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The Governance and Optimization of Urban Flooding in Dense Urban Areas Utilizing Deep Tunnel Drainage Systems: A Case Study of Guangzhou, China

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Abstract: With urban expansion, traditional drainage systems in densely populated cities face significant challenges, leading to frequent flooding and pollution issues. Deep tunnel drainage systems emerge as an innovative approach, offering underground storage for excess precipitation and alleviating urban inundation. This research investigates the deployment of a deep tunnel system in Guangzhou's densely populated urban core. By integrating with existing networks, this system aims to curtail over-flow contamination and boost sewage-handling capacity. Successful implementation hinges on the thorough evaluation and synchronization with broader urban development objectives. In Guangzhou, where traditional methods fall short, deep tunnels present a viable option. This study explores techniques for identifying drainage deficiencies, devising enhancements, and refining citywide strategies. Economic analysis indicates that deep tunnels are more cost-effective than conventional drainage upgrades, offering long-term benefits for land conservation and drainage efficiency. Following implementation, these systems markedly enhance sewage management, diminish overflow incidents, and improve pollution mitigation. Although initial investments are substantial, the enduring advantages in land preservation and drainage efficiency are significant. Thus, deep tunnel systems emerge as a practical flood control solution for high-density urban areas like Guangzhou, fostering sustainable metropolitan growth.

Keywords: deep tunnel drainage systems; urban flooding; densely populated urban core; combined sewer overflow (CSO)

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1. Introduction

With urban expansion, original reservoirs, hills, lakes, and fish ponds are gradually being encroached upon, and river cross-sections are narrowing. This significantly reduces the city's water storage, drainage, and natural purification capacities, making it highly susceptible to flooding during heavy rains that exceed its drainage capacity [1,2]. Furthermore, the high population density rapidly increases urban pollution loads, exacerbating overflow pollution in areas with combined sewer systems during the rainy season [3].

In the development of urban drainage systems, two focal issues have always been the discharge of industrial and domestic wastewater, and the discharge of rainwater [4]. Almost all old cities within the country and abroad use combined drainage systems. In practice, combined drainage systems allow part of the combined sewage to overflow directly into rivers during rainy weather, which seriously pollutes water bodies. To overcome this drawback, separate drainage systems have emerged, and most newly built urban drainage systems adopt separate systems. However, separate systems also have certain drawbacks: they are relatively expensive, and urban surface water is not clean, especially the initial runoff formed during the early stages of rainfall, which, if directly discharged into water bodies, can cause significant pollution.

Due to the limited areas suitable for implementing separate systems, many areas still maintain combined systems. Scattered separate areas cannot form a system, creating a mixed drainage system of separate and intercepted combined systems, unable to leverage the advantages of separate systems. Currently, none of the eight major sewage systems in Guangzhou's central urban area can fully operate according to separate systems.

Analyzing the actual construction of separate systems in recent years reveals the main problems in promoting separate system renovation:

(1) Partial coverage of separate systems leads to a chaotic overall drainage system: scattered separate areas within a predominantly intercepted combined system face significant difficulties in connecting with the old combined system, especially when separate areas are between two combined areas. The effectiveness of separate systems is very limited;
(2) It is difficult to achieve true separate drainage in separate areas: due to the lack of separate discharge systems among drainage users and their non-standard discharge methods, separate pipelines built along municipal roads cannot achieve true separation. New rainwater pipelines often discharge into sewage pipelines due to environmental pressure, turning new separate systems back into combined drainage systems;
(3) Investment in separate systems is large, making promotion difficult: separate areas are often densely populated, involving house demolition, protection, road restoration, pipeline relocation, and traffic relief issues, requiring significant construction costs. The end of the pipeline network involves renovating drainage systems for users, significantly impacting residents' daily lives. Difficulty in fully understanding all built drainage systems at the drainage terminals can lead to connection errors, causing drainage congestion and flooding issues, further complicating project construction and making promotion difficult;
(4) The initial rainwater pollution problem is not addressed: research shows that the pollution concentration of initial rainwater is even higher than that of typical domestic sewage. Separate systems, without considering initial rainwater collection, face pollution issues during the rainy season, especially in rain-prone areas like Guangzhou.

In recent years, the deep tunnel drainage system has gained widespread attention due to its significant advantages [5]. The deep tunnel drainage system first appeared in the urban network renovation and reservoir project in Chicago [6], USA. It not only reduced pollution caused by sewage overflow into Lake Michigan but also lowered the risk of urban flooding [7]. Cities with highly developed underground spaces, such as Singapore [8], Tokyo [9], and Hong Kong [10] have also adopted deep tunnel drainage systems to effectively address urban flooding problems. Recently, cities like Shanghai, Guangzhou [11], Wuhan [12], Beijing, Shenzhen, Chengdu, and Chongqing have gradually started the construction and research of deep tunnel drainage systems.

A deep drainage tunnel is a large drainage tunnel (typically 3 to 10 m in diameter) buried in deep underground spaces (below −30 m). During heavy rain, it can temporarily store rainwater underground [13], alleviating urban flooding, and then pump the water out for treatment and discharge after the peak drainage period.

Globally, the construction of deep tunnel drainage systems has been attempted continuously in recent years, achieving certain effects. However, whether a city is suitable for the construction of, or needs, a deep tunnel drainage system requires thorough demonstration during the planning stage for the following reasons: (1) The planning of a deep tunnel drainage system must be consistent with the overall urban drainage plan. (2) It needs to be co-ordinated with the urban underground space utilization plan. (3) It should be effectively connected with the existing and planned urban subway systems. (4) It must consider the comprehensive geological structure of the city. (5) It should be consistent with the construction of shallow drainage systems. Therefore, the construction of deep tunnels should be considered comprehensively around urban development, which is also significant for the city's future development and overall planning.

The existing shallow combined drainage systems generally have a low interception ratio [14] and cannot meet the control needs of Combined Sewer Overflows (CSO) [15]. In the densely populated old urban areas, building new, or expanding existing, combined drainage systems would require sufficient shallow underground pipeline space, making it extremely difficult to balance with the comprehensive urban road pipelines [16]. In areas severely affected by urban flooding in Guangzhou's central urban area, where dense buildings and complex underground pipelines make large-scale renovation of existing drainage systems infeasible, constructing deep tunnels, auxiliary storage, and inflow facilities, along with supporting drainage pumping stations, is a feasible solution to urban flooding. Developing deep underground space by constructing deep tunnel drainage systems can serve as overflow channels for combined sewage, while building CSO sewage treatment plants at the end can increase the interception ratio of the drainage system and control CSO [4].

This paper, based on the current situation of urban flooding and overflow pollution in Guangzhou's urban area, combines the necessity demonstration of urban deep tunnel planning, proposing the deep tunnel drainage system as a supplement to improve the existing urban drainage engineering to alleviate flooding and reduce overflow pollution. It discusses the planning objectives, principles, and overall planning methods of Guangzhou's deep tunnel drainage system, and analyzes the CSO reduction capacity after the deep tunnel construction.

