple stakeholders, including government entities, enterprises, and the public, in river basin management. Its objective is to establish a governance mechanism characterized by joint construction, shared governance, and mutual benefits, thereby facilitating the coordinated management of river basins. This dimension reflects the principle of "harmony between humans and water" and enhances the regulation of societal behaviors affecting the water environment. Environmental quality (E) focuses on the spatial and temporal variations of water quality indicators, including chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), and total phosphorus (TP), as illustrated in Fig.2. The migration and transformation of pollutants are simulated using hydrodynamic and water quality coupling models, such as MIKE11, MIKE21, and MIKE URBAN[2], to assess the impacts of point and non-point source pollution on the water environment and the effectiveness of pollution control measures. Ecosystem health (E) provides a comprehensive assessment of the structure and function of water ecosystems, encompassing biological communities such as phytoplankton, benthonic animals, fish, and submerged vegetation. It establishes an evaluation system for water ecological health that includes indicators such as biodiversity, habitat quality, and ecosystem service functions. This approach highlights the lag effects and reciprocal feedback mechanisms between water ecological restoration and water quality improvement.

Several prominent international examples of river management exemplify the SEE model. The governance framework of the River Thames in the United Kingdom consists of three primary components: social governance (S), environmental quality (E), and ecosystem health (E). In terms of social governance (S), the implementation of robust legislation, such as the *Water Resources Law*, alongside the establishment of a unified river basin administration, has effectively addressed the issue of "multiple management". Concerning environmental quality (E), extensive upgrades to coastal sewage treatment plants have been undertaken, and a stringent licensing system for industrial discharges has been enforced, resulting in a substantial reduction of point source pollution. With respect to ecosystem health (E), river reoxygenation initiatives have been implemented to enhance habitat conditions. The reappearance of the historically absent salmon in the Thames after a century serves as a notable indicator of successful ecological restoration[3]. Within the SEE governance framework of the Rhine River in Europe, the International Commission for the Protection of the Rhine was established to promote comprehensive cooperation among riparian states, which collectively set common objectives. The implementation of the *Salmon 2000 Plan* focused on the thorough treatment of industrial and urban wastewater along the river's course[4]. Additionally, ecosystem health efforts, such as the removal of hard revetments, the rehabilitation of river beaches and floodplains, and the reopening of fish migration pathways, ultimately succeeded in achieving the ecological goal of salmon population recovery. The SEE framework for the governance of the Huai River Basin in China is structured as follows. For social governance (S), a stringent "River Chief System" has been established, wherein local Party and government leaders serve as river chiefs responsible for maintaining water quality within their respective jurisdictions, thereby addressing the issue of accountability. Regarding environmental quality (E), the measures include the closure, consolidation, and transformation of heavily polluting enterprises, such as small-scale papermaking and chemical industries, alongside the construction of numerous sewage treatment plants. Considering ecosystem health (E), ecological slope protection and the construction of artificial wetlands have been implemented in certain river sections, signifying the initial efforts to transition from merely "clearer water" to a more "dynamic river" ecosystem[5].

1.2 Technical path for constructing the SEE model system

1.2.1 Multi-model coupling strategy. Three professional models have been integrated to develop a comprehensive coupling simulation system encompassing the entire process from rainfall to flow generation, pipe network, and river channel. These models include the MIKE 11 one-dimensional river channel hydrodynamic and water quality model, the MIKE URBAN (MOUSE) urban pipe network hydrology and hydrodynamic model, and the MIKE 21 two-dimensional surface hydrodynamic and water quality model[1].

1.2.2 Coupling methods and technical details.

(1) The urban pipe network is integrated with the two-dimensional surface system and interconnected via manholes to facilitate the interaction between surface water flow and sewer water flow. This configuration is applicable in scenarios such as the inflow of surface water into the pipe network, the overflow of water from the pipe network onto the surface, and the discharge of water from pumping stations, weirs, and other related facilities onto the surface.

(2) The urban pipe network is coupled with the river channel model to simulate three scenarios of water discharge into the river via the connected river drainage pipe network: discharge from the sewage outlet, discharge from the pumping station, and discharge from the weir.

