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Application of River Network Hydrodynamic Model in Determining Water Distribution Scale of Haishu Plain

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Abstract

The water distribution network is an important part of the plain water environment improvement system. To make efficient use of the regional water diversion source, scientifically distribute the water diversion flow and improve the water environment carrying capacity of Haishu Plain, the river network hydrodynamic model is used in this paper to simulate the water intake location, reasonable water quantity and influence range of water transfer in Haishu Plain. The simulation results have high accuracy, which can provide a scientific basis for the scale, water transfer mechanism and project layout of water transfer construction in Haishu Plain and show a strong reference value for the study of water diversion and distribution scheme of coastal plain river network.

Keywords

River Network Hydrodynamic Model, Water Distribution Planning, Water Diversion and Drainage Layout, Water Environment, Haishu Plain

1. Introduction

Since 2008, Ningbo Water Conservancy Department has organized and implemented the Ecological Water Diversion Project with Yao River as the main water source. In this project, 126 million m^3 of water for ecological use is allocated to the urban river network every year by using the gate pump to turn over and the river network to transport the water, 50 million m^3 of water is replenished to the river network every year by using the upstream reservoir discharge of Haishu

District and interval runoff. Thus, it provides water source guarantee for improving the water environment and maintaining a good water landscape. The water diversion project from Cao'e River to Ningbo is under construction, which creates favorable conditions for rationally utilizing Yao River water resources and increasing the amount of water diversion and distribution of urban river network. This study carries out prototype water transfer test, studies and analyzes the flow rate changes under different dispatching modes from the perspectives of hydrology, environmental science, water analytical chemistry and other relevant disciplines and constructs the hydrodynamic model in plain area, finds out and verifies the model parameters based on the investigation of hydrodynamic status and the results of water diversion test in the process of continuously promoting source control and pollution interception in Haishu District [1]. It aims at making efficient use of regional water diversion sources, scientifically distributing diversion flow and improving water environment carrying capacity of Haishu Plain. To further improve the hydrodynamic conditions and water environment of Haishu Plain, it analyzed the improvement of each water diversion and distribution project plan on the water mobility of the river network, proposed a reasonable pump station layout and practical ecological water diversion scale of the reservoirs and improved the water diversion, distribution and drainage pattern of Haishu Plain river network based on the main water diversion and distribution project plans and finally formed a scientific and reasonable ecological water diversion mechanism.

2. Hydrodynamic Model of River Network

2.1. Model Classification and Selection

The hydrodynamic model of the river network can be roughly divided as: the node-channel model, unit division model, hybrid model and artificial neural network model [2] [3], which provide reliable solutions for flood control, drainage, irrigation, water distribution scheme design and water environment management [4] [5]. Due to the characteristics of the river network and the situation of water conservancy projects in the Haishu Plain, the node-channel model was used for simulation. The one-dimensional hydrodynamic model was used to simulate the water transfer conditions of the river network by MIKE11 in this research [6].

2.2. Model Construction

2.2.1. Base Models

The one-dimensional river network confluence model in MIKE11 is constructed by the de Saint-Venant system of equations. The river network system of Haishu Plain was shown in Figure 1.

1) Flow equation

The plain river network for the flood routing calculation has multiple crisscrossed river sections. It belongs to the coastal river network. Its downstream is

Figure 1. River network water system map in Haishu Plain.

directly connected to the East China Sea and has inconstant flow. Its water level, discharge, velocity and cross-section in each river section change continuously with time and location. Its flood discharge is also affected by the tidal jacking of the estuary, which makes the water flow more complex under the interaction of the open sea tide and the upstream flood.

The one-dimensional unsteady flow method is used to describe the movement of water flow in the open channel. Its basic equation, the de Saint-Venant system of partial differential equations are:

$$B_T \frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{2-1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial Z}{\partial x} + gA\frac{|Q|Q}{K^2} = 0 \tag{2-2}$$

In the equations: q—Riverside inflow (m^3/s); B_T—Equivalent river width (m); Z—Section water level (m); Q—Flow rate (m^3/s); K—Discharge modulus.

2) Node Equation

In a river network, river sections are cross-connected, and their connection points are called nodes. Each node must satisfy two connection conditions, flow rate connection condition and dynamic connection condition.