2. Methods

2.1. Deep Tunnel Planning Objectives

Based on the construction of shallow drainage systems, the planning of deep tunnel drainage systems can comprehensively evaluate the functional goals and control strategies of deep tunnels, guiding the construction of deep tunnel drainage systems in central urban areas to ensure systematic and forward-looking construction projects. Further, deep tunnel drainage system planning can co-ordinate with urban control detailed planning, implement planning facility land scale and site selection, and incorporate urban planning and land use planning, providing a basis for water administration management and project construction approval. Therefore, the deep tunnel drainage system is an important part of urban drainage engineering, and it should be combined with the overall urban planning and control detailed planning, arranged from a global perspective. It should follow these principles:

(1) Strictly implement national and local laws, regulations, standards, and specifications;
(2) The deep tunnel drainage system must be combined with local shallow renovation to fully play its role in flood control, drainage, and overflow pollution control, supplementing and enhancing the existing shallow drainage system;
(3) Co-ordinate closely with urban underground space utilization planning, vertical planning, environmental protection planning, and disaster prevention planning, resolving conflicts with subways and other underground facilities to achieve comprehensive utilization of underground space;
(4) Comprehensive planning and reasonable layout benefit water environment protection and water quality improvement. The planning should consider the principles of "combining upstream and downstream, deep and shallow layers";
(5) The planning of deep tunnel drainage systems should be co-ordinated with the long-term relocation of major sewage treatment plants within the planning scope;
(6) Construction of deep tunnel drainage systems should leverage different conditions through dispatching operations to relieve urban flooding, and control initial rain and combined sewage overflow pollution;
(7) Under the premise of meeting the construction goals and functions, investment should be saved, and operating costs minimized as much as possible.

According to the needs of new urbanization, based on the existing shallow drainage systems and river networks, constructing deep tunnel drainage systems can address the "urban flooding" problem in Guangzhou's urban area, raising the drainage standard of urban drainage channels in the corresponding basin from the existing recurrence period of 0.5 to 1 year to a 10-year standard. It also provides conditions for increasing the interception ratio of sewage collection systems in combined areas, and initial rain collection in separate areas.

2.2. Planning Principles of Guangzhou Deep Tunnel Drainage System

Guangzhou is located in South China and is the capital of Guangdong Province. As of the end of 2023, Guangzhou had a permanent resident population of 18.827 million people [17]. Situated in the Pearl River Delta, Guangzhou has a pronounced marine climate. The city is rich in rainwater resources, with an average annual precipitation of over 1800 mm and approximately 150 days of rainfall each year [18]. As a mega-city in China, Guangzhou's central urban area has a high construction density, dense housing, and a large population density, making it difficult to renovate the existing shallow drainage system. Therefore, in addition to following the basic principles mentioned above, the planning of Guangzhou's deep tunnel drainage system should also consider the following key points:

(1) The protection of receiving water bodies and public health in the drainage planning of the catchment area during the rainy season is crucial;
(2) The actual water flow conditions during the rainy season, the collection system, and the operating capacity of sewage treatment plants vary greatly with weather conditions. It is necessary to continuously measure, model, monitor, and evaluate under full weather conditions;
(3) Clarify local rainfall patterns, topography, groundwater conditions, initial soil moisture status, and extreme changes in flood control facilities;
(4) Combine infrastructure operating conditions, and infiltration and inflow increment to comprehensively predict future flow changes;
(5) The operation and maintenance of collection systems and treatment facilities should include strict management of all pollution sources in the basin, effective control of initial rain pollution, and measures to maximize the reduction of dry season overflow pollution;
(6) Under the prerequisite of meeting engineering goals and functions, reduce investment and operating costs as much as possible;
(7) Emphasis on sustainable development: maintain and continue the basic principles of planning and design through information systems, avoid structural and functional defects, minimize environmental impact, and ensure long-term effective operation.

2.3. Overall Planning Method for Guangzhou Deep Tunnel Drainage System

Based on the aforementioned issues, the deep tunnel drainage system in Guangzhou's central urban area ultimately chose the "online combined storage tunnel + flood pumping station" type. This approach combines the characteristics of a combined storage tunnel with a stormwater discharge tunnel, utilizing flexible scheduling to maximize its comprehensive functionality. The overall planning can be summarized in the following four stages:

Stage One: Collect planning data from tributary areas and determine the assessment tools;

Stage Two: Confirm the current development conditions;

Stage Three: Develop and determine the preferred working scheme for the tributary areas;

Stage Four: Integrate the tributary schemes into the overall city plan;

The overall planning process is illustrated in Figure 1.

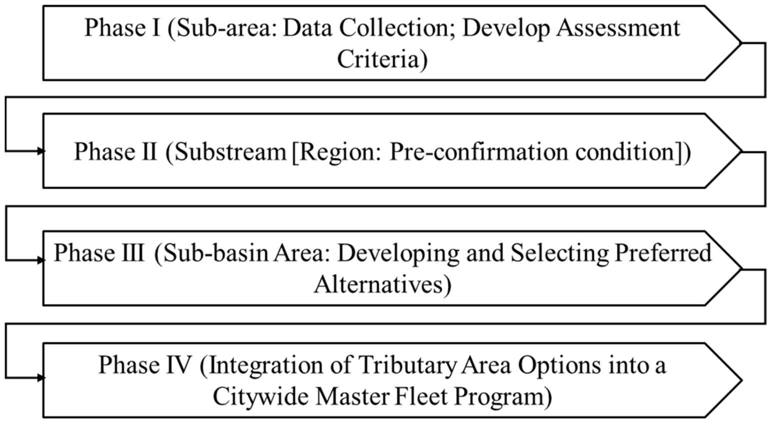

Figure 1. Schematic diagram of general planning method flow in Guangzhou.

Since the adoption of deep tunnel drainage is unprecedented in mainland China, there are numerous technical challenges. Therefore, the first phase requires selecting an experimental section for preliminary exploratory construction. Donghao Creek, as an important river in Guangzhou's old urban area, serves both sewage and flood discharge, as well as landscape functions.

The Dong Hao Creek originates to the west of Chang Yao Ridge on the Baiyun Mountain, with a total basin area of 13.11 km^2. The upper reaches of Donghao Creek are the Lu Lake, which controls a rainwater collection area of 2.52 km^2. The multi-year annual average precipitation is 1676 mm, with 81% of the annual total falling during the flood season (April to September), with the months of May and June having the most concentrated rainfall.

According to the data provided in the "Guangzhou City Flood and Drought Risk Atlas—Yuexiu District Donghao Creek Drainage Area", published by the Guangzhou Municipal Water Affairs Bureau, the storm parameters for the Donghao Creek area are as shown in Table 1.

Table 1. Donghao Creek area storm parameters table.

Duration	**Design Storm Value (mm)**			
	P = 100 Year	**P = 50 Year**	**P = 20 Year**	**P = 5 Year**
1 h	138.6	124.8	106.5	76.8
6 h	252.0	225.0	188.0	131.0
24 h	340.2	303.8	253.8	176.9
72 h	448.6	400.5	334.6	233.2

Note: P is the recurrence periods of the storm.

The Donghao Creek basin, located in the Yuexiu District, is part of the old city area, where the upstream drainage system is a complete combined sewer system, and the downstream is a catch-basin type combined sewer system. At the mouth of Donghao Creek, there is a tide gate and a pumping station. The tide gate has a clear width of 24 m and was constructed in 2002. The pumping station includes rainwater lifting pumps and sewage lifting pumps, with the rainwater lifting pumps being 8 pumps at 6.5 m^3/s each, with a total flow rate of 52 m^3/s, and the sewage lifting pumping station is 6 pumps at 2.83 m^3/s each, with a total flow rate of 16.98 m^3/s. During the south section renovation of Donghao Creek in 2009, a supplementary water pumping station was also built with a water replenishment flow rate of 1.5 m^3/s. The current flood discharge standard is designed to withstand a 20-year return period of a 24-h storm without causing disaster.