(3) The river channel model is coupled with the two-dimensional surface model, employing lateral connections to simulate two scenarios: river overflow into the floodplain and surface runoff converging into the river channel. Different connection methods are applied based on the width of the river channel; for wide channels exceeding 20 m, connections are established at the left and right banks, whereas for narrow channels less than 20 m, connections are made along the center line.

1.3 Introduction to the principle of the model module

MIKE11 HD (hydrodynamic module) is founded on the Saint-Venant one-dimensional non-uniform flow equations and employs a six-point implicit finite difference method to compute water levels and flow rates[6]. MIKE11 SO (structure module) simulates hydraulic structures, including gates, dams, bridges, and culverts, and dynamically simulates the scheduling processes based on the relationship between flow and water level[7]. NAM model (rainfall-runoff module) is an aggregated conceptual hydrological model designed to simulate processes including soil stratified water storage, surface runoff, and subsurface runoff[8]. ECO Lab (water quality module) simulates the migration and transformation of pollutants through ordinary differential equations and supports customizable water quality processes such as degradation, sedimentation, and biological reactions. MIKE21 (two-dimensional hydrodynamic model) is founded on the shallow water equation (two-dimensional Saint-Venant equation) and is well-suited for simulating two-dimensional phenomena such as flood overflow and water quality diffusion. MIKE URBAN (urban pipe network model) integrates hydrological models (such as the time-area method) with hydrodynamic models to simulate the comprehensive process of rainfall, runoff, and pipe flow within urban environments[5].

1.4 Decomposition of core points

System composition: the system innovatively integrates the three major professional models, namely MIKE 11 (one-dimensional river channel), MIKE URBAN (one-dimensional pipe network), and MIKE 21 (two-dimensional overflow).

Simulation capability: it encompasses a comprehensive process simulation, including rainfall flow generation, pipe network convergence, river hydraulics and water quality, and two-dimensional slope overflow, thereby covering the entire chain of "source–path–convergence".

Technological breakthroughs: key parameters, including zonal rainfall boundaries and intermittent hydrological inputs, have been refined, and the issue of boundary connectivity in multi-model coupling has been resolved. These advancements have significantly improved the simulation accuracy and resolution in densely populated urban areas.

Application value: this coupling system can generate key environmental indicators to forecast future trends in the basin's water environment under various governance scenarios, thereby providing a quantitative foundation for informed scientific decision-making.

1.5 Effect of SEE scenario integration on water environment governance

The model structure and parameter settings, including ground roughness, river roughness, and pollution load input methods, provide the foundation for subsequent scenario analyses. Social governance (S) is reflected by the management of sewage outlets, the operation of sewage treatment plants, and the regulation of sluice gates and dams. Environmental quality (E) simulates the migration and transformation of pollutants through the water quality module. Ecosystem health (E) is indirectly assessed using indicators such as dissolved oxygen (DO) levels and eutrophication status.

The fundamental impact of the SEE model on water environment governance is its broadening of the governance scope from solely "water treatment" to the integrated "territorial governance". It elucidates that water environment challenges extend beyond pollutant control, arising instead from the complex interplay among social behaviors, environmental engineering, and ecological responses. This model establishes a robust connection among the environmental management behaviors of social governance (S), the engineering and technical approaches to environmental quality (E), and the ultimate objective of ecosystem health (E). It thereby constructs a virtuous cycle in which "social regulation promotes environmental improvement, environmental enhancement facilitates ecological restoration, and ecological health, in turn, supports societal well-being". This framework addresses the governance challenge of "symptom-focused interventions", offering a systematic solution for achieving sustainable and clean water environments.

