Model and Application Research on the Collaborative Design of Stormwater Comprehensive Utilization and Drainage Network

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Abstract: The problem of urban rain and flood is severe, and the single system research can't meet the demand. This article is devoted to building a scientific collaborative design model to improve the urban storm water management ability. In this study, the system dynamics method and GIS technology are used to build a model including rainwater generation, collection and utilization, drainage pipe network and decision feedback module, and the improved SCS curve number method, linear programming algorithm and hydrodynamic algorithm based on Saint-Venant equations are used. The model is applied to the emerging urban area of a medium-sized city, and the classic rainstorm event proves that the error rate of simulation of rainwater production is 4.17%, the error rate of rainwater collection is 6.06%, the error rate of drainage pipe network is 2.27%, and the error rate of waterlogging depth is -16.67%. The application results show that after optimization, the utilization rate of rainwater collection is increased by 15% to 30%, the drainage efficiency of drainage pipe network is increased by 10%, and the frequency of waterlogging is reduced by about 30%. The research shows that the model has high accuracy and reliability, and can effectively optimize urban rain and flood management and drainage pipe network design.

1. Introduction

With the acceleration of global urbanization, the scale of the city continues to expand, the population density is increasing, and the hydrological environment of the city has undergone profound changes. As one of the important challenges in urban development, the problem of rain and flood is attracting more and more attention [1]. With the rapid increase of urban impervious area, such as the extensive laying of buildings and roads, the speed of surface runoff formed by rainfall is accelerated and the peak flow is increased. This makes the risk of urban floods significantly increased [2]. Futhermore, the shortage of water resources is becoming more and more serious in many cities, and urban water supply is under great pressure. Under this background, it is particularly urgent to study the collaborative design of rainwater comprehensive utilization and drainage pipe network.

The purpose of comprehensive utilization of rainwater and flood is to transform rainwater originally regarded as "disaster" into available water resources through a series of scientific and reasonable technologies and measures, and realize efficient recycling of water resources [3]. For example, by building a rainwater collection system, rainwater in areas such as roofs and pavements can be collected and purified for urban greening irrigation, landscape water supply, road washing and even some industrial production links [4]. As the core component of urban drainage system, drainage pipe network plays a role in timely and effectively eliminating surface runoff caused by rainfall and preventing urban waterlogging [5]. A reasonably designed drainage pipe network can ensure that rainwater can quickly gather and be smoothly discharged to natural water bodies or other designated places according to urban topography, landforms and rainfall characteristics [6].

Traditional rainwater management often regards the comprehensive utilization of rainwater and the design of drainage pipe network as two relatively independent parts, lacking systematicness and coordination [7]. This separate design concept makes it difficult for them to give full play to their respective advantages in the actual operation process, and even there may be mutual constraints [8].

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For example, the unreasonable layout of rainwater collection facilities may lead to the imbalance of water entering the drainage pipe network and increase the drainage pressure of the pipe network; On the other hand, if the design of drainage pipe network does not consider the demand of comprehensive utilization of rainwater and flood, it may miss the opportunity to collect and utilize some high-quality rainwater resources.

Part of the research focuses on the innovation and optimization of rainwater comprehensive utilization technology, such as developing new rainwater collection materials and improving rainwater purification technology [9]. Other studies focus on the hydraulic model construction and optimal design of drainage pipe network to improve the drainage efficiency of the pipe network and the ability to cope with extreme rainfall events [10]. However, the systematic research on the collaborative design of rainwater comprehensive utilization and drainage pipe network is still insufficient, lacking a complete, scientific and widely applicable theory and method system. The purpose of this article is to study the model and application of collaborative design of rainwater comprehensive utilization and drainage pipe network. By constructing a scientific and reasonable collaborative design model, considering all aspects of rain and flood generation, collection and utilization and the operation of drainage pipe network, the internal relationship and interaction mechanism between them are explored, so as to achieve efficient utilization of urban water resources and effective prevention and control of flood disasters.

2. Collaborative design model of comprehensive utilization of rain and flood and drainage pipe network

The purpose of this model is to realize the efficient utilization of rain and flood resources and the optimal operation of drainage pipe network system, and to ensure the safety of urban flood control and drainage and improve the comprehensive benefits of water resources as much as possible. The model construction follows the scientific principle and ensures the rationality and reliability of the model according to the theories of hydrology, hydraulics and other related disciplines. It is necessary to follow the systematic principle, comprehensively consider all links of rain and flood generation, collection, utilization and drainage pipe network, and design it as an organic whole; It also follows practical principles, so that the model can meet the actual engineering requirements and has operability and application value. System dynamics method is selected to build the model. Based on feedback control theory, system dynamics can effectively simulate the dynamic change process of complex systems with time by establishing causality diagram and flow diagram. This method is suitable for dealing with the comprehensive utilization of rain and flood and the drainage pipe network, which involves the interaction of multiple variables and factors and has dynamic characteristics. Futhermore, with the help of geographic information system (GIS) technology, the spatial data such as topography and land use can be accurately obtained, which can provide accurate basic information for the model and enhance the simulation ability of the model on spatial distribution characteristics.