Due to land acquisition and demolition issues during the river rehabilitation, the actual flow section did not meet the original design section, and the current flood control standard did not meet the original design standard of a 20-year flood return period. The Donghao Creek basin has a high urban construction density and a high surface hardening rate. In recent years, frequent extreme rainstorms have caused severe flooding in the basin, even resulting in rivers overflowing their banks, leading to significant economic losses and severely disrupting residents' everyday work and lives. Additionally, the extremely high population density and urban construction density in the Donghao Creek basin have rapidly increased urban pollution loads, and CSO pollution has become increasingly serious during rainy days, degrading the river water quality and affecting its landscape function. Consequently, Donghao Creek was selected as the initial experimental section for the construction of Guangzhou's deep tunnel drainage system.

2.4. Data Collection and Current Status Assessment

The primary purpose of this stage is to collect the necessary data for planning to establish, calibrate, and simulate hydrological and hydraulic models under current conditions and various improvement scenarios. The collected data include population and water usage information, rainfall and rainfall intensity, land use and imperviousness-related factors, groundwater conditions, overflow data, the current state of the shallow drainage system, existing sewage collection and treatment facilities, and characteristics of receiving water bodies. At the end of the first stage, all necessary data and information are integrated to construct the corresponding hydrological, hydraulic, and receiving water body models.

Based on the collected data, the gap between the current performance of the shallow drainage system and the planning objectives was assessed. The hydrological and hydraulic models constructed in the first stage were primarily used to simulate the system's performance under existing conditions, and identify and quantify the problems. This typically involves quantifying and spatially locating issues related to dry season overflows, wet season overflows, street flooding, hydraulic limitations of the collection system, and tributary areas' development conditions.

Comprehensive assessment reveals that Guangzhou's existing shallow drainage system has the following deficiencies: (1) insufficient interception capacity of sewage pipes, failing to meet the required interception multiples; (2) inadequate control over CSO pollution interception, frequency, and pollutant discharge; (3) the shallow system does not meet the standards for rainwater management and flood control, and existing rivers do not meet the required flood control standards.

2.5. Development of Drainage Facility Improvement Plans for Each Tributary Basin

The main objective of the improvement plans for drainage facilities in each tributary basin is to enhance the capacity to handle a ten-year, two-hour-duration rainstorm, reduce CSO, and alleviate street flooding, like the example of the Donghao Creek deep tunnel system. The plan includes improvements to the shallow drainage system and the planning of deep branch tunnels. Based on the deficiencies identified in the existing drainage system during the second stage, the feasibility of achieving the above goals by improving the shallow drainage system is first evaluated. Considerations include: (1) modifying local pipelines to alleviate local flooding issues; (2) enhancing the interception capacity of the main shallow sewage pipes and primary interception pipes to meet CSO pollution interception standards; (3) modifying rivers to increase their flood discharge capacity. When improving the shallow drainage system alone is insufficient to address the drainage issues, deep branch tunnels are introduced to enhance the drainage system's efficiency. Typically, the planning of deep branch tunnels involves three main aspects: functional positioning, scale justification, and scheme comparison.

It is important to note that the third stage is an iterative process, where different improvement schemes are developed to evaluate the benefits of each scheme for achieving the overall planning objectives. The drainage facility improvement plan is ultimately determined based on the principle of maximizing benefits. The main methods and steps are illustrated in Figure 2.

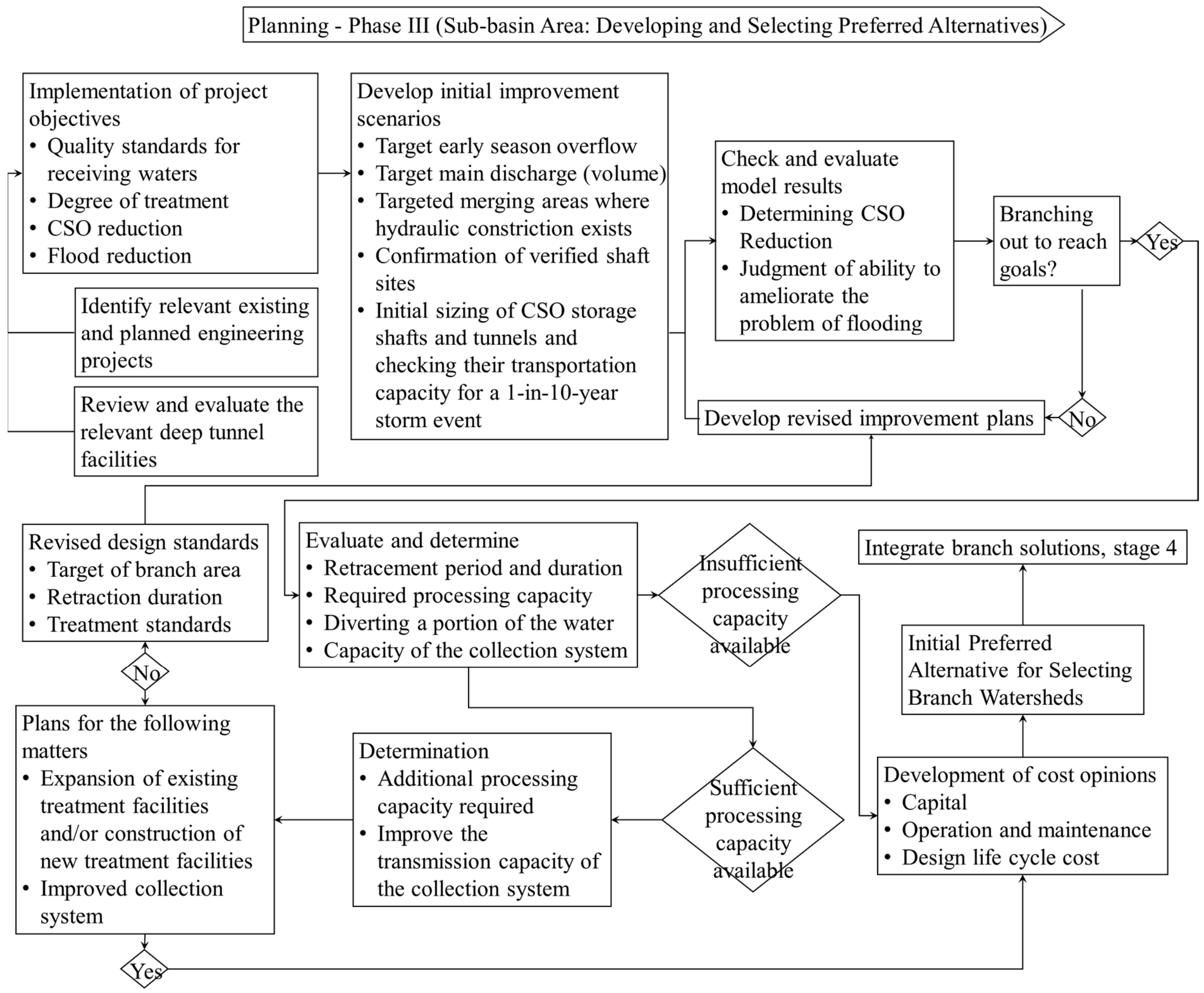

Figure 2. Main methods and steps in the third stage of Guangzhou deep tunnel drainage system planning.

2.6. The Calculation Method for the Intercepting Ratio of Combined Piping Network and CSO Retention Rate

The intercepting ratio of combined piping network is a key parameter in the design of such systems. The selection of the intercepting ratio (n) must consider the degree of surface pollution of the runoff, as well as the water quality target control values that surface waters should achieve.

The benchmark rainfall intensity refers to the rainfall intensity that corresponds to the detention of rainwater at the intercepting ratio $n = 1$. Overflow occurs when the flow exceeds the current dry weather sewage flow by a multiple of 1.