2 Case analysis of water environment governance of the Thames River in London from the perspective of the SEE model

Since the Industrial Revolution, rapid

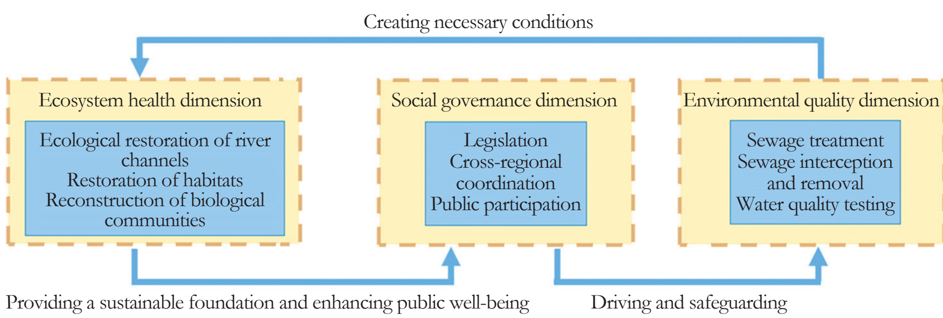

Fig.1 Collaborative framework of the SEE model

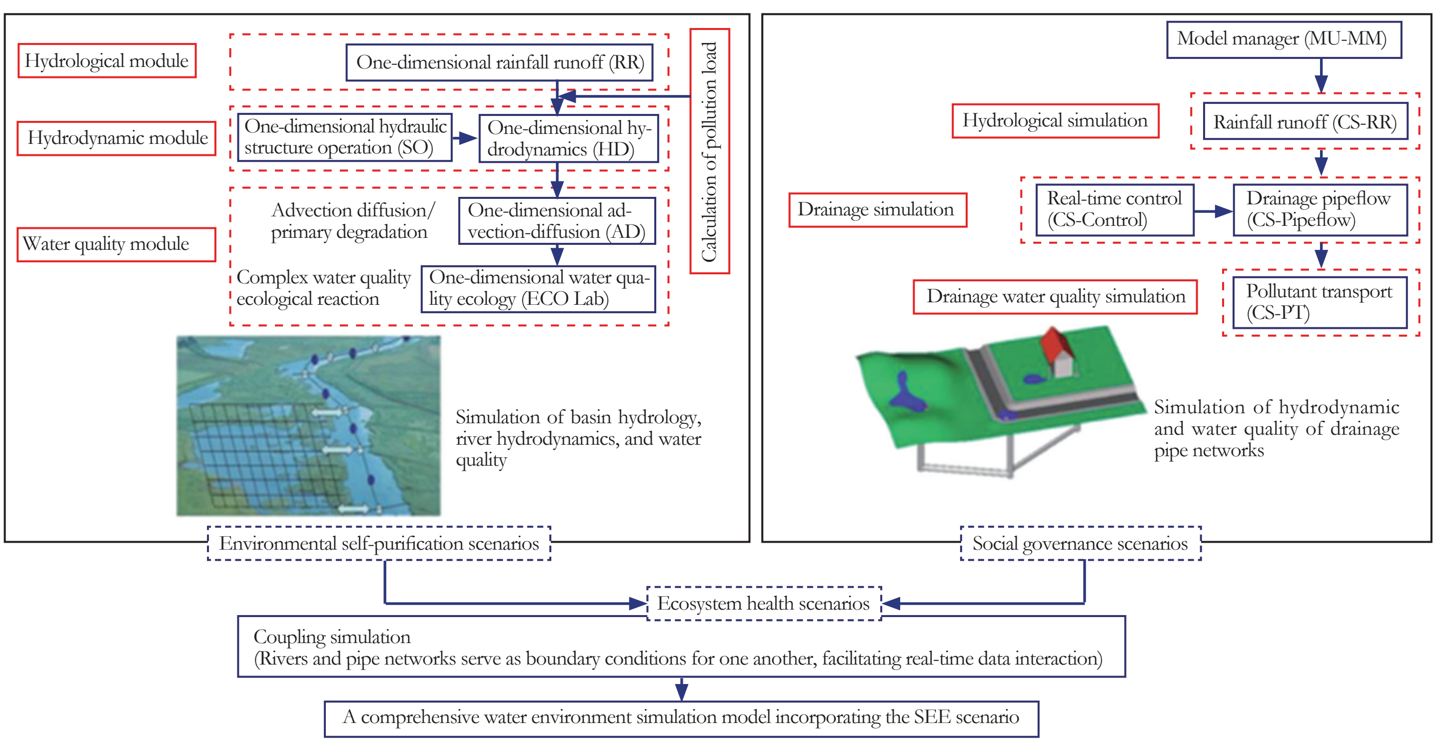

Fig.2 Simulation illustration of the SEE model[1]

urbanization has resulted in substantial pollutant discharge into the River Thames, overwhelming its ecosystem and posing significant risks to the public health of London residents. In response to this crisis, the British government implemented a comprehensive governance strategy that spanned more than a century beginning in the middle 19^{th} century. Key measures included the enhancement of sewage collection and treatment infrastructure, the enactment and rigorous enforcement of environmental regulations, and the adoption of integrated management across the entire river basin. This series of effective interventions offers valuable practical insights for advancing urban water environment governance in contemporary China[9].

