Journal of Architectural Research and Development, 2025, Volume 9, Issue 5
https://ojs.bbwpublisher.com/index.php/JARD
Online ISSN: 2208-3537
Print ISSN: 2208-3529

Optimization of Water Supply and Drainage System: Coordinated Development of Pipeline Network Maintenance and Sewage Plant Expansion and Operation

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Abstract: This article focuses on the optimization of water supply and drainage systems, involving theories such as hydraulic models of pipeline systems and multi-objective collaborative optimization. It introduces the system dynamics model of sewage treatment facility expansion. Elaborating on detection technology, construction of an intelligent operation and maintenance system, and factors to be considered for sewage plant expansion, it emphasizes the importance of collaborative development and verifies benefits through the PSR model.

Keywords: Water supply and drainage system; Pipeline network maintenance; Expansion of sewage treatment plant

Online publication: October 10, 2025

1. Introduction

With the acceleration of urbanization, the water supply and drainage system is facing many challenges, and the coordinated development of pipeline maintenance and sewage plant expansion and operation has become the key. The *Several Opinions on Strengthening Urban Infrastructure Construction*, released in 2022, emphasizes the importance of improving the level of urban infrastructure construction. In this context, the optimization of the water supply and drainage system needs to be carried out from multiple aspects. This involves the construction of hydraulic models for pipeline systems, the application of multi-objective collaborative optimization strategies, the establishment of system dynamics models for sewage treatment facility expansion projects, the application of detection technology, the construction of smart pipeline operation and maintenance systems, the matching of sewage plant expansion processes and the improvement of treatment capacity, collaborative optimization, the development of intelligent aeration control systems, the construction of digital twin models, the linkage between pipeline coverage and plant site selection, the composite utilization of land resources, the establishment of joint investment decision-making models, and the construction of cross departmental information sharing platforms, in order to achieve efficient operation and sustainable development of the water supply and drainage system.

2. Theoretical basis for collaborative development of water supply and drainage systems

2.1. Theoretical framework for optimization of water supply and drainage network system

The theoretical framework for optimizing water supply and drainage pipeline systems involves the principles of constructing hydraulic models for pipeline systems and the application mechanism of multi-objective collaborative optimization strategies. The hydraulic model construction of the pipeline system is based on the basic principles of fluid mechanics, considering the continuity equation and energy equation of water flow, combined with the topology structure and pipeline characteristics of the pipeline network, and accurately describing the water flow state inside the pipeline network through mathematical modeling methods [1]. The application of a multi-objective collaborative optimization strategy in pipeline maintenance and sewage plant expansion requires comprehensive consideration of multiple objectives, such as cost, water quality, and water quantity. By establishing an objective function and using optimization algorithms to find the optimal solution, we aim to achieve rational resource allocation and overall system performance improvement. This collaborative optimization mechanism can meet the needs of sewage treatment while reducing maintenance costs and operational risks, and improving the sustainability and stability of the water supply and drainage system.

2.2. System dynamics analysis of sewage treatment plant expansion and operation

Establishing a system dynamics model for the expansion project of sewage treatment facilities is key to understanding its complex operating mechanism. Through this model, the coupling relationship between production capacity matching, environmental capacity, and economic costs can be explored in depth. Capacity matching involves the adaptation of sewage treatment capacity to the amount of sewage generated, which directly affects the effectiveness and efficiency of sewage treatment [2]. The environmental capacity determines the limit of sewage discharge and plays an important guiding role in the treatment scale and technology selection of sewage plants. Economic costs cover multiple aspects such as construction, operation, and maintenance, and are factors that cannot be ignored in the decision-making process. These factors are interrelated and influence each other, and the system dynamics model can simulate their dynamic changes, providing a scientific decision-making basis for the expansion and operation of sewage treatment plants.

3. Research on key technologies for pipeline network maintenance

3.1. Pipeline health diagnosis and early warning technology

CCTV detection technology can penetrate deep into the pipeline network and obtain internal image information through high-definition cameras, accurately identifying structural defects such as cracks and deformations. Hydraulic pressure testing relies on monitoring and analyzing pressure changes in the pipeline network to infer whether there are damage and leakage issues in the pipeline. A leakage warning system based on the Internet of Things installs sensors at key nodes of the pipeline network to collect real-time data, such as pressure and flow, and transmit it to the monitoring center [3]. Using data analysis algorithms to process data, issuing timely warnings when data anomalies occur, achieving real-time monitoring and rapid response to pipeline leakage, and effectively ensuring the normal operation of the pipeline network.

3.2. Construction of an intelligent pipeline network operation and maintenance system

The construction of an intelligent pipeline operation and maintenance system requires the use of advanced technology to improve management efficiency and accuracy. The GIS BIM integrated platform plays an important role in pipeline asset management. Its technical path includes data collection and integration, 3D model construction, and real-time information updates [4]. By integrating spatial data from geographic information systems (GIS) and detailed attribute data from building information models (BIM), it achieves comprehensive visual management of pipeline assets. The development and application of a preventive maintenance decision support system is also crucial. The system can analyze pipeline operation data, historical maintenance records, and real-time monitoring information, predict possible failure points and maintenance needs, provide a scientific basis for the formulation of maintenance plans, thereby improving the initiative and effectiveness of pipeline maintenance, reducing maintenance costs and failure risks.