The annual characteristic rainfall was used to calculate the overflow volume of each discharge outlet of the tributaries and the reduction rate of stormwater overflow pollution. One of the planning goals is to reduce pollutant emissions by 70%. Chemical Oxygen Demand (COD) was selected as the water quality parameter to assess the effectiveness of deep tunnel systems in reducing pollution discharged into rivers.

To calculate the pollution status of the drainage system and assess the reduction efficiency of stormwater overflow pollution after the implementation of the project, Guangzhou Municipal Engineering Design and Research Institute Co., Ltd. carried out the monitoring of CSO water quality concentration during rainy days for some rivers and streams in the central urban area.

The COD reduction rate was calculated as the COD mass, reduced by detention, divided by the total COD mass in the basin during the rainfall period.

$$COD\ Reduction\ rate = \frac{Detention - reduced\ COD\ mass}{Total\ COD\ mass\ in\ the\ basin\ during\ the\ rainfall\ period}$$

The relevant parameters for the HEC-RAS model, as seen in Tables S1 and S2, are utilized for simulating the drainage standards of the watershed.

3. Results

3.1. Development of Overall Urban Tunnel System and Facilities Planning

After completing the information assessment, it is clear that main purpose of constructing the deep tunnel system is to control flood disasters and reduce CSO. Upon completing the first three stages, the primary goal of the fourth stage is to develop the optimal overall city-wide plan to control flood disasters and reduce CSO. The main tasks of this stage include: (1) determining the scheme for connecting main tunnels to each branch tunnel; (2) developing the main tunnel planning scheme; (3) planning sewage collection and treatment facilities (such as sewage treatment plants); (4) co-ordinating the overall deep tunnel drainage system and sewage treatment plants.

The overall planning should be based on the previously selected improvement plans for tributary basins and aligned with the main tunnel scheme. The planned main tunnels should be capable of transporting sewage from tributary basin storage facilities to downstream treatment facilities. The configuration of each main tunnel should be integrated with the selected tributary basin schemes, comprehensively assessing their operational efficiency and cost. If the expected improvement objectives are not met, adjustments to the main tunnel configuration and the selected tributary basin improvement schemes are necessary. When modifying schemes, the goal is to achieve the highest economic efficiency and meet the city-wide planning objectives, with flexibility in achieving tributary basin improvement targets. Additionally, the requirements for draining storage facilities, the transportation capacity of the collection system, and available downstream treatment capacity should be reconsidered to further refine the overall plan. The main methods and steps for the fourth stage are illustrated in Figure 3.

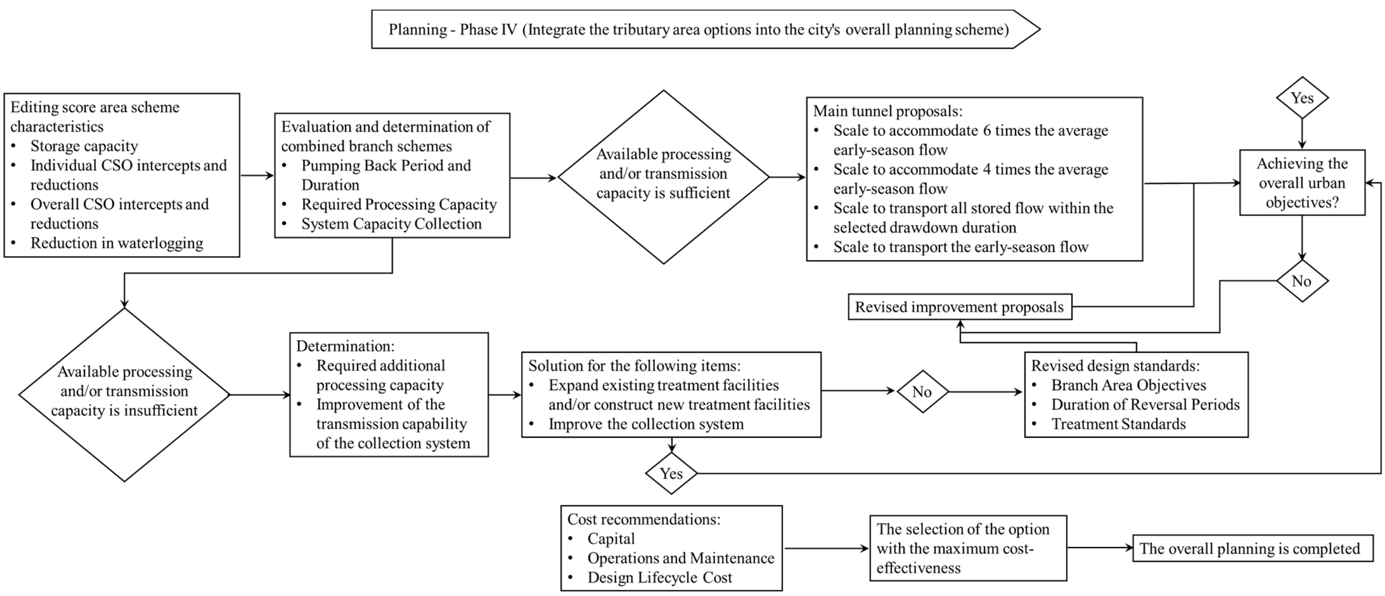

Figure 3. The main methodological steps for formulating the deep tunnel drainage system plan in Guangzhou City.

The above example demonstrates the considerations and development process of the Guangzhou deep tunnel drainage system planning scheme, providing a reference and guidance for corresponding planning in other cities in China. However, specific problems should be analyzed to develop comprehensive planning schemes that align with urban development directions.

Taking Donghao Creek as an example, the Yuexiu District where the Donghao Creek basin is located is part of the old city area. The upstream section of the drainage system operates on a complete combined sewer system, while the downstream section operates on a catch-basin-type combined sewer system. In the upstream section of the covered channel, rainwater and wastewater from the basin are discharged into Donghao Creek's covered channel through the combined sewer pipes. Then, on Dongfeng Road, it is diverted into the downstream sewage pipe through a pollution control gate. In the downstream section of the open channel, sewage is collected through the sewage pipes on both sides and then discharged into the main sewage channel box on the north side of the Pearl River. According to the data from the "Guangzhou City Flood (Tide) Defense and Drainage Planning—Hydrological Analysis and Water Surface Profile Calculation Special Report", the hydrological data of Donghao Creek are shown in Table 2.

Table 2. Donghao Creek Hydrological Data.

Cross-Section Name	Catchment Area (km^2)	River Length (m)	Slope Gradient (‰)	Urban Hydrological Method Flow Rate (m^3/s)	
				5%	10%
Donghao Creek-Luhu basin	9.42	6.81	2.84	106	91
Donghao Creek-Yudaihao and Xinhepu basin	11.10	6.81	2.84	119	105

The Guangzhou Deep Tunnel Drainage System—Donghao Creek Pilot Project is the first deep tunnel drainage project designed and constructed in China, which started in 2012. The total investment of the project is RMB 770 million, with the main tunnel having a diameter of 6 m, laid more than 30 m underground along the Donghao Creek from north to south, with a total length of 1.7 km; the coverage area is about 17.68 km^2, with a total population of about 1.2 million, and the current dry weather sewage volume is about 350,000 m^3/d. It includes four inflow shafts, with an upgrade pumping station at the end.