2.1 Three-dimensional interpretation

Environmental (E) dimension: strict control of point sources is enforced through legislation requiring municipal and industrial enterprises along the coast to construct wastewater treatment plants, accompanied by a stringent discharge permit system. Through extensive infrastructure development, a substantial sewage interception pipeline system, exemplified by the Thames Tidal Tunnel, was constructed to redirect sewage to large-scale treatment plants for centralized processing (Fig.3). A comprehensive water quality monitoring network has been implemented to enable continuous real-time assessment of treatment efficacy. Regarding ecological restoration, improvements in water quality have facilitated the return of diverse aquatic species, including salmon, to the River Thames, signifying the successful rehabilitation of the river's ecosystem[2].

Economic (E) dimension: although the governance process entails considerable costs, it has yielded substantial economic benefits. A sustainable funding mechanism has been established through measures such as the imposition of "sewage fees". The improvement of river cleanliness has significantly enhanced London's urban image and property values, thereby stimulating industries including waterfront tourism, leisure and entertainment, and commercial development. The indirect economic benefits considerably surpass the costs associated with governance.

Fig.3 Sewage treatment plant

Social (S) dimension: a series of parliamentary bills, including the *Law on River Pollution Prevention and Control*, have established legal frameworks to support environmental governance. Significant pollution events, such as "the Great Stink" incident, have heightened public environmental awareness, generated substantial social pressure, and prompted governmental responses. The restoration of public spaces has revitalized both banks of the River Thames, transforming them into some of the most vibrant public areas in London following governance efforts, thereby improving the quality of life and well-being of the city's residents.

The governance of the River Thames originated in response to environmental crises and social pressures. Through the implementation of robust legislation and economic strategies, including taxation and investment, large-scale environmental initiatives were undertaken, ultimately resulting in multiple mutually beneficial outcomes for the environment, economy, and society.

2.2 Enlightenment

The governance experience of the River Thames provides valuable insights for numerous water-adjacent cities in China. Its successful management demonstrates that urban river governance is a long-term, systematic endeavor that must align with natural laws. Comprehensive management across the entire basin should be implemented, with the primary objective of enhancing sewage collection and treatment infrastructure to effectively control pollution at its origin. The governance process should follow planning-led methods, integrating water environment remediation with the enhancement of waterfront space quality through scientific planning to address the city's multifaceted development goals. Concurrently, improvements in water quality fundamentally depend on technological innovation and ongoing scientific research, which necessitates the establishment of a comprehensive monitoring system to inform decision-making. Furthermore, it is essential to delineate the roles of government and market mechanisms. While market-oriented operations can stimulate vitality, government oversight must be reinforced to ensure the maintenance of environmental safety baselines[10].

3 Effect of the SEE model on climate resilience of the Beijing-Hangzhou Grand Canal and the paths to enhance climate resilience

The Beijing section of Beijing-Hangzhou Grand Canal functions as the primary drainage channel and ecological corridor for Beijing. Nevertheless, its water environment and ecosystem are subject to ongoing pressures from various sources, including point source pollution, non-point source pollution, and overflow contamination. In the context of global climate change, the increasing frequency of extreme weather events, such as intense short-duration rainfall and extended drought periods, has intensified fluctuations in water quality and heightened the risk of ecological degradation along the canal. These challenges pose significant threats to urban flood control, water supply security, and ecological stability[11]. The central element of the comprehensive water environment simulation model, which incorporates the SEE scenario, is the integration of three previously independent dimensions, namely social governance (S), environmental quality (E), and ecosystem health (E), into a unified and quantifiable numerical simulation framework. This model functions not only as an assessment tool but also as "a climate resilience stress tester" and "an optimizer for governance solutions".