Flow rate connection condition: it means the flow rate at each node must meet the water balance principle, which refers that the flow entering the node at each moment is equal to the change of the water storage capacity of the node.

$$\sum Q_i = \frac{d\omega}{dt} \tag{2-3}$$

In the equations: i—ID number of all the river sections that intersect in a certain node; ω—Storage capacity of node.

The nodes can have storage function, which is shown as the equation of continuity below:

$$\frac{\partial H}{\partial t} = \frac{\sum Q_t}{S_t} \tag{2-4}$$

In the equations: S—Wetted cross-section area of node at time t (m^2); H—Water level of node (m); $\sum Q$—Sum of nodal flow (m^3/s).

Difference expression of the nodal equation:

$$H_{t+\Delta t} = H_t + \frac{\sum \bar{Q}_t \Delta t}{\bar{S}_t} \tag{2-5}$$

For the node: without storage function:

$$\sum \bar{Q}_t = 0 \tag{2-6}$$

Dynamic connection condition: It means that the water level and flow rate of each connecting river section and the average water level of the nodes must meet the actual dynamic connection conditions and satisfy the Bernoulli equation.

The dynamic connection condition can be simplified if the nodes do not have storage function:

$$H_i = H \tag{2-7}$$

In the equations: H_i—Water level of river cross-section that connects to a certain node (m); H—Water level of node (m).

The whole river network is a combination of several river channels and nodes. The control equation of river network water volume is system of simultaneous differential equations obtained by the control equation of each river channel, the connection conditions between river channels and their nodes and initial boundary conditions. By solving this system of differential equations of river network water volume, the hydraulic variables such as water level and flow rate at the specified section or node of each river channel can be obtained.

3) Assume the flood discharge form of water gate is free outflow:

$$Q = mB\sqrt{2g}H^{3/2} \tag{2-8}$$

Submerged discharge equation:

$$Q = \phi B H_s \sqrt{2g\left(Z_u - Z_d\right)} \tag{2-9}$$

In the equations: m—Discharge coefficient of free outflow of sluice hole; ϕ—Discharge coefficient of submerged discharge of sluice hole; Z_u—Water level before sluice gate; Z_d—Water level after sluice gate; H—Water head before sluice gate; H_s—Water head after sluice gate; B—Width of sluice hole.

4) Pump Station Inflow

The flow of the pump station is determined by the design capacity and dispatching mode of the pump station.

2.2.2. River Reach Generalization

The flood routing of a single river channel is simulated by one-dimensional hydrodynamic calculation software, and the generalization of the river channel is mainly section division. The sections are set in the river reach with significant changes in river morphology and the engineering place with river channel, and the data interpolation encryption of the upper and lower adjacent sections is adopted to obtain the virtual middle section. The river reach generalization was shown in Figure 2.

2.2.3. Parameters

According to the roughness value requirements in "hydraulic calculation manual (Second Edition)" and the land use of the calculation area, the roughness parameters of one-dimensional river network model were selected and calibrated. Based on the relevant historical data and experience, the roughness parameters of each river section were selected between 0.025 and 0.035.