After the completion of the project, through the effective co-ordination of the deep tunnel with the shallow drainage system and the existing river channels, as shown in the schematic diagram of the connection between the deep tunnel and the shallow network in Figure 4, it can comprehensively improve the detention multiple of the Donghao Creek basin sewage collection system, reduce the pollution of combined sewage and initial rainwater overflow during the rainy season, and improve the water quality environment and drainage standards of the Donghao Creek basin in the central area of Guangzhou. At the same time, it can achieve the regulation or diversion of rainwater under different rainfall conditions, comprehensively improving the drainage, flood prevention, and flood discharge system standards of the Donghao Creek basin water system.

The Donghao Creek Deep Drainage Tunnel supplements and enhances the shallow drainage system and river channel system of Donghao Creek, with its primary functions being:

(1) Reducing Overflow Pollution: During the rainy season, the tunnel serves as a storage conduit for combined sewage and initial rainwater from the Donghao Creek basin. Post-rainfall, sewage is lifted by the terminal sewage pump station to the shallow drainage system and then sent to the sewage treatment plant. This significantly increases the interception multiple of the entire basin's interception system, greatly reducing the number of times sluice gates are opened for various tributaries (or culvert boxes) in the Donghao Creek basin. It aims to cut over 70% of the combined overflow pollution (measured by COD) during the rainy season.

(2) Assisting Flood Control and Mitigating Shallow Water Flooding: Under heavy rainfall conditions, the tunnel acts as a flood drainage channel, performing flood discharge functions. After being lifted by the terminal flood pumping station, the floodwater is discharged into the Pearl River, thereby lowering the water level at the culvert box outlet. This works in conjunction with the shallow system renovation to elevate the shallow drainage standard to a P = 5-year return period (95.55 mm), enhancing the drainage standard of the combined main channels in the basin to a P = 10-year return period (109.71 mm), and ensuring the open section of the Donghao Creek meets a 50-year flood control standard.

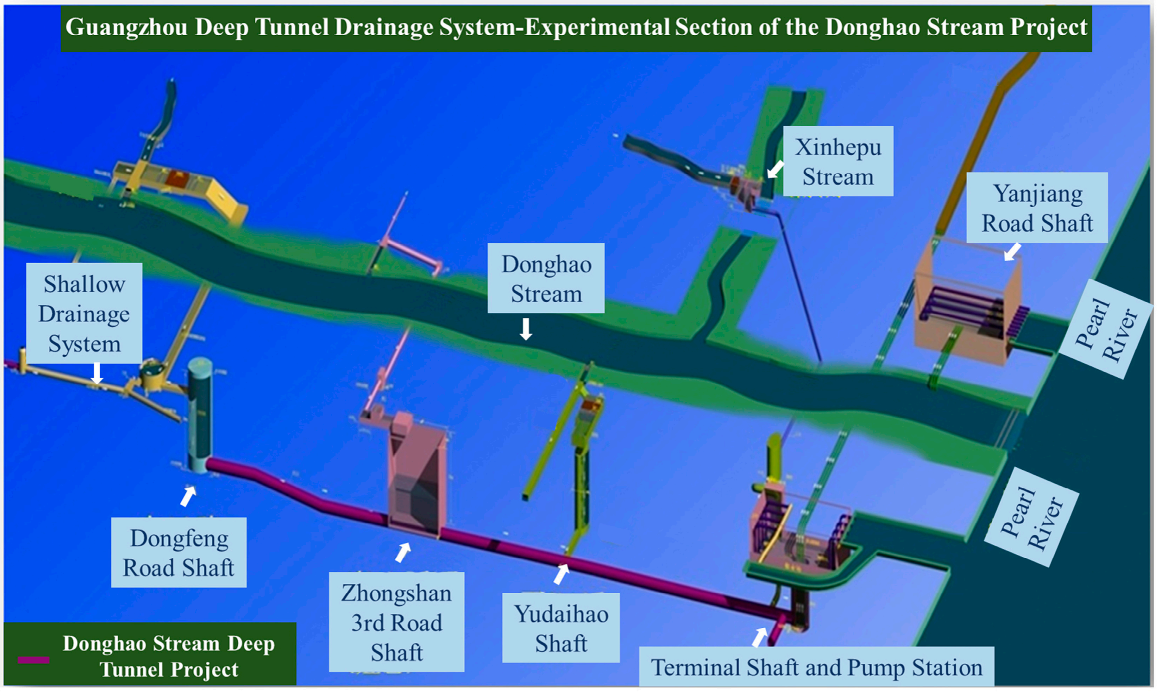

Figure 4. Guangzhou deep drainage system—Donghao Creek experimental section schematic diagram.

3.2. Economic Comparison Analysis

The construction of a tunnel drainage system primarily offers the following advantages:

(1) Land Space Advantage: It conserves land resources by utilizing underground space, which is crucial in urban areas where surface area is limited;
(2) Increased Detention Ratio: It enhances the existing drainage network's ability to handle stormwater and sewage loads by increasing the detention ratio, which is the capacity to store and release water during heavy rainfall;
(3) Operational Flexibility of Wastewater Treatment Plants: The system allows for more flexible operation of wastewater treatment plants, accommodating fluctuations in inflow and improving the overall efficiency of the drainage system;
(4) Provides conditions for the treatment of initial rainwater and control of the pollution caused by the first flush of rain.

Taking the Donghao Creek deep tunnel pilot section as an example, an estimation of the investment for the deep tunnel scheme is compared with the original shallow drainage renovation scheme (conventional scheme) and the rainwater and wastewater diversion renovation scheme, considering aspects such as the volume of work, land expropriation, and pipeline relocation. The results are shown in Table 3.

Table 3. Comparison between deep tunnel scheme and original shallow drainage renovation scheme (conventional scheme).

Plan	Conventional Scheme (Shallow Drainage Renovation)	Separate Rain and Sewage Scheme	Deep Tunnel Scheme
Scheme Description	Donghao Creek Whole Basin Waterlogging Transformation: Shallow Network Expansion, etc.	Separate rain and sewage in the entire Donghao basin	Donghao Creek whole watershed waterlogging control and initial rainwater collection
Project Cost (billion yuan)	0.47	0.98	0.59
Total Investment (billion yuan)	1.02 (including 0.37 for land acquisition and pipeline relocation)	2.87 (including 1.82 for land acquisition and pipeline relocation)	0.77 (including 0.1 for land acquisition and pipeline relocation)
Implementation Effect	① Flood renovation: Dihao Creek to 1-year standard.	① Separate rain and sewage (drainage system reaches 2–5 year standard).	① Flood renovation: reaches 5-year standard. ② Initial rain interception: adds about 60,000 m^3 storage capacity.

As shown in Table 3, the engineering cost of the deep tunnel scheme is between the conventional scheme (shallow drainage renovation) and the stormwater and sewage diversion scheme, that is, the initial investment is relatively large. However, it greatly reduces the cost of demolition, relatively reduces the difficulty of implementation, and the deep tunnel scheme is more conducive to the regulation and treatment of the initial rainwater.

Accordingly, the deep tunnel drainage system also has many limitations, mainly reflected in:

(1) The initial investment is relatively large;
(2) The operating cost is high. Due to its location in deep underground spaces, the power consumption of the pumping stations during operation is relatively large;
(3) The cost of cleaning and maintenance is relatively high. After each use, cleaning and maintenance are required.

For the above reasons, the tunnel drainage system should serve as a supplement to the shallow drainage system. While making full use of the shallow drainage system, the deep drainage system should be flexibly operated and combined with intelligent scheduling to maximize the role of the deep tunnel system.

Therefore, considering relocation costs, implementation difficulty, and effectiveness, the deep tunnel scheme has clear advantages over the conventional and separate rain and sewage schemes.