The model mainly consists of rain and flood generation module, rain and flood collection and utilization module, drainage pipe network module and decision feedback module. According to the rainfall data, soil type, vegetation coverage and other factors, the rain flood generation module simulates the process of surface runoff formed by rainfall. The rainwater collection and utilization module includes elements such as rainwater collection facilities, storage facilities and utilization channels, and calculates the rainwater collection and availability in different scenarios. The drainage pipe network module simulates the flow and discharge process of rainwater in the pipe network according to the parameters such as pipe network layout, pipe diameter and slope. The decision feedback module provides an optimized decision scheme according to the operation results of the first three modules, and feeds back the decision information to other modules to realize the dynamic adjustment of the system. The improved SCS curve number method is used to generate rain and flood. In this method, the factors such as soil moisture and land use type in the early stage are considered, and the runoff generated by rainfall is obtained by calculating the number CN of runoff curves:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (1)$$

$$S = \frac{25400}{CN} - 254 \quad (2)$$

Where: Q is runoff, P is rainfall, and S is potential maximum storage capacity. By updating the parameters such as soil moisture in real time, the algorithm is more suitable for the actual rainfall-runoff process.

Rainwater and flood collection and utilization use linear programming algorithm, take the maximization of rainwater and flood utilization benefit as the objective function, and consider the constraints such as collection facility capacity and utilization demand. The objective function is:

$$MaxZ = \sum_{i=1}^{n} a_i x_i \quad (3)$$

Among them, Z is the total benefit of rainwater utilization, a_i is the benefit coefficient of i utilization mode, and x_i is the rainwater utilization amount of i utilization mode. Constraints include the capacity limit of collection facilities, the upper and lower limits of different water demand, etc.

Simplification and discrete solution based on Saint-Venant equations. Using Preissmann four-point implicit difference scheme, the continuity equation and momentum equation are discretized in space and time, and the relationship between water level and flow rate of each node in the pipe network with time is obtained. Through iterative calculation, the dynamic flow process of rainwater in the pipe network is simulated, and the drainage capacity and operation state of the pipe network are evaluated.

3. Application example of collaborative design model of rain and flood drainage pipe network

The experiment selects the emerging urban area of a medium-sized city as the application case area. The area covers an area of 30 square kilometers, and the terrain is relatively flat with an average slope of about 0.3%. There are various types of land use in the region, including residential land accounting for 35%, commercial land accounting for 15%, public green land accounting for 20%, industrial land accounting for 10%, and roads and other land accounting for 20%. The average rainfall in this area for many years is 800 mm, and the rainfall is concentrated in May-September, with heavy rain, and waterlogging disasters have occurred many times in history.

Firstly, GIS technology is used to collect and process the data of topography and land use in this area, which provides accurate basic information for the model. The collected rainfall data, soil types and other data are input into the rain flood generation module, and the improved SCS curve number method is used to simulate the rain flood generation process in this area. In the rainwater collection and utilization module, according to the planned rainwater collection facilities capacity and different water demand in this area, the linear programming algorithm is used to calculate the rainwater collection and utilization. For the drainage pipe network module, according to the layout, pipe diameter, slope and other parameters of the existing drainage pipe network in this area, the simplified discrete hydrodynamic algorithm based on Saint-Venant equations is adopted to simulate the flow and discharge of rainwater in the pipe network. Through the decision feedback module, the optimization decision is provided according to the operation results of each module, and the model parameters are dynamically adjusted. Table 1 takes a typical rainstorm event in this region (rainfall of 100 mm, duration of 6 hours) as an example for comparison.

Table 1 Model Simulation Results Under Typical Rainstorm Event

Assessment Metric	Model Simulated Value	Actual Monitored Value	Absolute Error	Relative Error Rate
Rainwater yield (m^3)	125,000	120,000	5,000	4.17%
Rainwater collection (m^3)	35,000	33,000	2,000	6.06%
Drainage volume (m^3)	90,000	88,000	2,000	2.27%
Waterlogging depth (cm)	5	6	-1	-16.67%
Utilization rate of collection facilities (%)	70	68	2	2.94%
Pipe network overload duration (h)	1.5	1.8	-0.3	-16.67%

As can be seen from Table 1, the model is close to the actual monitoring value in all key indicators, and the error rate is within the acceptable range, indicating that the model has high accuracy and reliability.

