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Evaluation of river network planning layout in plain city consideration for combining water quality and flood control

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ABSTRACT

Economic and social development has brought higher requirements for the adjustment of river network layout. The paper took Nanhai Future City of Yancheng as the research object, and considered factors such as urban development, land use covers and landscape structure to preliminarily formulate river network planning layout, demonstrating the rationality of river network planning layout based on comprehensive consideration of water quality and flood control. The quantity of ecological outer water diversion was considered separately in the dry season and the flood season, the water diversion projects and the controlling projects – sluices and pump stations – were rationally arranged to realize the water quality control effect in the district and met the water flood control requirement, which were regarded as the premise of evaluation of river network layout. The results showed that for the outstanding water quality problems of river network in plain, the water quality improvement effect of several replenishment points was better than that one point. When the water surface rate remained unchanged, the river network layout adjustment could slightly affect flood control and could meet the flood control requirements. Generally, this method provided a reference for river network planning layout in other similar areas.

Keywords: River network in plain; Water quality; Flood control; River network planning layout

1. Introduction

Cities are often established near rivers, as it is more conducive to trade, transportation and natural resource utilization. In recent decades, with the intensification of urbanization, land use of river network in plain has undergone significant changes in China, affecting the natural river network layout and water quality management as well as biodiversity [1–3]. Related studies have shown that the hydrological change process caused by land use contributes was more than 50% to the impact of water quality [4].

In the initial stage of urban construction, the river network mainly provides functions such as flood control, water supply, production and transportation. With the continuous development of regional social economy, the conservancy function, environmental function and tourist function of the river network are increasingly important to the sustainable development of cities. As a significant part of the urban natural environment, the river network not only affects the development direction of the city, the layout of land use, etc. but also is a critical factor in determining the characteristics of cities. In the process of economic and social development, residents are increasingly aware of the value of the river network and have higher requirements for the rational layout of the river network [5]. Therefore,

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scientific planning of the spatial layout of urban river network is the premise and basis for rationally arranging urban resources, enhancing urban functions and competitiveness, improving the living environment and achieving sustainable development, which are the crucial factors to ensure the coordinated development of "people, water, city and nature" in the region.

Flood control is the primary function of river network of related construction projects [6]. Many existing research results provided a basis for flood control and river network planning by constructing numerical models to analyze flood risk of river network in plain [7]. Besides, the degree of layout optimization is measured by economic cost, etc. [8], and urban flood control and construction disaster reduction can be promoted by low-impact development or the concept of sponge city [9]. Water resources allocation and water resources planning and distribution are also important functions of the river network. Currently, the main concern is on water resources systems and managing and planning of reservoir [1,10–16], water supply and distribution systems and water allocation systems and other aspects [17–19]. With the continuous advancement of water environmental protection work, the water pollution problem of river network has gradually become one of the current research hotspots. By establishing a water quantity and water quality coupling model, analyzing the role of land use and drainage system in water quality and quantity control and proposing water quantity and water quality control measures are necessary [20–23], according to the situation of the entire river basin, the allowable pollution discharges and emission reductions for each basin can be obtained, which could be used to formulate emission reduction plans for each source of pollution in each emission zone [24]. Artificial wetlands are also one of the most commonly used methods, which take a variety of integrated measures to alleviate water pollution issues of the urban river network [25].

In plain cities with river network, water resources are relatively abundant, and its main water problems are flood control and water pollution. In the existing achievement of water network planning, it is more targeted to a single aspect, such as flood control, water resources or water environment perspective on the needs of the river network layout, there are few achievements about the actual comprehensive consideration of this function. Studies have shown that the higher connectivity and fluidity of river network are the essential requirements for the construction of ecological flood control systems [26]. Meanwhile, improving the connectivity of river network is conducive to pollutant degradation and desilting in river network, which could enhance the water quality in urban rivers [27]. Therefore, scientific planning of the river network water system requires further research in the perspective of improving the connectivity of river network and fluidity of water system.

In addition, the river network area of plain cities is mostly controlled by sluices and pumping stations to maintain the demand for water level of landscape, etc. However, it has a significant impact on the water quality of the river network [28]. The managing mode of the sluice gate and pumping station is also one of the important conditions for the realization of the flood control and improvement of functions of water environment of the river network.

This study chose Nanhai Future City of Yancheng as the research object, based on the current river network and preliminary river network planning layout, comprehensively considering the water quality and flood control and evaluating the rationality of river network layout. According to it, this study scientifically adjusted the river network layout and rationally established relevant projects to achieve the effect of water purification as well as to meet the flood control requirements simultaneously.

2. Materials and methods

2.1. Overview of the Nanhai Future City

Yancheng is located in the central part of the coastal area of northern Jiangsu, northern edge of the Yangtze River Delta as well as at the end of Huaihe River basin and the shore of the Yellow Sea. Nanhai Future City is located in Chengnan New District of Yancheng (Fig. 1), with a planning area of about 16 km^2. It is planned to establish a new area with multiple functions for commercial use, office work, cloud industry of scientific research and living, etc.

