Study on Green Design and Operation Optimization of Urban Drainage System under the Concept of Low Carbon

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Abstract: Under the background of China's "double carbon" strategy, the traditional "quick discharge" drainage system is in urgent need of low-carbon transformation due to high energy consumption, high emission and ecological fragmentation effect. In this study, a multi-objective collaborative optimization framework of "low-carbon-elasticity-economy" was constructed: ① A dynamic carbon footprint evaluation system covering the whole life cycle was established, and the carbon emission of "grey-green-blue" facilities was quantified in real time by SWMM-LCA (storm water management model-life cycle evaluation) coupling model, and the concept of "carbon sensitivity" was put forward to reveal its collaborative mechanism; ② In the planning and design stage, SWMM-LCA iteration is driven by NSGA-II algorithm to optimize the layout and scale of pipe network and green infrastructure, and realize Pareto optimization of carbon emission, waterlogging risk and cost; ③ In the operation stage, an intelligent control platform based on deep reinforcement learning (DRL) is developed, with the real-time hydrological state as the input, the start-stop of the pumping station and the opening of the gate are dynamically adjusted, so as to reduce the operation energy consumption. The empirical study shows that compared with the traditional scheme, the carbon emission of the optimized "gray-green combination" scheme is reduced by 40%, the waterlogging amount is reduced by 72%, and the life cycle cost is only increased by 3.3%. DRL real-time control can further save energy by 23.5% in a single rainstorm, and the annual emission reduction benefit is remarkable. The integrated framework of "optimal design-intelligent operation" proposed in this study provides feasible technical path and decision support for the low-carbon transformation of urban drainage system.

1. Introduction

The traditional "fast drainage" mode drainage system faces double challenges: on the one hand, pumping station lifting and pipe network transportation consume a lot of electric energy, which indirectly produces high-intensity carbon emissions; On the other hand, the hardened surface cuts off the natural infiltration path of rainwater, which intensifies the urban heat island effect and water shortage [1]. In this context, China's "Double Carbon" strategy clearly requires that the infrastructure sector should achieve peak carbon dioxide emissions by 2030. As a key component of the urban lifeline project, the low-carbon transformation of the drainage system has become an inevitable choice to realize the sustainable development of the city.

In this study, a multi-objective collaborative optimization framework of "low carbon-elasticity-economy" was constructed, which broke through the single water safety orientation of traditional drainage system. Initiate the concept of "carbon sensitivity", establish the response model between design parameters and carbon emission, and reveal the carbon synergy mechanism of "grey-green-blue" facilities by using the theory of complex adaptive system; A SWMM-LCA (storm water management model-life cycle evaluation) coupling simulation platform is developed to realize dynamic carbon assessment, and an intelligent scheduling algorithm for pumping stations is proposed based on deep reinforcement learning (DRL) to reduce energy consumption in storm simulation.

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2. Research method

2.1 Multi-scale carbon footprint assessment system

This system focuses on quantifying the carbon emissions of the drainage system in the whole life cycle from construction to abandonment, paying special attention to the carbon emissions of "grey facilities" and "green facilities". Its goal is to upgrade the traditional static carbon emission inventory to a dynamic carbon emission assessment that can reflect the impact of rainfall process through the combination of dynamic process LCA and SWMM [2-3].

The core method adopts the coupling method of dynamic process LCA and SWMM, and the key is to use the real-time dynamic data obtained by SWMM simulation as the input of LCA. Formula (1) is used to calculate the carbon emission of pumping stations in the operation stage.

$$C_{pump} = \sum_{t=1}^{T} \left[P_t \times EF_{electricity} \times \Delta t \right] \quad (1)$$

Where C_{pump} represents the total carbon emission of a single pumping station in a rainfall event, P_t is the instantaneous power of the pumping station, $EF_{electricity}$ is the power carbon emission factor of the local power grid, Δt is the simulation time step, and T is the total simulation duration.

A SWMM model suitable for specific scenarios is constructed, and time series data such as energy consumption of pumping stations and water volume changes of facilities are obtained through this model. Subsequently, these data are imported into the pre-built LCA inventory database, which contains carbon emission factors in building materials, transportation, operation and maintenance. Finally, based on the above information, the carbon emission of the system at any time scale in the whole life cycle is calculated, so as to realize the comprehensive evaluation of the carbon footprint of the drainage system.

2.2 Low-carbon design optimization model

The low-carbon design optimization model aims to determine the optimal allocation ratio and spatial layout of gray infrastructure and green infrastructure through scientific methods in the planning and design stage of drainage system, and realize multi-objective collaborative optimization of low carbon, flexibility and economy [4]. The model takes the multi-objective optimization algorithm NSGA-II as the core, and drives the coupling system of SWMM model and LCA carbon footprint evaluation platform to perform iterative simulation, so as to search the optimal solution among a large number of possible schemes [5].