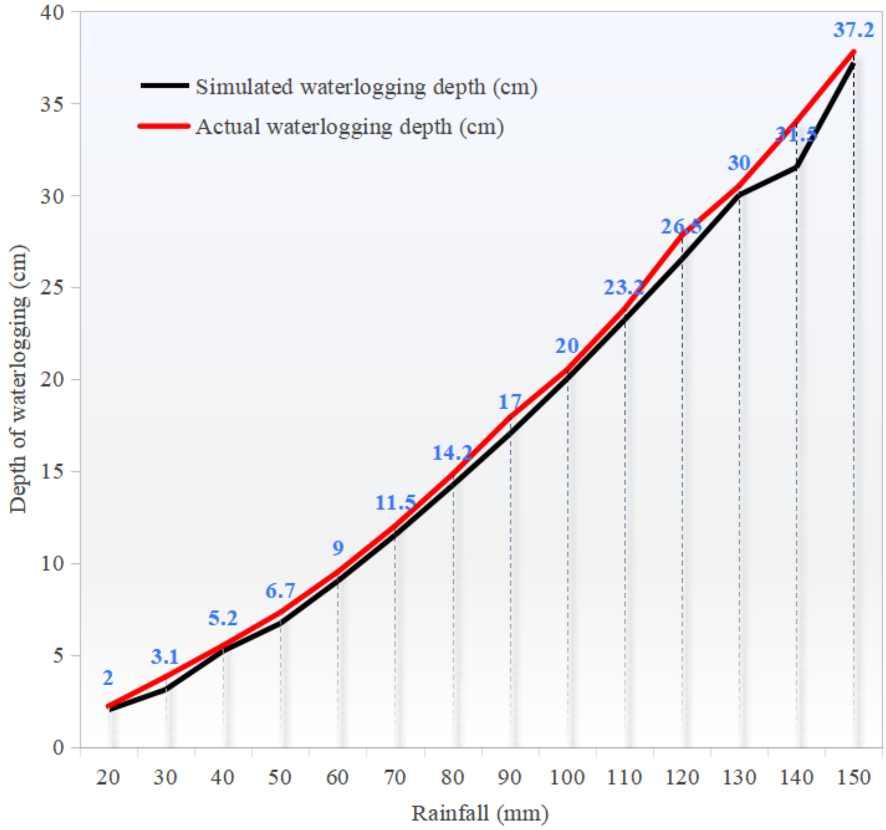

Figure 1 Comparison between simulation and practice of waterlogging depth

Further analyze the simulation effect of the model on the depth of regional waterlogging under different rainfall conditions, as shown in Figure 1. With the increase of rainfall, the trend of changes in the depth of waterlogging simulated by the model is basically consistent with the actual situation, which once again verifies the good simulation ability of the model for the comprehensive utilization of rainwater and flood and the coordinated operation of drainage networks in the region. The comparison of the comprehensive utilization of rainwater and flood in the case area and the optimization of the drainage network before and after is shown in Table 2.

Table 2 Comparison of Stormwater Utilization and Drainage Network Performance Before/After Optimization

Assessment Item	Pre-Optimization	Post-Optimization	Change	Regional Impact
Rainwater utilization rate	15%	30%	+15%	Alleviates water scarcity
Drainage efficiency (m^3/h)	800	880	+10%	Enhanced drainage capacity
Waterlogging frequency (annual)	10	~7	~30% reduction	Significant flood mitigation improvement

By applying this model, the comprehensive utilization of rain and flood and the drainage pipe network in the case area are optimized. After optimization, the rainwater collection and utilization rate increased by 15%, reaching 30%, which alleviated the shortage of water resources in the region. Futhermore, the drainage efficiency of the drainage pipe network increased by 10%, and the frequency of waterlogging decreased by about 30%, which significantly improved the flood control and drainage situation in the region. The successful application of this model in this case area provides an effective reference for rain and flood management and drainage pipe network design in other similar areas.

4. Conclusions

In this article, a collaborative design model of rainwater comprehensive utilization and drainage pipe network is constructed, and a series of results are obtained through practical case analysis. From the point of view of model construction, the system dynamics method combined with GIS technology fully considers all links of rain and flood generation, collection and utilization and drainage pipe network. Each module complements each other and uses a variety of scientific algorithms to ensure accurate simulation. In terms of model application and performance assessment, the model is applied to a specific emerging urban case. By comparing with the actual monitoring data, it is found that the error rate of the model is at a low level in the simulation of key indicators such as rainfall and flood generation, collection, drainage pipe network displacement and waterlogging depth. This verifies the accuracy and reliability of the model and can accurately reflect the actual rain and flood and drainage situation. From the application effect, after the model optimization design, the utilization rate of rainwater collection in this area has been significantly improved, by 15%, reaching 30%, effectively alleviating the problem of regional water shortage; Futhermore, the drainage efficiency of the drainage pipe network increased by 10%, the frequency of waterlogging decreased by about 30%, and the urban flood control and drainage situation was obviously improved.

To sum up, the model constructed in this study is feasible, which provides scientific and effective methods and ideas for urban rain and flood management and drainage pipe network design. However, there are some limitations in the research, such as not fully considering the impact of extreme climate events on the model. On this basis, future research can further improve the model and enhance its adaptability to complex and changeable climatic conditions.

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