The Nanhai Future City is located in the flood control area IX of Yancheng, it collectively prevents flood with flood control area during flood period while its sluice gates are closed during the non-flood period. The area of flood control area IX is 67.8 km^2, as far east as Tongyu River, as far south as Wangxiang Riverto Bengting River, as far west as Zhongxin river, and as far north as Xiaoxin River to Sandungang River. The connection between the river network of Nanhai Future City and the river network of flood control area IX is relatively good. The main rivers in the area are the main drainage channels of the flood control area IX. Therefore, in order to clarify the future drainage strategy of the Nanhai Future City, the entire flood control area IX was selected as the scope of the study (Fig. 2).

The Nanhai Future City is low and flat, its ground elevation is mostly 2.0–2.5 m, and the area below 2.5 m accounts for 60% of the total area. The Nanhai Future City is in the transition zone from the north of subtropics to the south of temperate zone. The monsoon climate is obvious with oceanic climate characteristics. Besides, the four seasons are distinct with rainy season which coincided with high temperature, the sufficient sunshine, long frost-free period and abundant rain.

The distribution of precipitation in the Nanhai Future city is very uneven during a year. The rainfall from June to September is relatively large, accounting for 65% of the annual precipitation. The precipitation in July is the most, accounting for 24% of the annual precipitation. In addition, the interannual variation of precipitation is also large, with a maximum precipitation of 1,463 mm in 1965 and a minimum precipitation of 498.5 mm in 1978. At the East Asian rainy season (plum rain season), from the second half of June to the first half of July, the rainfall of plum rain in the Nanhai Future City is 200–250 mm. There are many typhoons and thunderstorms, in August and September after the rain season. Thus, plum rain and typhoon are the main factors that

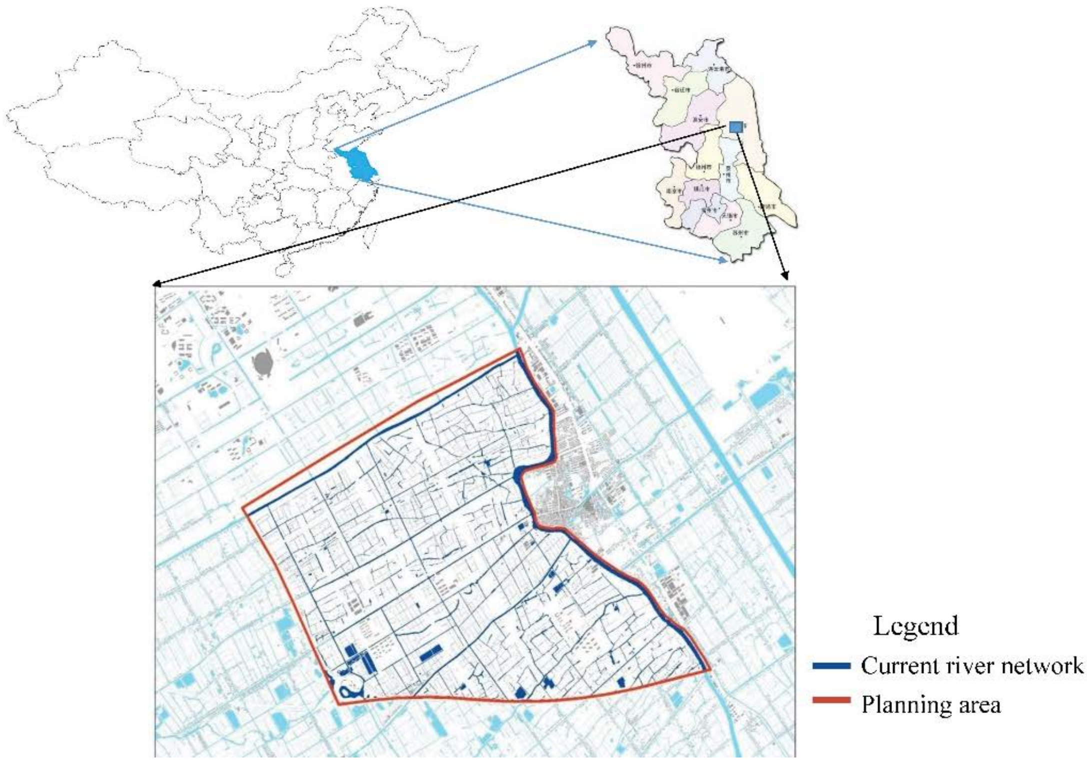

Fig. 1. Location of the Nanhai Future City.