4. Collaborative optimization of sewage plant expansion project

4.1. Expansion process compatibility design

4.1.1. Load forecasting and processing capacity improvement plan

The expansion of sewage treatment plants requires comprehensive consideration of multiple factors to achieve process matching and improve treatment capacity. Based on the population growth model, predict the trend of changes in sewage production, and combine it with the demand for improving water quality standards to develop reasonable expansion process selection strategies for different stages. For example, with the increase in population and industrial development, the composition and concentration of pollutants in sewage may change, and processes that can effectively treat new pollutants need to be selected. For the improvement of processing capability, it can be achieved by increasing the number of processing units and optimizing the operating parameters of existing units [5]. At the same time, it is necessary to ensure that the expanded process can operate in coordination with the original process, avoiding problems such as poor connection, in order to ensure the stable and efficient operation of the sewage treatment plant.

4.1.2. Network sewage plant linkage regulation and storage mechanism

To achieve optimization of the water supply and drainage system, it is necessary to synergistically optimize the storage capacity of the pipeline network and the treatment process of the sewage plant. On the one hand, analyzing the storage capacity characteristics of the pipeline network, including the influence of different pipe diameters, materials, and laying methods on storage, and determining its storage potential under different working conditions [6]. On the other hand, in combination with the treatment process requirements for the expansion of the sewage treatment plant, the two should be matched with each other. For example, for biological treatment processes, it is necessary to ensure the stability of the water quality and quantity of the sewage transported by the pipeline network, and to avoid the impact of shock loads on microorganisms. When constructing a peak load response plan for the rainy season, the storage capacity of the pipeline network is utilized to temporarily store excess rainwater, and the flow entering the sewage treatment plant is reasonably allocated to avoid overloading. At the same time, by optimizing the operating parameters of the sewage treatment plant, the treatment efficiency is improved to ensure that the effluent quality meets the standards.

4.2. Intelligent operation of expansion projects

4.2.1. Optimization design of an intelligent control system

Develop an intelligent aeration control system based on MBR technology, which can accurately control the aeration process of sewage treatment plants. By monitoring various indicators in sewage in real-time, such as dissolved oxygen content and organic matter concentration, the system can automatically adjust the aeration intensity and time according to preset algorithms. This can ensure effective treatment of pollutants in sewage and avoid energy waste caused by excessive aeration, thereby achieving a balance and optimization of energy consumption and treatment efficiency. The system can also be integrated with other intelligent control systems of the sewage treatment plant to achieve information sharing and collaborative work, further improving the overall operational efficiency and management level of the sewage treatment plant [7].

4.2.2. Application practice of digital twin technology

Building a digital twin model for sewage treatment plants is the key to achieving collaborative optimization and intelligent operation of sewage plant expansion projects. By accurately collecting physical data of sewage treatment plants, including equipment operating parameters and water quality and quantity changes, advanced modeling techniques are used to create virtual digital twin models. This model can reflect the actual operating status of sewage treatment plants in real time and simulate and analyze expansion projects. By simulating different operating conditions and expansion plans, the improvement effect of expansion projects on system processing efficiency can be accurately evaluated. For example, predicting the extent of improvement in sewage treatment capacity after expansion and its impact on water quality improvement [8]. This not only provides a scientific basis for engineering decision-making but also enables refined management and optimized control of sewage treatment plants through the interaction between digital twin models and actual systems during operation.

5. Collaborative development mechanism and empirical research

5.1. Space collaborative planning mechanism

5.1.1. Analysis of the linkage between pipeline coverage and plant site selection

In the optimization of water supply and drainage systems, the linkage between pipeline coverage and plant site selection is crucial. Using geographic spatial analysis techniques, taking into account multiple factors such as terrain, population distribution, and water flow direction [9], optimize the topology structure of the pipeline network and the site selection plan for sewage treatment plants. Firstly, analyze the weak areas covered by the existing pipeline network and potential locations for sewage treatment plant construction to improve sewage collection efficiency. By simulating the water flow path and pollutant diffusion situation, determine the appropriate direction of the pipeline network and the location of the sewage treatment plant to ensure that the sewage can be effectively transported to the treatment plant. At the same time, considering future urban development plans and population growth trends, space is reserved for pipeline network expansion and sewage plant expansion to achieve sustainable and coordinated development of the water supply and drainage system.

5.1.2. Comprehensive utilization mode of land resources

The composite utilization mode of land resources under the spatial collaborative planning mechanism is crucial in optimizing the water supply and drainage system. Reasonable spatial coordination development is required between underground pipe galleries and above-ground facilities. For example, in combination with the expansion needs of sewage treatment plants, when planning land use, the construction of underground pipe galleries can be integrated with the layout of sewage pipelines to improve land use efficiency while ensuring the efficient operation of the water supply and drainage system [10]. At the same time, the expansion of above-ground facilities such as sewage treatment plants should be coordinated with the surrounding land use planning to avoid adverse effects on the surrounding environment and other land uses. By reasonably planning the spatial layout of underground pipe galleries and above-ground facilities, the composite utilization of land resources can be achieved, promoting the optimization of water supply and drainage systems and the coordinated development of the entire urban infrastructure.