In the process of optimization, decision variables include design parameters such as pipe diameter D and slope i of gray facilities, and key indicators such as biological retention pool area and infiltration channel depth of green facilities. The model sets three minimization objective functions:

$$\left.\begin{aligned} F_{carbon} &= C_{construction} + C_{operation} \\ F_{flooding} &= \sum_{t=1}^{T} \left(V_{flood}, t \right) \\ F_{cost} &= Cost_{capital} + Cost_{O\&M} \end{aligned}\right\} \quad (2)$$

One is the total carbon emission F_{carbon} (covering the construction and operation stages), the other is the total waterlogging overflow $F_{flooding}$ (measuring system toughness), and the third is the total life cycle cost F_{cost} (including construction and operation and maintenance expenses). At the same time, the optimization process should meet the engineering and planning constraints such as pipeline velocity, node water depth, green space rate and investment budget to ensure the feasibility of the scheme.

The implementation process is shown in Figure 1. The optimization algorithm generates the initial design scheme combination, automatically calls SWMM-LCA platform for hydraulic simulation and carbon emission accounting, and obtains the objective function values of each scheme; Based on this, the algorithm evaluates the performance of the scheme and generates a new generation scheme, which finally converges to Pareto optimal solution set through several rounds of iteration [6]. The solution set provides a series of feasible schemes with different trade-offs among carbon emission, flood control ability and economy, and assists decision makers to make scientific choices according to actual needs [7].

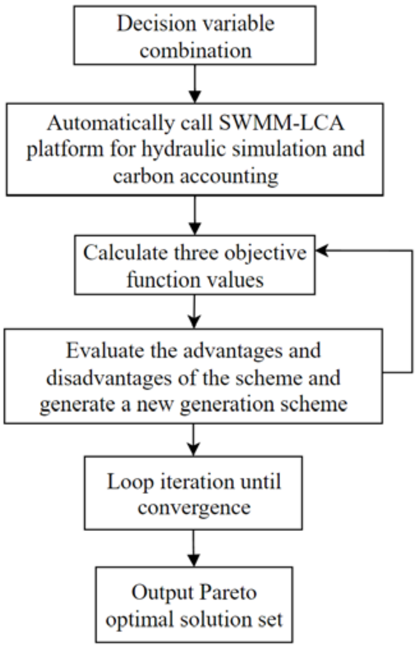

Figure 1 Implementation process

2.3 Intelligent operation control platform

The intelligent operation control platform is dedicated to the efficient operation of the drainage system after its completion. By optimizing the control strategy in real time, it can dynamically adjust the operation states such as the start and stop of the pumping station and the opening of the gate, so as to minimize the energy consumption and carbon emissions of the system under the premise of ensuring the safety of flood control and drainage [8]. The platform breaks through the limitations of traditional empirical or fixed rule control, realizes the transformation from passive response to active intelligent regulation, and improves the low-carbon and intelligent level of system operation.

The core method of the platform adopts DRL, especially the DDPG (Deep Deterministic Policy Gradient) algorithm suitable for continuous control tasks [9-10]. In the model, the control system, as an Agent, constitutes a state space (s_t) with real-time rainfall intensity, water level at key nodes and water level in the forebay of the pumping station, and takes the speed regulation or gate opening of the pumping station as an action space (a_t). The reward function r_t is designed as a comprehensive index, including energy consumption P_t, overflow V_{flood},t and water level deviation $\left|H_t - H_{set}\right|$, which are balanced by the weight coefficient α, β, γ, which not only encourages energy saving and carbon reduction, but also severely punishes the risk of waterlogging, while maintaining the stability of water level and ensuring the safety of facilities.

$$r_t = -\alpha P_t - \beta V_{flood},t - \gamma\left(\left|H_t - H_{set}\right|\right) \quad (3)$$

In the simulation environment, DRL agent learns from "reward" and "punishment" by interacting with SWMM model for millions of times, and finally trains a neural network model that can automatically give the optimal control instruction (a_t) according to the real-time hydrological state (s_t), thus realizing the leap from "passive response" to "active intelligent optimization".

3. Empirical research

A new town area (with an area of about 5 km^2) being planned in the south of China is selected as the empirical research object. Based on topographic map, land use planning map and rainfall data, the SWMM model of this area is constructed. The traditional scheme (Business-as-Usual, BAU) mainly adopts the "grey" infrastructure, and designs a large-scale pipe network and a central lifting pump station. For comparison, several schemes of integrating green infrastructure (GI) are set up, and different planning scenarios are formed by adjusting the area ratio of biological detention ponds, infiltration pavements and other facilities (from 10% to 30%).