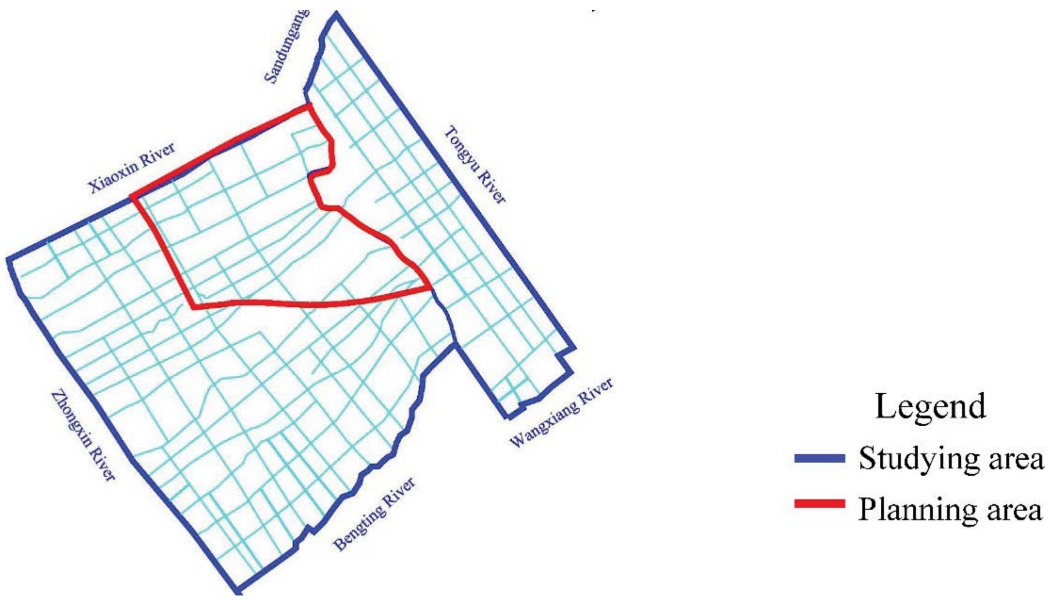

Fig. 2. Studying area.

lead to floods. The amount of precipitation in autumn and winter is relatively small, and it is prone to result in autumn drought and spring drought. When there is little rain after the plum rain season, there will be droughty weather. At that time, the water quality problem of the river network is outstanding.

2.2. Current water problems

In the flood control area IX, the river network is densely covered, and the periphery is protected by embankments and sluices to prevent flood. The current embankments have been basically reached the standard, and the internal flood is drained by the pumping stations. There are 12 pumping stations with a total capacity of 62 m^3/s. The status of Nanhai Future City is that the length of main rivers is 35.54 km, with water surface area of 2.14 km^2, and the water surface rate accounts for 13.3%. The current water conservancy projects are established on the right bank of Xiaoxin River, and there are five control sluices, of which three of them are integrated as one. The north sluice and pumping station of Chuanchang River is one of the most important drainage projects in the flood control area IX, which has been basically completed.

In the Nanhai Future City, the river network is chaotic, and there are many weirs which block the river network, causing many dead-end rivulets. The rivers and ponds are dense, while the connectivity is poor, resulting in a large water surface rate, but it is difficult to exert the function of drainage. Meanwhile, it also affects the fluidity of water bodies, which easily leads to deterioration of water quality and eutrophication.

2.3. Planning requirements

Under the premise of ensuring the water surface rate in the area, according to the urban development, land use type and landscape structure, the river network planning layout was preliminarily formulated. For this plan, the urban flood control and water quality protection issues should be resolved. (1) Urban flood control. The urban flood control problem has been regarded as the comprehensive issues to be addressed in the flood control area IX of Yancheng. This study focused on the impact of river network layout adjustment on urban flood control after comprehensively considering water quality issues to adjusting river network layout, it was necessary to explore whether it can satisfy the demand for flood prevention in urban area. (2) Water quality protection. During the non-flood period, the sluices were built around the Nanhai Future City to eliminate the impact of peripheral water quality on the internal river network. However, the rules of managing sluices will significantly affect the water quality of the river network [28]. Meanwhile, the river network in the region also has losses of evaporation and permeability. Therefore, based on the ecological water demand of the rivers in the region, the ecological outer water quantity should be determined. In addition, the corresponding water diversion project will be constructed to realize the flow of the river network in the region and finally achieve the goal of water quality guarantee.

2.4. Research models

2.4.1. Design of heavy rainfall

According to the standards of the Nanhai Future City, it had to design the heavy rainfall for 24 h with a 20-year return period. After calculating the rainfall of design point at different recurrence intervals of Yancheng Station, the point-area conversion coefficient was 0.98, which can be calculated to obtain the maximum rainfall of designed area at 6 h and 24 h in terms of once-in-two-decades pouring rain, which were 127 and 172.3 mm, respectively. The hydrological calculations of drainage were calculated by using 24-h rainfall, and the process of measuring rainstorm was selected to design the allocation of time course of heavy rain.

2.4.2. Hydrological-hydraulic model

The NAM model in the MIKE software was chosen for the rainfall runoff model. The NAM model was a conceptual hydrological model of lumped parameters connected by a series of various continental features in a hydrological cycle described by a simple quantitative relationship, simulating the rainfall runoff process in natural watersheds. This rainfall runoff module can be used to calculate one or more than one zones of runoff generation and the generated runoff flows into the river network of the MIKE11 hydrodynamic (HD) model was regarded as a side inflow. In this way, single or numerous confluence areas and large river basins of complex river networks can be processed within the same model framework. NAM simulated the process of runoff generation and concentration by continuously calculating the water content of four different aquifers that affected each other, the aquifers represented different physical units within the basin. Moreover, these aquifers are aquifers of snow storage, aquifers of surface water storage, aquifers of soil or water storage of plant root zone, and aquifers of groundwater storage.