3.1 Influence mechanism of the SEE model on climate resilience through comprehensive model

3.1.1 Social Governance (S). Social governance (S) enhances system coordination and adaptability by implementing mechanisms of co-construction, co-governance, and shared benefits. Through the participation of multiple stakeholders, including government entities, enterprises, and the public, it establishes a collaborative governance framework that improves the capacity to respond effectively to extreme climate events such as heavy rainfall and drought. Intelligent dispatching and early warning systems, exemplified by "the factory-network joint dispatching system", are developed to monitor pipeline network overflow and water quality changes in real time, enabling timely warnings and proactive dispatching to mitigate pollution impacts during flood seasons[12]. Consequently, social governance strengthens the system's rapid response and recovery capabilities in the face of climate shocks, thereby enhancing overall resilience.

Social governance (S) is conceptualized in the model as "the capacity for system regulation", which directly enhances "adaptability and resilience". The model integrates MIKE URBAN (pipe network model) with MIKE 11/21 (river channel model), thereby achieving a fully dynamic coupling of the entire process: rainfall runoff generation, pipe network convergence, and river channel hydraulic water quality[5,13]. This integration effectively digitizes the core aspect of social governance, namely the coordinated management of "factories, networks, and rivers".

When simulating extreme rainfall scenarios, the model is capable of predicting overflow points, overflow volumes, and the consequent effects on river water quality under various dispatching strategies. Within the SEE model framework, social governance, such as an intelligent dispatching platform, can proactively optimize the operational strategies of sluice gates, dams, pumping stations, and sewage treatment plants through model-based forecasting. This enables precise interception, regulation, or redirection of rainwater to facilities with surplus treatment capacity, thereby mitigating peak flood flows and overflow-related pollution. Consequently, this approach significantly enhances the canal system's resilience and buffering capacity against heavy rainfall events, thereby preventing the undesirable condition in which rainwater results in black, foul-smelling water.

3.1.2 Environmental governance (E). Environmental quality (E) is critical for maintaining the health and self-purification capacity of water ecosystems. Implementing strategies such as source governance (e.g., ecological restoration of small watersheds), non-point source control (e.g., substitution with organic fertilizers), and end-of-pipe treatment (e.g., storage tanks) can substantially reduce pollutant loads, including COD, NH_3-N, and TP. These interventions improve water quality from Class V to Class IV or even Class III, thereby enhancing the resilience and self-purification capacity of water bodies in response to climatic disturbances such as storm runoff[14]. Consequently, maintaining clean water bodies supports ecological balance and mitigates the adverse impacts of climate-related events on water ecosystems.

Environmental quality (E) is reflected in the model as "the capacity for pollution load reduction" and is conceptualized as "resilience under stress". This is demonstrated through the model's precise simulation of the convection, diffusion, degradation, and transformation processes of pollutants, including COD, NH_3-N, and TP, within the river channel, utilizing the ECO Lab water quality module. Pollution load inputs, such as surface sources, point sources, and overflow outlets, are quantified as boundary conditions within the model. The model further simulates scenarios during drought periods, wherein insufficient ecological flow leads to a diminished self-purification capacity of water bodies, resulting in more severe water quality deterioration under equivalent pollution loads[5,15].

The measures implemented to enhance environmental quality within the SEE model, namely ecological restoration of small watersheds, substitution with organic fertilizers, and the installation of terminal storage tanks, are represented in the model as direct reductions in the pollution load entering the river. A water body exhibiting improved baseline environmental quality possesses a greater "capacity" to accommodate and mitigate climate-induced shocks (such as initial rainwater), thereby demonstrating increased resilience. Model predictions, including the projected decrease in COD concentration at the Shahe sluice to 19.6 mg/L by 2035, suggest that enhancing environmental quality functions as a "buffering pad" for the canal to withstand climatic pressures[1].

3.1.3 Ecosystem health governance (E). Ecosystem health (E) can be promoted by constructing biodiversity buffer systems through the reconstruction of underwater ecosystems, exemplified by the integration of species such as *Vallisneria natans*, *Ceratophyllum demersum*, *Hydrilla verticillata*, and *Ctenopharyngodon idella*, to improve water stability and biodiversity. The restoration of biological communities, including phytoplankton and benthic fauna, can enhance the system's adaptive and regulatory capacities in response to climate change[16]. A healthy ecosystem can better absorb and mitigate climate-related shocks, such as reducing the impacts of floods and increasing water retention during drought periods.