3.3. Analysis of the Effects after Deep Tunnel Implementation

The Donghao Creek deep tunnel project officially entered the trial operation phase in January 2022. According to the operation records of the Guangzhou Municipal Drainage Company, since the trial operation of the Donghao Creek deep tunnel pilot section started in 2022, as of 25 May there has been a cumulative rainfall of 78 days, with a total of 68 rainfall events, a total rainfall duration of 769 h, and a total rainfall volume of 809.46 mm. The maximum daily rainfall was 89.90 mm (12 May), and the maximum hourly rainfall was 46 mm/h (23 April). At the end of the Donghao Creek pilot section project of the deep tunnel drainage system, a pump station with flood discharge pumps was set up, with a total of 8 flood discharge pumps installed. The maximum flow rate of a single pump is Q = 21,600 m^3/h; the head H is 12.6 to 20 m; the power N is 1100 kW. The maximum flow rate Q = 21,600 m^3 is reached when the head H = 13.6 m. In the event of extreme rainstorms, when the shallow drainage system's flood discharge capacity is insufficient, the deep tunnel serves as a flood discharge channel. The inflow gates of the deep tunnel and the flood discharge pump group are activated to pump and discharge the floodwater into the Pearl River.

The initial operation period can be divided into two phases: the flood season and the non-flood season, with the specific timing based on the annual flood season notification issued by the Municipal Three Defenses Office. The main operation and management content is as follows:

(1) Flood Season—Operation Phase

During this phase, the deep tunnel system is normally put into operation. Combined with the surrounding shallow network and the runoff generated by rainfall in the basin, the operation of the deep tunnel system is carried out according to the preset conditions of the scheduling plan to fully exert the multifunctionality of the deep tunnel system and accumulate experience for the subsequent formal operation of the system. In case of emergencies, such as maintenance and emergency repairs during this phase, the system will be shut down after reporting to the Guangzhou Municipal Water Affairs Bureau.

(2) Non-Flood Season—Maintenance Phase

During this phase, the deep tunnel system is generally not put into operation. After the flood season each year, it enters the cleaning and maintenance period. During this period, all vertical shaft inflow corridors are closed, and personnel and machinery enter each vertical shaft and tunnel to carry out routine maintenance work, such as equipment maintenance and tunnel cleaning, to ensure that all equipment, facilities, and tunnels are functioning properly, in preparation for the next flood season's operation.

The deep tunnel facilities were activated a total of 11 times, with eight instances serving the function of regulating and storing rainwater and sewage, and three instances providing auxiliary flood discharge capabilities. The inflow gates were opened a total of 62 times, the emptying pumps were operated 98 times with a cumulative duration of 774.33 h, and the flood discharge pumps were operated 26 times with a cumulative duration of 1096 min. A total of 313,200 t of initial rainwater was regulated and stored, reducing 43.85 t of COD pollutants and 0.62 t of ammonia nitrogen. The sedimentation gate in MaYuGang was opened a total of eight times (25 times in 2021).

The Donghao Creek deep tunnel includes four inflow shafts. From January to the end of May 2022, the Dongfeng Road shaft opened its gate 28 times, and the Baizi Chong water intake well opened its gate 32 times. The Zhongshan Third Road shaft did not open its gate, and the Yudai Canal shaft opened its gate twice. From the above data, it is evident that the Dongfeng Road shaft and the Baizi Chong water intake well are the main inflow points of the Donghao Creek deep tunnel. The gates in front of the Zhongshan Third Road shaft and the Yudai Canal shaft did not reach the water level required to open the gates. A preliminary judgment is that this is because some local areas have undergone rainwater and sewage diversion reconstruction. During the rainy season, a large amount of rainwater was discharged through the stormwater pipes, resulting in a reduction of water volume in the shallow pipelines connected to these two shafts, which did not reach the gate opening level.

3.3.1. CSO Reduction Efficiency Analysis

In terms of overflow pollution, the water quality and flow data from the operation of the deep tunnel system are used as the basis for statistics. In 2022, the Donghao Creek deep tunnel cumulatively reduced the overflow of sewage (including initial rainwater) by approximately 2.48 million t, a total reduction of 361.88 t of COD pollution in the overflow, and 15.40 t of ammonia nitrogen pollution in the overflow. According to the actual measured overflow data from the pollution control gates and flap gates within the basin, the actual overflow volume controlled by the Donghao Creek deep tunnel drainage basin in 2022 was about 688,900 t, with 148.04 t of COD pollution in the overflow and 5.32 t of ammonia nitrogen pollution. Therefore, the total amount of overflow COD was 509.92 t, and the total amount of overflow ammonia nitrogen was 20.72 t. The control of pollutants by the deep tunnel system is shown in Figure 5.

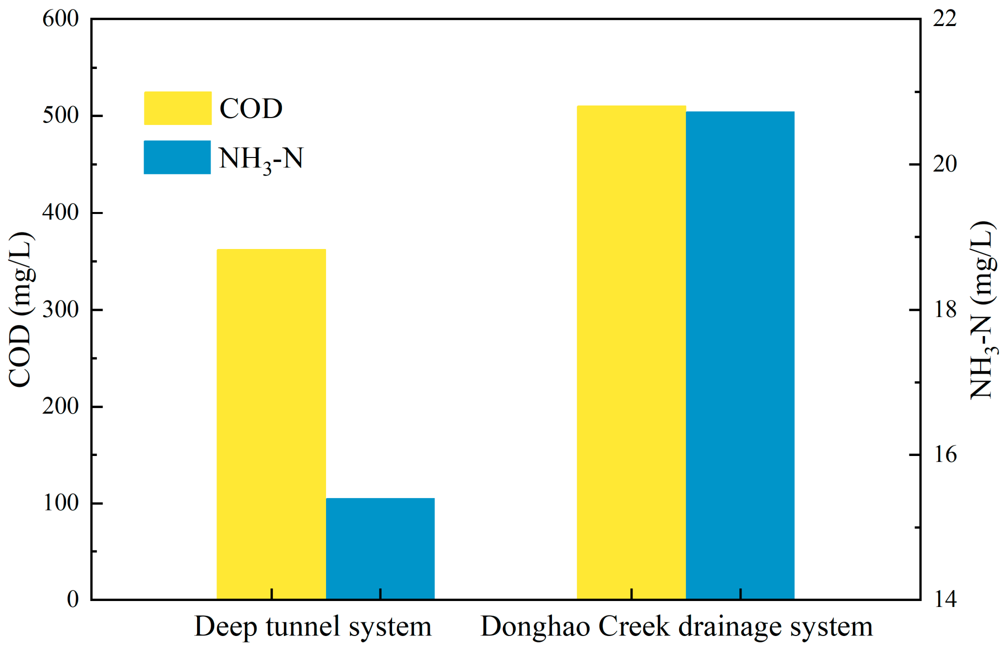

Figure 5. The post-implementation CSO reduction efficiency of the deep tunnel system.

Based on the above statistical results, the following calculations were made: the Donghao Creek deep tunnel system reduced the total amount of COD in the rainy season overflow of the basin by 62.60% in 2022, and reduced the total amount of ammonia nitrogen in the overflow by 72.85%.

The total annual rainfall in the Donghao Creek basin was approximately 1956 mm in 2022 and about 1758 mm in 2019. Since the rainfall amounts of these two years are relatively close, operational monitoring data from 2019 and 2022 were selected for a comparative analysis of the CSO interception before and after the operation of the deep tunnel system throughout a complete flood season, as shown in Figure 6.