The flood concentration in river network was simulated by establishing a one-dimensional hydraulic model. The hydrodynamic simulation of one-dimensional non-constant flow in the rivers was based on the Saint Venant equations.

Continuity equation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

Momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\alpha\frac{Q^2}{A}\right)+gA\left(\frac{\partial y}{\partial x}\right)+gAS_f-u\times q=0 \tag{2}$$

where A—catchment area of the river; Q—flow discharge; u—flow velocity from the lateral flow in the direction of the river; t—time; x—horizontal coordinate along the flow direction; q—flow discharge from the lateral flow; α—momentum correction coefficient; g—gravitational acceleration; y—water level; Sf—friction gradient.

The parameters of the model were based on the existing research results of Yancheng. The boundary conditions were the main constraints of the river network model, they were controlled by the sluices and pump stations. The water level of drainage of the flood control area IX was designed to be 1.6 m. If there was a heavy rainstorm in the flood season as predicted, the precautionary measures can be taken according to the situation as well as the reservoir should be vacated in advance. The minimum operating water level of the drainage was not less than 1.0 m, and the highest control water level of flood control was not higher than 2.0 m. Accordingly, the operation mode of the pumping station at each boundary was determined.

2.4.3. Model of water quantity and water quality

On the basis of MIKE11 HD, the one-dimensional convection–diffusion model was constructed by means of MIKE11 AD (water quality diffusion model). MIKE11 AD is a tool for simulating the convective-diffusion process of soluble and suspended matter in water in the series of software of MIKE. Which was based on the hydrodynamic conditions generated by the HD module and was calculated by the convection–diffusion equation. The MIKE11 AD model adopted the one-dimensional river quality model, as shown in Eq. (3):

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}=\frac{\partial\left(E_x\frac{\partial c}{\partial x}\right)}{\partial x}-K_C \tag{3}$$

In the equation, c—concentration of the simulated matter; u (m/s)—average flow velocity of the river; E_x (m²/s)—convection–diffusion coefficient; K—first-order attenuation coefficient of the simulated matter; x (m)—spatial coordinate; t (s)—time.

The convection–diffusion coefficient, E_x, is a comprehensive parameter that includes molecular diffusion, turbulent diffusion, and shear diffusion effects. The MIKE11 AD model estimates the convection–diffusion coefficient Ex by an empirical equation, as shown in Eq. (4).

$$E_x = aV^b \tag{4}$$

In the equation, V is the flow velocity (m/s), the value comes from the hydrodynamic calculation result; a and b are the parameters set by the user.

In this study, the normal water level was 1 m, the roughness was 0.025, the initial setting of the concentration of NH_3–N was 1.5 mg/L, which was regarded as 1.5 mg/L, the diffusion coefficient was 5–10, and the degradation coefficient in the rivers was 0.1 d^{-1} while the degradation coefficient in lakes was 0.04 d^{-1}.

2.5. Quantity of ecological outer water diversion

As for the consideration of river network planning layout of urban development, land use type and landscape structure. The ecological water demand in the study river network only considered the demand of water that compensated for evaporation or leakage, and the calculation results for the whole year and the dry season (October–April) are shown in Table 1.

Evaporation capacity is shown in Eq. (5) as follows:

$$Q_{\text{evap}} = k_i \times A \times q_i \tag{5}$$

In the equation, k_i—designed factor, which was regarded as 1.2; A—water surface area, m²; q—maximum evaporation capacity, mm/(m²·d).

Leakage, it was considered based on local geological conditions and anti-permeation treatment;

$$Q_{\text{Leakage}} = Q_k \times \alpha \tag{6}$$

In the equation, Q_k—average capacity of reservoir; α—permeability coefficient.

Natural runoff replenishment is used for ecological water demand. Under natural conditions (non-station control of outer river water supply), the main source of water supply is water surface precipitation and surrounding surface runoff water supply. The data of dry season and the annual summary are presented in Table 2.

$$\text{Surrounding water convergence, } W_{\text{runoff}} = C \times P \times F \tag{7}$$

Here C—runoff coefficient; P—average annual rainfall; F—area of the confluence.

$$\text{The precipitation at water surface, } W = P \times F \tag{8}$$

Considering the independent operation mode of the central lake in the Nanhai Future City, there is no rainwater concentration, so the surrounding water convergence is supplied to other rivers.