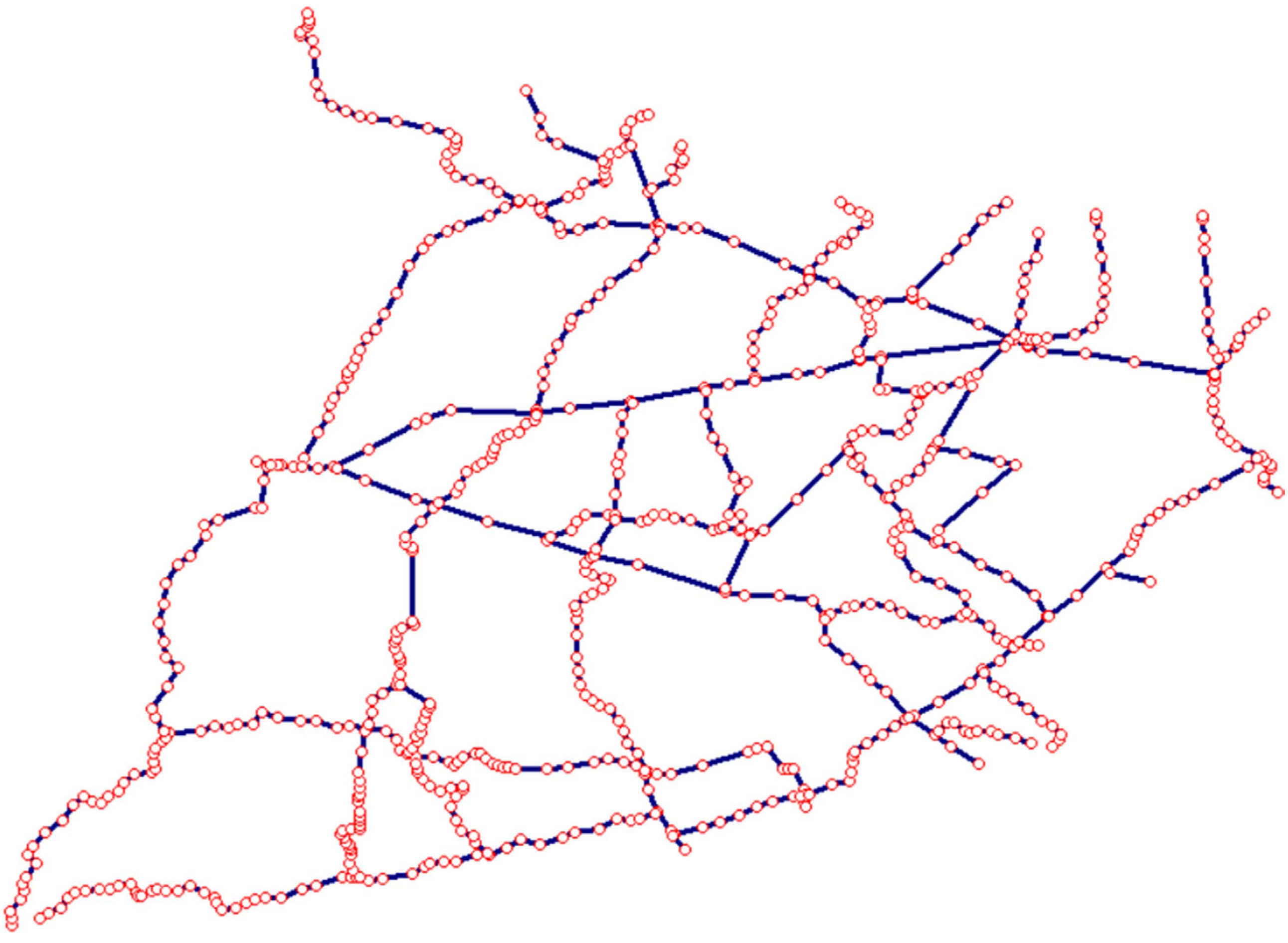

Figure 2. One-dimensional generalized map of river network.

2.2.4. Boundary Condition

The design tide level of 2-year return period was adopted as the model boundary. The tide level in different time periods of each water gate is shown in Table 1.

2.3. Model Calibration

In this research, 13 days of water transfer test was done in Haishu District from December 11, 2018 to December 23, 2018. This test aims to make full use of the existing engineering facilities, explore the measures and methods to activate water body and achieve the objectives of active water, clean water and purified water in regional river through measures such as multi-gate dispatching and water exchange. It designed 11 kinds of water diversion schemes, set 26 synchronous

Table 1. Tidal level of each water gate.