Ecosystem health (E) is reflected in the model by "the system's capacity for self-purification and stability", which contributes to its "restorative resilience". Although the model has limitations in directly simulating complex ecological processes, these processes can be indirectly characterized through key parameters. For instance, the recovery of submerged plants influences the water body's reoxygenation capacity and nutrient absorption rate. Such processes can be generalized within the reaction equations of ECO Lab. Additionally, the assurance of ecological base flow constitutes a critical hydrological boundary condition for model operation, which is directly calculated and incorporated using the Tennant method[17].

A river channel characterized by a healthy underwater ecosystem (comprising submerged plants, fish, and benthic animals) exhibits high biodiversity and a complex food web. Within the model, this condition is reflected by a more rapid recovery of water quality indicators to baseline levels following pollution shocks. For example, the model simulates that after an overflow pollution incident, the DO concentration in a river section containing submerged plants recovers significantly faster than in a hardened, canalized river section. This capacity for swift recovery from disturbances is fundamental to climate resilience. The restoration measures aimed at enhancing ecosystem health in the SEE model effectively strengthen the canal system's "immune response" and "self-healing capabilities".

3.2 Specific measures for enhancing climate resilience based on model principles

This comprehensive simulation model facilitates "computer-based experimentation", thereby enabling the precise formulation and optimization of strategies to improve climate resilience.

Measure 1: dual-driven simulations integrating "climate scenarios and governance scenarios" are conducted to develop resilience blueprints. Verified models are employed to incorporate future climate change prediction data, such as more intense and concentrated rainfall events, and these are combined with various SEE governance scenarios for simulation purposes.

Scenario A (baseline): maintain current

governance levels.

Scenario B (enhanced S): increase smart dispatch nodes and storage tank capacity.

Scenario C (enhanced E): elevate nonpoint source pollution control standards.

Scenario D (SEE synergy): implement all measures comprehensively.

The performance of each scenario under extreme weather conditions (such as peak water levels, duration of standard exceedance, and the magnitude of decline in ecological indices) is quantitatively evaluated. This assessment facilitates the identification of the most cost-effective strategy for enhancing resilience and offers a scientific foundation for informed decision-making.

Measure 2: "resilience weak points" are systematically identified and strengthened to facilitate targeted investments. Through model simulations, critical vulnerable sections throughout the basin (e.g., the Yulin Zhuang sluice frequently experiences water quality exceedances due to inflows from the Liangshui River) and key vulnerable infrastructure (e.g., certain nodes within the pipeline network are prone to overflow) are precisely located under various scenarios, such as heavy rainfall and drought. These findings contribute to the development of "A North Canal Climate Resilience Risk Map". Consequently, governance resources and funding can be strategically allocated to these identified weak points. For example, targeted expansion of storage tanks within the Liangshui River basin, coupled with enhanced coordinated dispatching among treatment plant networks, enables precise resilience reinforcement through "tailored strategy for each identified vulnerable point".

Measure 3: "ecological restoration measures" are quantified as model parameters to evaluate their contribution to system resilience. The parametrization of ecological restoration outcomes examined in Chapter 4 (such as the purification rates of NH_3-N achieved through the combined use of *V. natans* and *C. demersum*, and growth responses under varying water depths and flow velocities) will be incorporated into the integrated model. This method facilitates a quantitative assessment of the extent to which submerged vegetation planting areas can replicate the purification capacity of wastewater treatment plants of specific scales during drought conditions, or how riparian vegetation effectively attenuates flood peak velocities. Consequently, this approach elucidates the resilience value of "nature-based solutions (NbS)", thereby encouraging their broader implementation in engineering projects[18].

Measure 4: a "digital twin canal" has been developed to facilitate resilient operations and provide real-time early warnings. This integrated model has been enhanced into a digital twin system that synchronizes continuously with the physical canal, updating in real time. It integrates real-time data on rainfall, water quality, water levels, and gate operations. The system is capable of forecasting water quality and hydrological changes over periods ranging from hours to days, enabling preemptive water release to optimize reservoir capacity and adjust gate opening strategies prior to heavy rainfall events. This approach advances climate resilience from "a passive response framework" to "a highly proactive early warning and forward-looking adaptation strategy"[12,19].