Using NSGA-II algorithm, taking the layout and size of pipe network and GI as decision variables, and taking LCA carbon emissions, total waterlogging and total cost as objective functions, the optimization solution is carried out. After thousands of iterations, the optimal solution set (Pareto frontier) is obtained. It can be seen from Table 1 that Scheme B achieves the best balance among carbon emission, waterlogging control and cost. Compared with the traditional BAU scheme, its carbon emission is reduced by 40%, waterlogging is reduced by 72%, and the cost is only slightly increased by 3.3%, which proves that the "gray-green combination" mode has great potential for low-carbon emission reduction and elastic improvement.

Table 1 Multi-objective performance comparison under different planning schemes

Plan	Proportion of green facilities	Total carbon emission (ton CO_2-eq)	Total waterlogging (m^3)	Life cycle cost (100 million yuan)
Traditional scheme (BAU)	0%	8,500	15,000	3.0
Program A	15%	6,200	8,500	2.8
Scheme B (recommended)	25%	5,100	4,200	2.9
Scheme C	30%	4,800	3,500	3.3

On the basis of the layout of Scheme B, the traditional fixed water level start-stop control (Baseline) and the trained DDPG intelligent algorithm are used to simulate a rainstorm event with a recurrence period of 5 years (see Figure 2). The results show that the traditional method has some problems such as frequent start and stop of pumping stations and delayed response, and the energy consumption of a single rainstorm event is as high as 285 kWh； . However, DRL intelligent control can effectively avoid unnecessary peak energy consumption by predicting the incoming flow in advance and smoothly adjusting the operation of the pumping station, and reduce the total energy consumption to 218 kWh, achieving an energy saving rate of 23.5%, which is equivalent to reducing carbon emissions by about 180 kg CO_2-eq, showing a remarkable energy saving and carbon reduction effect. If it is extended to the whole year operation, the emission reduction benefits will be even more impressive.

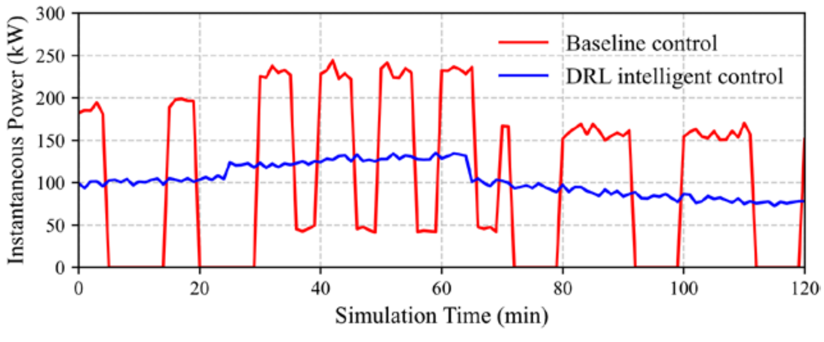

Figure 2 Comparison of energy consumption of pumping station during rainstorm

The introduction of green infrastructure and multi-objective collaborative optimization in the planning and design stage can greatly reduce the carbon emissions of the whole life cycle of the system from the source and enhance the climate resilience. The real-time control strategy based on

DRL can further "tap" the low-carbon operation potential of the built system and realize the leap from "static low carbon" to "dynamic low carbon". The integrated framework of "optimal design-intelligent operation" provided an effective technical path and decision support for the low-carbon transformation of drainage system.

4. Conclusion

Under the guidance of low-carbon concept, this study puts forward a multi-objective collaborative optimization framework of "low-carbon-elasticity-economy" in view of the dual challenges faced by urban drainage system. By constructing multi-scale carbon footprint evaluation system and low-carbon design optimization model, the green transformation of drainage system in planning and design stage is realized. The empirical study shows that scheme B with "gray-green combination" mode reduces carbon emissions by 40% and waterlogging by 72% compared with the scheme with traditional "gray" infrastructure, while the cost is only slightly increased by 3.3%. In addition, the intelligent operation control platform based on deep reinforcement learning significantly reduces energy consumption and carbon emissions by optimizing the start and stop of pumping stations and the opening of gates in real time, and the energy saving rate of a single rainstorm event reaches 23.5%. These results prove the effectiveness of the proposed integrated framework in realizing low-carbon transformation of drainage system, and provide technical path and decision support for urban sustainable development.

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