Table 1
Calculation results of ecological water demand in the Nanhai Future City

Period	Evaporation at water surface		Leakage		Ecological water demand	
	Central lake	Other rivers	Central lake	Other rivers	Central lake	Other rivers
Dry season (thousand m³/month)	56	116.9	48	63.6	104	180.5
Whole year (thousand m³/annum)	1,969.2	4,109.6	581.7	770.9	2,550.9	4,880.5

Table 2
Aggregate of runoff replenishment in the Nanhai Future City

Period	Precipitation at water surface		Surrounding water concentration	Aggregate of water replenishment	
	Precipitation at central lake	Other rivers		Central lake	Other rivers
Dry season (thousand m³/month)	27	56	55	27	111
Whole year (thousand m³/annum)	959.1	2,001.6	1,918.7	959.1	3,920.3

The natural runoff replenishment of the Nanhai Future City mainly supplied ecological water demand. The quantity of outer water diversion considered for the whole year and the dry season (October–April, next year). Therefore, the balancing analysis of the supply and demand of the Nanhai Future City was carried out, as shown in Table 3. According to the plan of water diversion operation of the central lake of the Nanhai Future City, the water was directly transferred to the lake via the outer river, and then raised the level of lake before the sluices were opened to release water, and then the water demand of the surrounding river had been satisfied. The supply and demand balance of lake and water surface in the whole year and dry season were analyzed, respectively. It can be seen that the maximum water supply was 2,552,100 m^3/annum, the water supply in the dry season was 146,100 m^3/month, and the water supply in the flood season was 305,900 m^3/month. According to the 15-d water exchange cycle, the time of cycle of water diversion was calculated according to 24 h, and the diversion water discharge was 1.21, 0.85 and 1.77 m^3/s, respectively.

2.6. Water quality control effect

2.6.1. Source of water diversion and water supply route

Considering the preliminary planning layout of the river network based on urban development, land use type and landscape structure, according to the water quality around e Nanhai Future City, the possible water source mainly took into account the water source of the Chuanchang River as well as the Tongyu River reservoir nearby (Fig. 3).

At present, the water quality of the Chuanchang River is Grade IV-worse than Grade V. The main limit-exceeding factors are dissolved oxygen, total phosphorus, chemical oxygen demand and 5-d biochemical oxygen demand. The spatial distribution of ammonia nitrogen is uneven, and factors near the Xiaoxin River exceed the limit. Before water diversion, it must be treated to meet the water quality requirements by the technique at intensive pretreatment zone with high purification efficiency to efficiently remove suspended solids and total phosphorus cooperated with “ecological purification”, such as constructing estuarine ecological wetlands and underwater forests, strengthening self-purification capacity to meet water quality requirements. Tongyu River reservoir is located in the east of Nanhai Future City and has a pretreatment capacity of 300,000 m^3/d, the water after pretreatment can reach the water quality standard of Grade III.

In light of the calculation results of ecological outer water diversion, the maximum quantity of outer water diverse was 1.77 m^3/s. Therefore, the scale of the auxiliary water supply project was 2 m^3/s, including the south pumping station and north pumping station of Chuanchang River as well as the Tongyu River water diversion project of pipelines. In order to ensure the water quality of the central lake of the Nanhai Future City, it was necessary to ensure the independence of the water diversion route. According to the river network planning layout, five new sluices needed to be established inside the Nanhai Future City, which were located at the junction of the surrounding river network and the central lake.

In light of the current situation of water quality of the diversion source and future planning conditions and under the condition that the water quality of the Chuanchang River did not reach the standard, the water from the Tongyu River was planned to be used to replenish the water to the central lake. After the water quality of the Chuanchang River met the standard, two water diversion points, the south pumping station and north pumping station of Chuanchang River were pre-set on the Chuanchang River to supply for the river network.

In order to guarantee the water quality of the central lake in the Nanhai Future City, the principle of independent control of the central lake and the surrounding river network was adopted by setting the sluices to form independent flexible river network between the central lake and the surrounding river network. Meanwhile, the corresponding clearing route was determined cooperated with the water diversion point to ensure that the river network between the water diversion point and the central lake remains closed during the diversion period.

The water replenishment plan (Fig. 3) was to directly divert water from the Tongyu River into the central lake and raise the water level of the lake. The water pumping stations in the south and North of the Chuanchang River conducted diversion, respectively, while the central lake overflowed outward, and the living water was replenished to other rivers in this area to achieve the purpose of improving the water environment.

2.6.2. Water quality improvement effect

According to the water replenishment plan, since the Tongyu River diversion water only replenished the central lake, the other rivers in the area were replenished by two water pumping stations in the north and south and overflowing from the central lake. The following two types of water diversion rules were proposed. The distribution of the main pollutants, NH_3–N, was analyzed and calculated to

Table 3
Analysis of the balance of supply and demand of water in the Nanhai Future City during a whole year

Period	Central lake		Central lake plus other rivers		Quantity of outer water diversion	
	Demand	Supply from rainfall	Demand	Supply from rainfall	Lake surface	Other rivers
Dry season (thousand m^3/month)	2,550.9	959.1	7,431.5	4,879.4	1,591.8	2,552.1
Whole year (thousand m^3/annum)	104	27	284.5	138.3	77	146.1

determine the managing mode of the north and south water pumping stations. Rule 1: the quantity of water diversion of south pumping station was 2.0 m^3/s, central lake water supply was 2.0 m^3/s; Rule 2: the quantity of water diversion of south pumping station was 1.0 m^3/s and that of north pumping water was 1.0 m^3/s, central lake supply was 2.0 m^3/s.