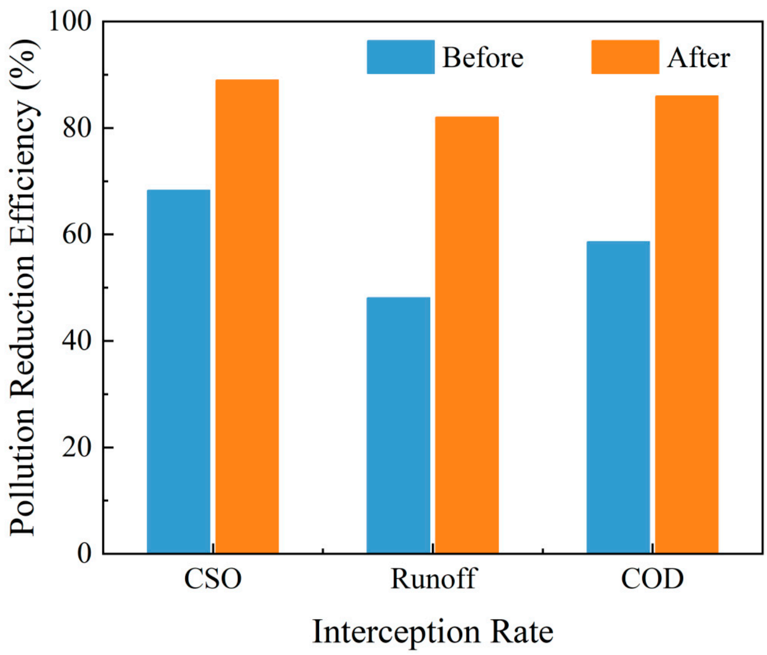

Figure 6. Comparison of pollution reduction efficiency before and after deep tunnel implementation.

The deep tunnel can provide about 60,000 m^3 of storage capacity. The annual overflow of combined sewage during rainy days in the Donghao region is 2.662 million m^3, with a COD overflow total of 57.2 t. As shown in Figure 6, the interception rate of CSO sewage increases from the current 68.3% to 89%, the runoff interception rate increases from the current 48.1% to 82%, and the reduction rate of COD overflow pollution on rainy days increases from the current 58.6% to 86%.

This comparison illustrates the significant improvement in pollution reduction efficiency achieved through the implementation of the deep tunnel system. The deep tunnel enhances the storage capacity, reduces the frequency and volume of overflows, and effectively intercepts and treats pollutants, leading to a cleaner and more efficient urban drainage system.

3.3.2. Drainage Standard Analysis of the Basin

(1) Combined Sewer Boxes and River Creeks

Currently, the comprehensive drainage standards for combined sewer boxes and canals (ensuring no overflow from sewer boxes and no overtopping from canals) meet a 3-year recurrence period (municipal, approximately 80 mm rainfall). After the completion of the deep tunnel, utilizing four vertical shafts and tunnels to serve as auxiliary drainage channels for Donghao Creek, the water level at the least favorable times in the southern section of Donghao Creek and various main combined sewer boxes is shown in Figure 7. The comprehensive drainage standards for deep tunnels and canals are raised to a 10-year frequency (canal water levels lower than 0.6 m below ground level, canals not overflowing).

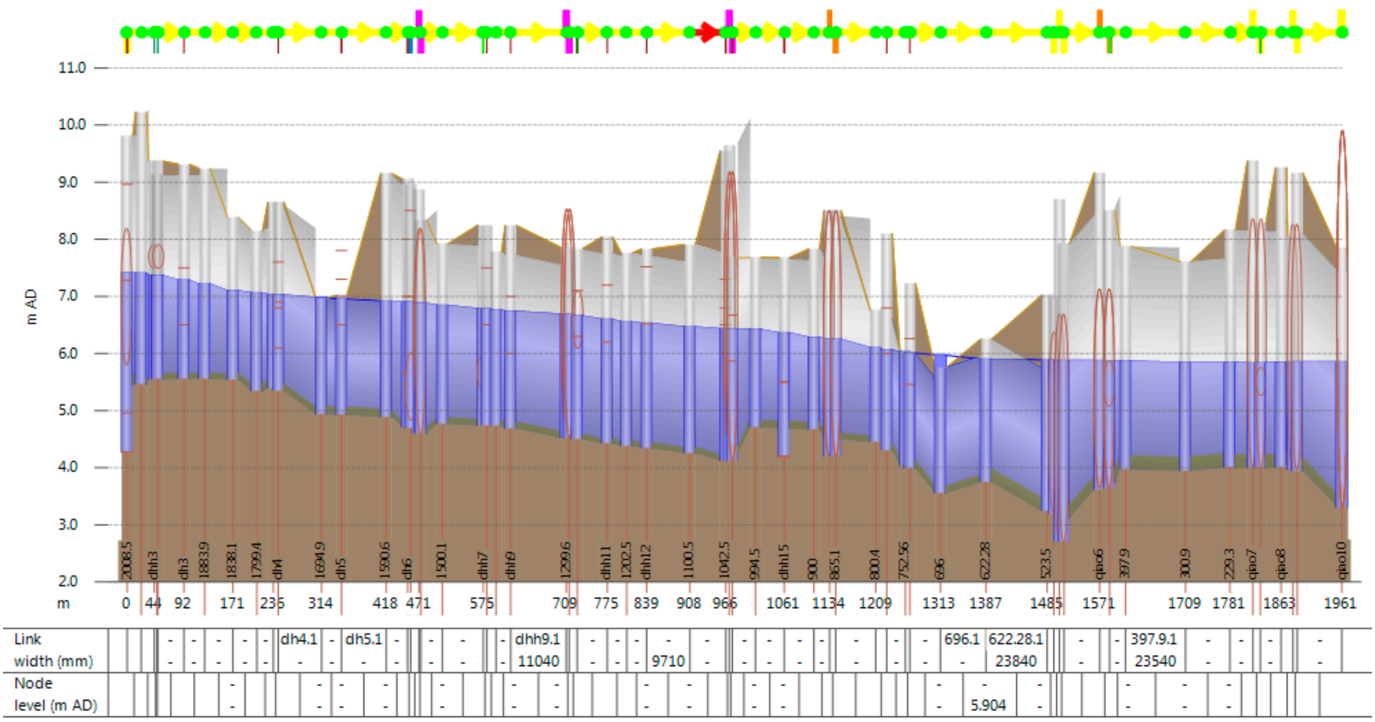

Figure 7. The hydraulic gradient profile of the southern section of Donghao Creek under the worst-case scenario after the implementation of the deep tunnel (with a 10-year return period and 120-min rainfall intensity).

Simultaneous calculations were conducted for the hydraulic drainage capacity of the waterway according to hydraulic standards, with the water surface profile simulated using HEC-RAS 4.0 hydraulic simulation software [19]. The watershed area is 12.47 km^2, with a basin length of 6.5 km. Considering the tidal gate and the existing drainage pump station with a capacity of 52 m^3/s, the initial water level at the tidal gate is set at 6.2 m as the control level, while also accounting for the diversion effects of the deep tunnel at four vertical shaft locations. Hydrological calculation parameters are shown in Figure 8. Verification post-implementation of the deep tunnel confirms that the southern section of Donghao Creek can achieve drainage standards equivalent to a 50-year return period, according to hydraulic standards.