5.2. Management collaborative innovation mechanism

5.2.1. Whole-lifecycle cost control system

Establishing a joint investment decision-making model that covers pipeline maintenance and sewage plant expansion is key to achieving whole-lifecycle cost control. This model needs to comprehensively consider the cost factors of the pipeline network and sewage treatment plant at different stages, including construction costs, operating costs, and maintenance costs. During the construction phase, it is necessary to weigh the impact of pipeline materials, pipe diameters, sewage treatment processes, and scale on costs. During the operation process, analyze the impact of changes in sewage treatment capacity and water quality on costs. At the same time, consider factors related to maintenance costs, such as maintenance frequency and the difficulty of repairs. By integrating these factors, a dynamic joint investment decision-making model is constructed to achieve the rational allocation of resources, minimize the whole-lifecycle cost, and promote the coordinated development of pipeline maintenance and sewage plant expansion and operation in the water supply and drainage system.

5.2.2. Construction of a cross-departmental information sharing platform

Building a cross-departmental information-sharing platform is crucial in the water supply and drainage system. Design a data exchange mechanism for water supply and drainage facility management based on blockchain technology, which can achieve secure and efficient data sharing. The distributed ledger feature of blockchain ensures the immutability and traceability of data, making the maintenance, operation, and other aspects of water supply and drainage facilities data authentic and reliable. Different departments can obtain the required information in real time through this platform, such as the pipeline maintenance department being able to timely understand the operation data of the sewage plant in order to arrange maintenance plans reasonably; wastewater treatment plants can also obtain real-time information on the pipeline network and optimize expansion and operation strategies. This information-sharing mechanism breaks down information barriers between departments, improves collaborative work efficiency, and promotes the overall optimization and sustainable development of the water supply and drainage system.

5.3. Empirical study: A case study of the Guangdong Hong Kong Macao Greater Bay Area

5.3.1. Analysis of regional load characteristics

The industrial agglomeration area in the Greater Bay Area has a unique industrial structure, and its special water quality characteristics have multiple impacts on the coordinated development of the water supply and drainage system. On the one hand, some industries, such as electronic information and biomedicine, may discharge wastewater containing special chemicals, which puts higher demands on the treatment process of sewage plants. These substances may affect microbial activity, reduce sewage treatment efficiency, and increase treatment costs. On the other hand, the variation in water quantity of special water quality may be related to the industrial production cycle, leading to unstable inflow load of sewage treatment plants. For example, some industries may discharge large amounts of wastewater during peak production seasons, exceeding the treatment capacity of sewage plants, while during off-seasons, the amount of wastewater discharged sharply decreases, affecting the stable operation of sewage plants. This requires full consideration of these special water quality characteristics in the coordinated development process of pipeline maintenance and sewage plant expansion and operation, in order to achieve efficient operation of the water supply and drainage system.

5.3.2. Evaluation of collaborative optimization effectiveness

Validate the benefits of collaborative development through the PSR model. At the Pressure level, evaluate the pressure of population growth, urbanization process, and other factors on the water supply and drainage system, as well as how inadequate maintenance of the pipeline network and insufficient expansion of sewage treatment plants exacerbate these pressures. At the State level, analyze the operational status of the existing water supply and drainage system, including the degree of pipe network aging, sewage treatment capacity, etc., to determine the starting point for collaborative optimization. At the Response level, consider the implementation of pipeline maintenance measures and sewage plant expansion and operation strategies, as well as their mutual coordination effects. By integrating the three levels of PSR, constructing an indicator system, using appropriate data analysis methods, and quantifying the benefits of collaborative development, such as the improvement of sewage discharge rate and water resource recycling rate, it provides a basis for the continuous optimization of the water supply and drainage system.

6. Conclusion

The optimization of water supply and drainage systems is crucial for the sustainable development of cities. The coordinated development of pipeline maintenance and sewage plant expansion and operation is the key to achieving this goal. Through collaborative optimization, the efficiency and reliability of the water supply and drainage system can be improved, reducing energy consumption and environmental pollution. The implementation path includes strengthening pipeline monitoring and maintenance, optimizing sewage treatment processes, and improving water resource recycling and utilization. The value of innovation lies in improving the adaptability and resilience of the system, and promoting the sustainable development of cities. In the future, digital twins and low-carbon treatment technologies will provide new opportunities and challenges for optimizing water supply and drainage systems. Facing the new urbanization, it is necessary to further strengthen the integration and optimization of the water supply and drainage system, improve the intelligence level and management efficiency of the system, and achieve sustainable utilization of water resources and sustainable development of cities.

Disclosure statement

The author declares no conflict of interest.

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