Since the internal river network in the urban area of the Nanhai Future City was controlled by sluices of the external river network in the non-flood period, there was no relationship of water conservancy. Therefore, this water quantity and water quality model had 18 rivers and 117 nodes with a total length of 30.5 km in the generalization area. The calculation period was 15 d, and three control cross-sections (Fig. 4) were selected to analyze and calculate the concentration changes of ammonia nitrogen (NH_3–N) in the control cross-section 1, the control cross-section 2 and the control cross-section 3 under two water diversion rules (Fig. 5).

As shown in Fig. 5, in the control cross-section 3 and the control cross-section 2, the purification effect of the rule 2 was better, indicating that the purification effect of the two points water diversion was better than that of the single-point water diversion. The water diversion point was dispersedly arranged, which showed better improving effect. The purification effect of control cross-section 1 was slightly worse than the purification effect of rule 2, but the difference was not large, mainly because the cross-section was far from the water diversion point, and the holistic diversion flow was small, as the result, the water of diversion flowed through the cross-section was small.

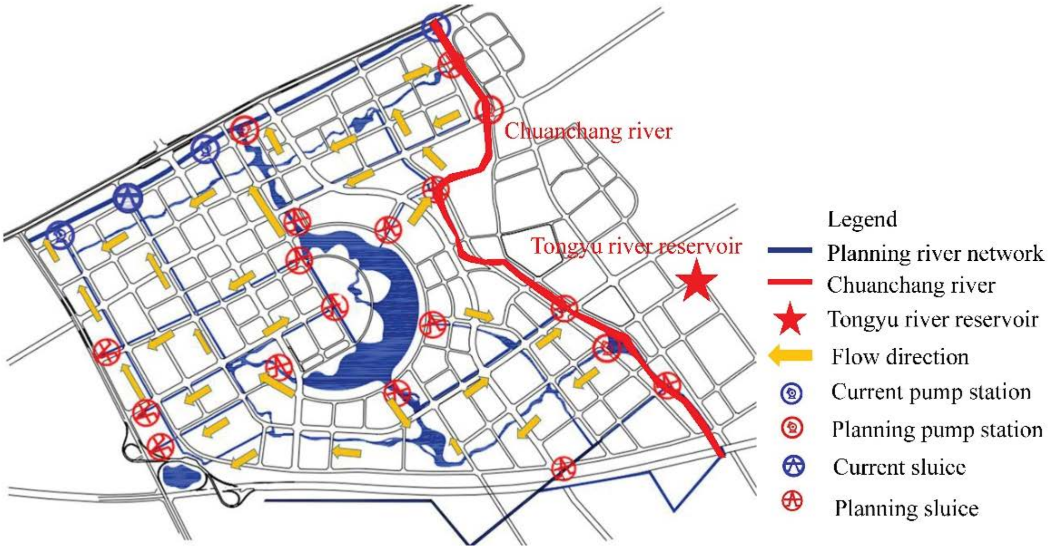

Fig. 3. Source of water diversion and water supply route.

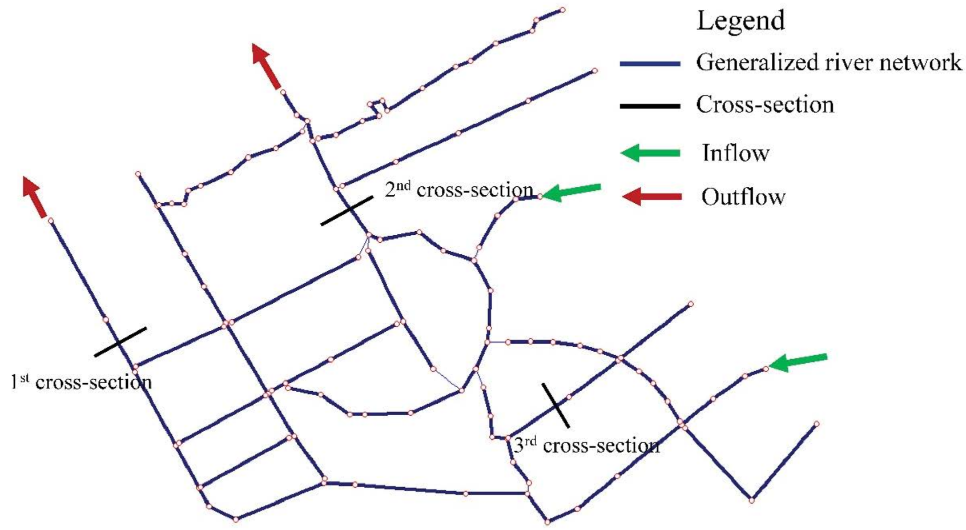

Fig. 4. Layout plan of the generalization of river network and control cross-sections in Nanhai Future City.

2.7. Flood control

In view of the preliminary development of the river network planning layout considering urban development, land use type and landscape structure, since the Nanhai Future City and the flood control area IX would be considered in the flood period, the entire flood control area should be considered when analyzing the flood control effect. When constructing the hydrological-hydraulic model, the current river network system and the planning river network system were generalized (Fig. 6). The 24-h design of a 20-year return period rainstorm was adopted.