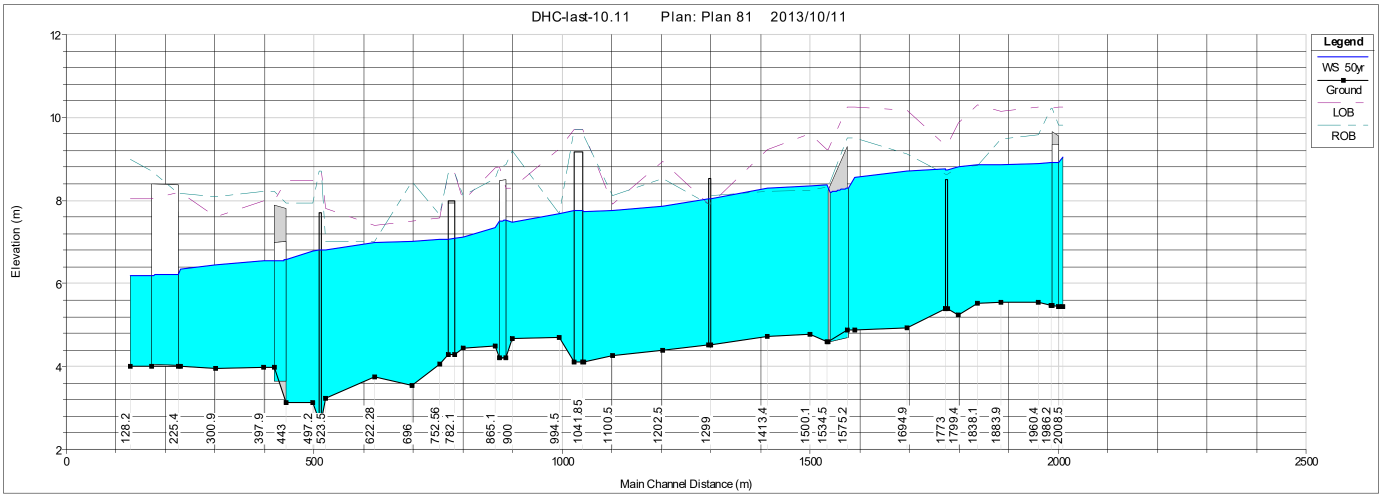

Figure 8. The water surface profile of Donghao Creek under a 50-year return period after diversion through the deep tunnel (according to hydraulic standards).

(2) Shallow Drainage System

Based on maintenance information from the Guangzhou Drainage Center, calculations were conducted to assess the 5-year return period, 120-min rainfall inundation risk of the shallow drainage system in the Donghao Creek after the implementation of the deep tunnel. As shown in Table 4, before and after the implementation of the deep tunnel there was a significant decrease in water levels at various critical outfalls, leading to a substantial reduction in the inundation area compared to the current situation.

Table 4. Comparing water levels at key outfall locations before and after implementation of the deep tunnel (5-year return period, 120-min rainfall).

No	Outfall Locations	Water Level before (m)	Water Level after (m)
1	Mayugang Channel Box	7.958	7.322
2	Zhongshan 3rd	7.451	6.794
3	Haoxian Road	7.845	7.194
4	Yudaihao	6.891	6.299
5	Junction of Xinhepu and Donghao Creek	6.55	5.862
6	Dongchuan Road Channel Box	6.571	5.910
7	Baizichong Channel Box	6.588	5.925

Upon completion of the shallow drainage network improvement project in the Donghao Creek, aimed at mitigating 5-year return period inundation points, the relevant departments are working towards achieving this enhanced standard.

Additionally, with the construction of the deep tunnel experimental section in Donghao Creek, the expected goals of reducing overflow pollution, controlling CSO, assisting in river channel drainage, alleviating shallow inundation, and improving flood control and drainage standards have all been met.

3.3.3. Urban Waterlogging Risk Control Effect

Based on the on-site records of water accumulation within the controlled area for urban waterlogging, in 2019 there were a total of 13 occurrences of waterlogging, including four instances of moderate waterlogging and nine instances of mild waterlogging. The total duration of waterlogging was 35 min, with an average duration of 41.15 min per event and an average water depth of 26 cm.

After the Donghao Creek deep tunnel system was put into operation, in 2022, there were a total of 12 occurrences of waterlogging, including three instances of moderate waterlogging and nine instances of mild waterlogging. The total waterlogging time was 369 min, with an average duration of 30.75 min per event and an average water depth of 35 cm. The waterlogging conditions before and after the activation of the deep tunnel system are shown in Figure 9.

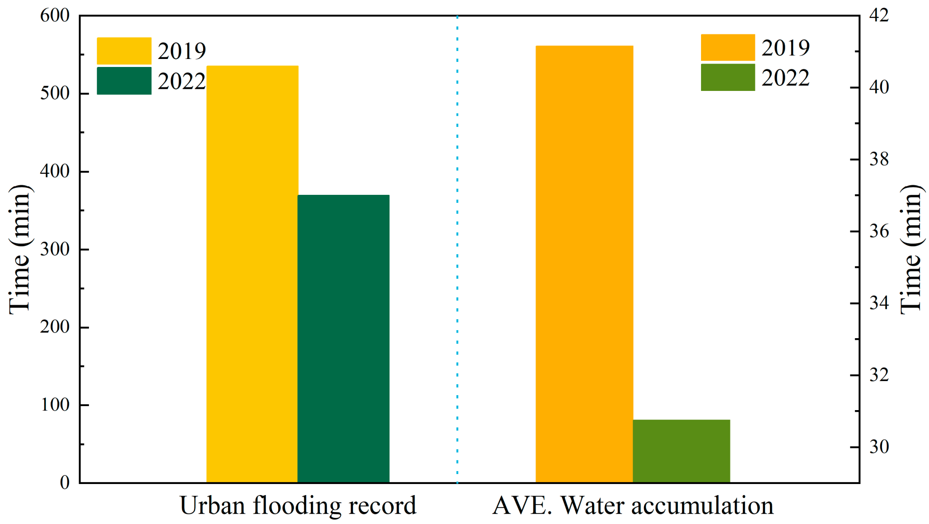

Figure 9. The urban flooding and average water accumulation record before and after the operation of the deep tunnel system in 2019 and 2022, respectively.

Compared to 2019, after the activation of the deep tunnel system in 2022, the total waterlogging duration in the Donghao Creek basin decreased by 31.03%, and the average duration of water accumulation decreased by 25.27%.

4. Conclusions

This study highlights the significant advantages and feasibility of implementing deep tunnel drainage systems in densely populated urban areas, using the case of Guangzhou. The deep tunnel system effectively addresses the limitations of traditional drainage infrastructure by providing substantial underground storage for excess rainwater, thereby reducing the frequency and severity of urban flooding and mitigating combined sewer overflow (CSO) pollution.

The construction of tunnel drainage systems offers significant benefits for urban water management. Firstly, it protects land resources by utilizing underground space, which is particularly advantageous in densely populated urban areas. Secondly, it enhances the interception capacity of the existing drainage network, thereby improving overall system efficiency. Additionally, it allows for the more flexible scheduling and operation of sewage treatment facilities, adapting to varying demands. Lastly, it provides effective conditions for the treatment and control of initial rainwater pollution, contributing to better environmental management.

However, these costs are offset by the optimization of scheduling between the shallow pipe network and the deep tunnel system, as well as the long-term benefits and efficiency improvements brought about by better flood control and pollution management.

The successful implementation of the deep tunnel drainage system in Guangzhou sets a precedent for other cities facing similar urban flooding challenges. By integrating deep tunnels with existing infrastructure and urban planning goals, cities can achieve more resilient and sustainable urban development. Future research and planning should continue to refine these systems, addressing any emerging challenges and optimizing their performance to meet the evolving needs of urban environments.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16172429/s1, Table S1: The parameters of hydrological calculation; Table S2: HEC Model parameter adjustment range table.

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