Time $\Delta t = 1$ h	Baofeng gate (m)	Chenglang gate (m)	Duantang gate (m)	Xingchun gate (m)	Xiachen gate (m)	Tujiayan gate (m)	Shuilingchi gate (m)	Fengpeng gate (m)
1	2.04	1.95	1.83	1.75	1.69	1.64	1.54	1.76
2	2.10	2.05	1.99	1.94	1.91	1.88	1.83	2.06
3	1.42	1.52	1.62	1.69	1.74	1.77	1.86	2.33
4	0.93	1.07	1.20	1.30	1.37	1.42	1.54	2.13
5	0.65	0.81	0.96	1.06	1.14	1.20	1.32	1.91
6	0.35	0.51	0.67	0.78	0.86	0.92	1.05	1.63
7	0.04	0.21	0.37	0.49	0.58	0.64	0.78	1.37
8	−0.18	−0.01	0.16	0.28	0.37	0.43	0.57	1.14
9	0.21	0.18	0.27	0.33	0.37	0.40	0.47	0.97
10	0.91	0.83	0.74	0.67	0.63	0.60	0.52	0.94
11	1.46	1.37	1.27	1.19	1.14	1.10	1.01	1.17
12	1.82	1.72	1.61	1.53	1.47	1.42	1.33	1.52
13	2.18	2.08	1.96	1.87	1.80	1.75	1.65	1.82
14	2.41	2.35	2.26	2.20	2.16	2.13	2.06	2.27
15	1.92	1.98	2.03	2.07	2.10	2.12	2.17	2.55
16	1.40	1.50	1.61	1.69	1.75	1.79	1.88	2.47
17	1.05	1.17	1.30	1.39	1.45	1.50	1.60	2.16
18	0.78	0.91	1.04	1.13	1.20	1.25	1.36	1.90
19	0.45	0.68	0.82	0.92	0.99	1.04	1.16	1.71
20	0.21	0.52	0.65	0.75	0.82	0.88	0.99	1.55
21	0.15	0.46	0.58	0.67	0.73	0.78	0.88	1.43
22	0.71	0.73	0.76	0.78	0.80	0.82	0.84	1.32
23	1.35	1.30	1.20	1.14	1.09	1.05	0.98	1.29
24	1.76	1.71	1.65	1.60	1.56	1.54	1.48	1.63

monitoring sections of water quantity and quality and 13 water quality monitoring sections, basically covered the main river network in Haishu District. Generally, during the test, the control water level of Jishigang was not lower than 1.47 m, that of huanggulin was not lower than 1.45 m and that of Beidou river was not lower than 1.15 m. It considered various water diversion and drainage dispatching modes, such as diversion and drainage at the same time, diversion without drainage, no diversion and drainage, diversion after drainage and diversion before drainage, set flow diversion schemes based on different water sources (Yaojiang River and upstream reservoirs) and different combinations of drainage gates to find out the rule of water body flow and the improvement of regional water quality. The water quantity and water quality of each measurement section were monitored through stationary gauging during the water transfer period. The best water transfer scheme was determined by comparing the improvement on the regional water environment of different schemes. The model was calibrated by the measured data in the whole period of water transfer test, its results were compared with the measured water level of river network. The hourly water levels of Beidou River, Duantang, Shiqi, Wangjiacao and Wangchun stations were measured and compared with the model results. The locations of measured points for obtaining water level are shown in **Figure 3**. The comparison results are shown in **Figures 4-8**.

Figure 3. The locations of measured points for obtaining water level.