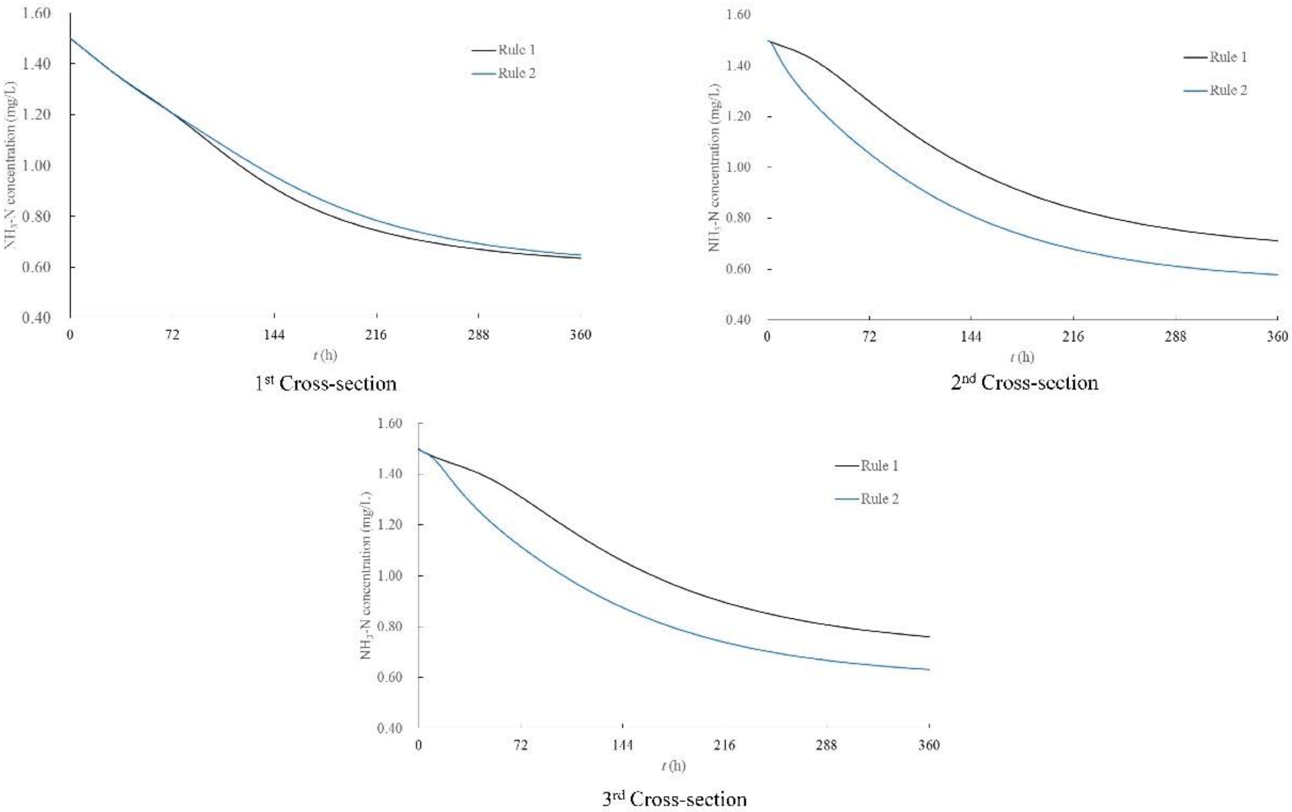

Fig. 5. Changes of the concentration of NH_3–N in the control cross-sections.

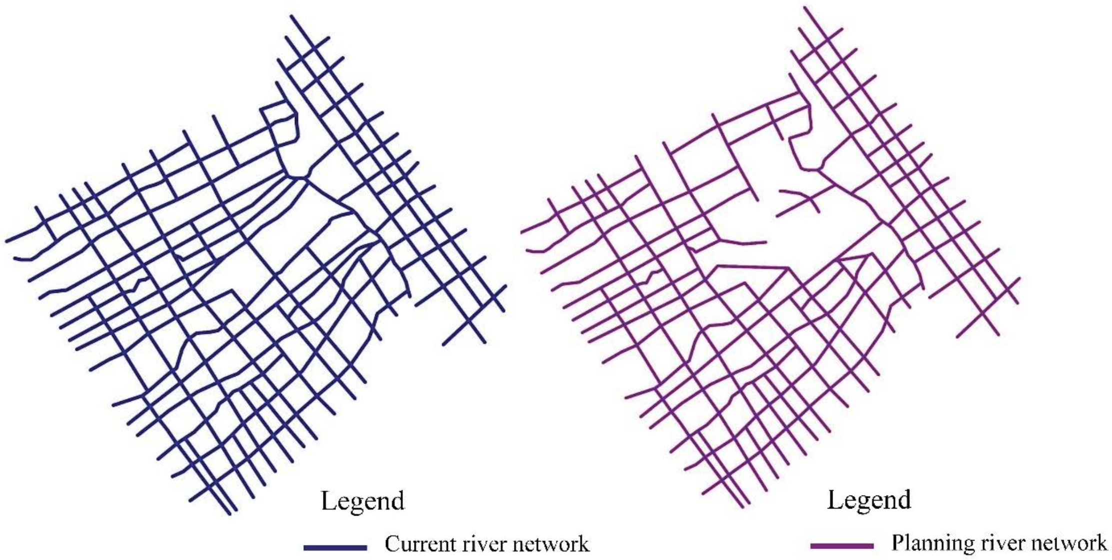

Fig. 6. Status of the Nanhai Future City and generalization results of the planning river network.