3.3 Summary

Through digitalization and system integration, the abstract concept of SEE governance is converted into computable and predictive scientific tools. This framework clearly demonstrates that social governance (S) functions as the "intelligent brain" for climate resilience, determining the system's adaptability and regulatory capacities. Environmental quality (E) provides a "healthy foundation" for climate resilience, influencing the system's ability to withstand and buffer environmental stresses. Ecosystem health (E) acts as the "immune system" for climate resilience, governing the system's self-healing and recovery capabilities. The central aspect of the proposed improvement method, grounded in the SEE model, involves utilizing "the digital laboratory" for scenario simulation, precise identification, and dynamic optimization. This approach aims to transform the Beijing-Hangzhou Grand Canal into a genuinely resilient system capable of effectively addressing future climate change challenges with maximum efficiency and minimal cost.

4 Conclusions

This study integrates the SEE model with advanced numerical simulation techniques for water environments to systematically investigate the path for enhancing climate resilience in the Beijing–Hangzhou Grand Canal, a critical drainage corridor and ecological zone. The research not only develops an innovative "comprehensive water environment simulation model" but also elucidates the systematic approaches and implementation strategies that urban river management should adopt in the context of intensified climate change and increasing frequency of extreme weather events. In response to the fundamental urban safety requirements of "flood control and drainage", the SEE model has demonstrated distinctive value. It challenges the conventional engineering perspective that "flood control and ecological preservation are mutually exclusive". Model simulations indicate that intelligent management, guided by social governance (S), enables the pre-release and emptying of storage tanks prior to heavy rainfall, as well as precise control of sluice gates and dams during precipitation events. This approach not only ensures the safe discharge of floodwaters but also significantly mitigates the impact of overflow pollution on the ecosystem. The enhancement of environmental quality(E), particularly the management of non-point source pollution, results in cleaner rainwater entering rivers, thereby mitigating secondary ecological disasters caused by "pollution dispersion during flood drainage". The restoration of ecosystem health (E), exemplified by the construction of ecological revetments and the rehabilitation of riverbanks and wetlands, can attenuate flood peaks and promote rainwater infiltration. These measures provide an auxiliary flood control function through NbS, thereby achieving a synergistic benefit for both safety and ecological integrity. In the context of flood control and drainage, the SEE model has effectively integrated the dual objectives of "safety" and "ecology", facilitating a transition in the management of the Grand Canal from an exclusive emphasis on disaster prevention and mitigation to a comprehensive approach that simultaneously advances safety, environmental health, and sustainable development[20-21].

The SEE model and its technical implementation path possess significant potential for widespread application. Its fundamental framework and model coupling approach can be adapted to a variety of urban rivers and canals across China and globally that encounter analogous climate challenges and pollution issues. Regardless of whether the water body is an urban river in the southern regions or a water-scarce river channel in the northern areas, adjusting the model parameters and boundary conditions in accordance with local climate, hydrological conditions, pollution source characteristics, social management systems, and other relevant factors enables the development of a tailored "digital twin" system. This system can facilitate the preliminary assessment and optimization of governance strategies.

The future application and development of the SEE model can be expanded in multiple directions. Specifically, the integration of the

SEE model with artificial intelligence, big data, and Internet of Things technologies has the potential to enhance its real-time prediction and self-learning capabilities, thereby rendering the "digital twin canal" more intelligent and precise[22]. The model has been extended from a single river channel to encompass the entire river basin scale. This expansion facilitates the investigation of mechanisms that enhance collaborative resilience between upstream and downstream areas, as well as between the left and right banks, addressing governance challenges that span administrative boundaries. Additionally, the intersection of water environment governance and carbon neutrality is examined, including the quantification of carbon sequestration benefits derived from ecological restoration measures, thereby promoting the coordinated achievement of "climate resilience" and "carbon neutrality" objectives. Deepening research on the dimensions of social governance and investigating methods to more effectively incentivize the participation of enterprises, communities, and the public can facilitate the establishment of sustainable, long-term operational and management mechanisms.

In conclusion, the governance approach grounded in the SEE model and scenario simulation delineates a scientifically informed path toward enhancing climate resilience for the Beijing-Hangzhou Grand Canal. This systematic methodology and its practical tools offer direct guidance for the management of the Beijing-Hangzhou Grand Canal and present a "Chinese framework" that may serve as a reference for global cities seeking to manage their valuable water system resources and develop sustainable, vibrant urban public spaces amid an uncertain climatic future.

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