The maximum water level in the current river network and the planning river network were both 1.99 m after calculation. According to the requirements of the existing achievements, the highest control water level of the drainage in the flood control area IX in the Nanhai Future City was 2 m. After the adjustment of river network planning layout was fully considered, the highest water level of planning river network was consistent with that of the current drainage system, which were both no more than 2 m and less than the highest control water level of drainage, this met the water level control requirements.

2.8. Final river network layout

In view of the preliminary development of river network layout considering urban development, land use type and landscape structure, and taking into account the double requirements of water quality and flood control, 10 rivers were extensively reconstructed on the basis of the original river network. Besides, 11 rivers and a central lake were newly excavated [29–40]. After the planning, the water surface rate reached 13.3%, which was consistent with the current situation. In combination with the drainage pattern of the flood control area IX, the corresponding control sluices, and pumping stations for drainage and water diversion, needed to be planned to ensure the independent control of the river network of Nanhai Future City and the internal central lake (Table 4; Fig. 7).

3. Conclusions

As for the river network in plain, water quality and flood control issues are critical issues to be considered in river network planning layout. According to the preliminary proposed river network planning layout, comprehensive consideration should be given to the two aspects of water quality and flood control, and it was proposed to determine the scale of the water diversion project and the water diversion route based on the quantity of ecological outer water diversion. When setting the water replenishment points,

Table 4
Project scale of sluices and pumping stations

Projects	Name of constructions	Project scale	Description
Diversion projects	North pumping station	2 m^3/s	New construction
	South pumping station	2 m^3/s	New construction
	Tongyu River pumping station for water diversion	2 m^3/s	New construction
	Tongyu River water diversion pipelines	2.1 km	New construction
Drainage Project	Central lake pumping station for drainage	8 m^3/s	New construction
Control sluices		15 constructions in total	7 internal control sluices and 8 external control ones

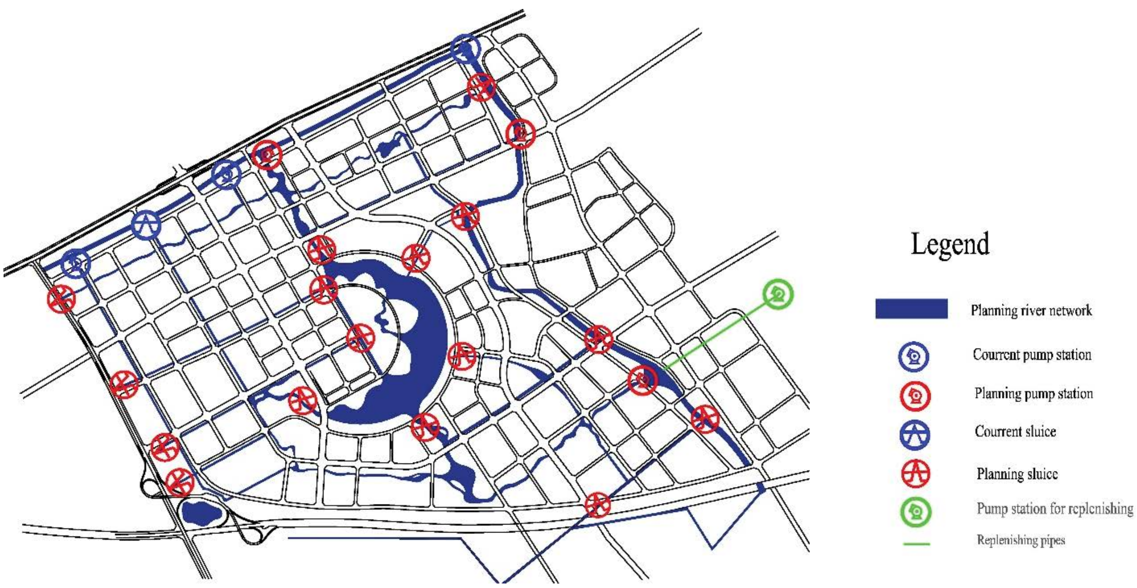

Fig. 7. Final river network layout results of the Nanhai Future City.

the model analysis showed that the water quality improvement effect of the several dispersed points is better than that of single point. Owing to the little flow discharge, the water quality improvement effect of the cross-section far away from the water diversion point was worse. When the water surface rate remained unchanged, the river network layout adjustment should slightly affect flood control and could meet the flood control requirements.

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