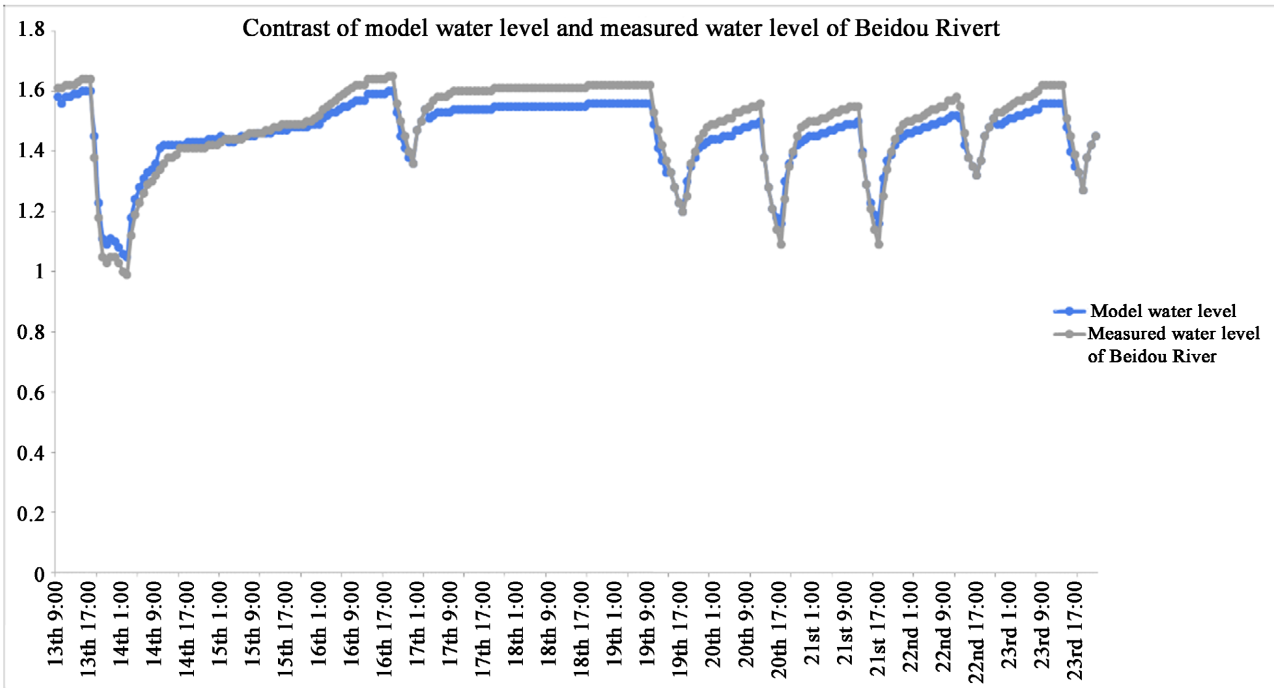

Figure 4. Contrast of model water level and measured water level of Beidou River.

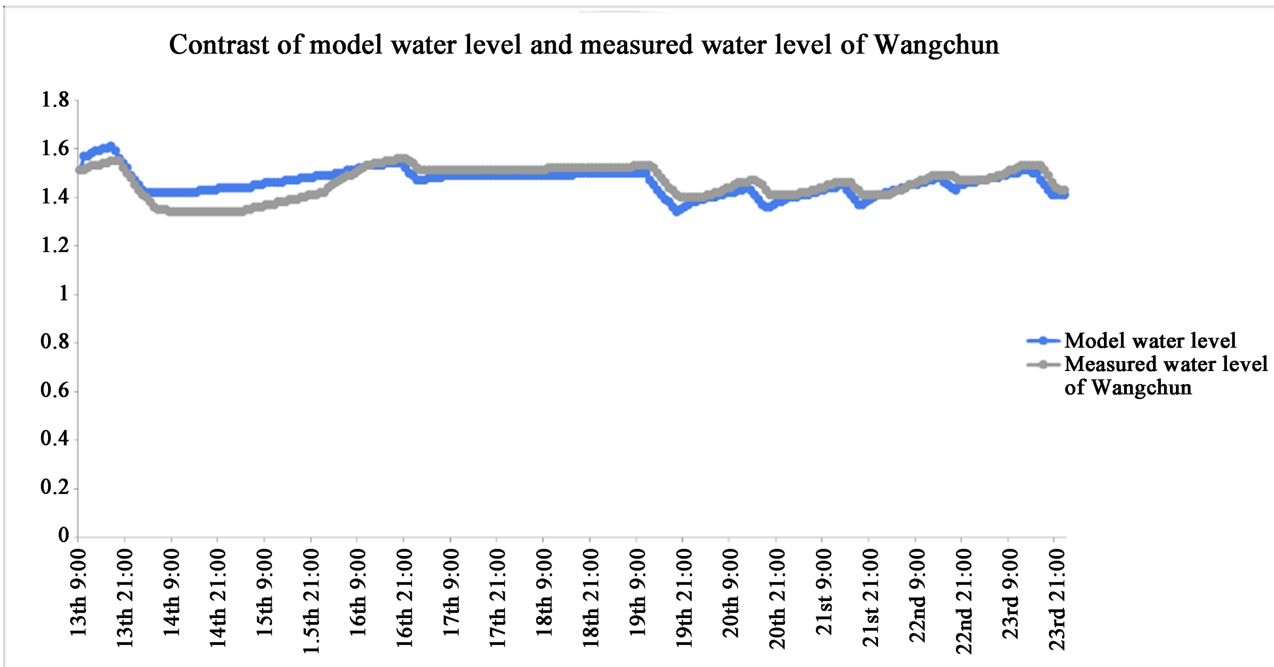

Figure 5. Contrast of model water level and measured water level of Wangchun.

Through the comparison between simulation calculation results of the measured water transfer and the measured values, the calculated water level of each control point is similar with the measured water level and the average error of the calculation results is controlled below 3 cm, which proves that the river network hydrodynamic model in Haishu Plain has high accuracy in simulation.

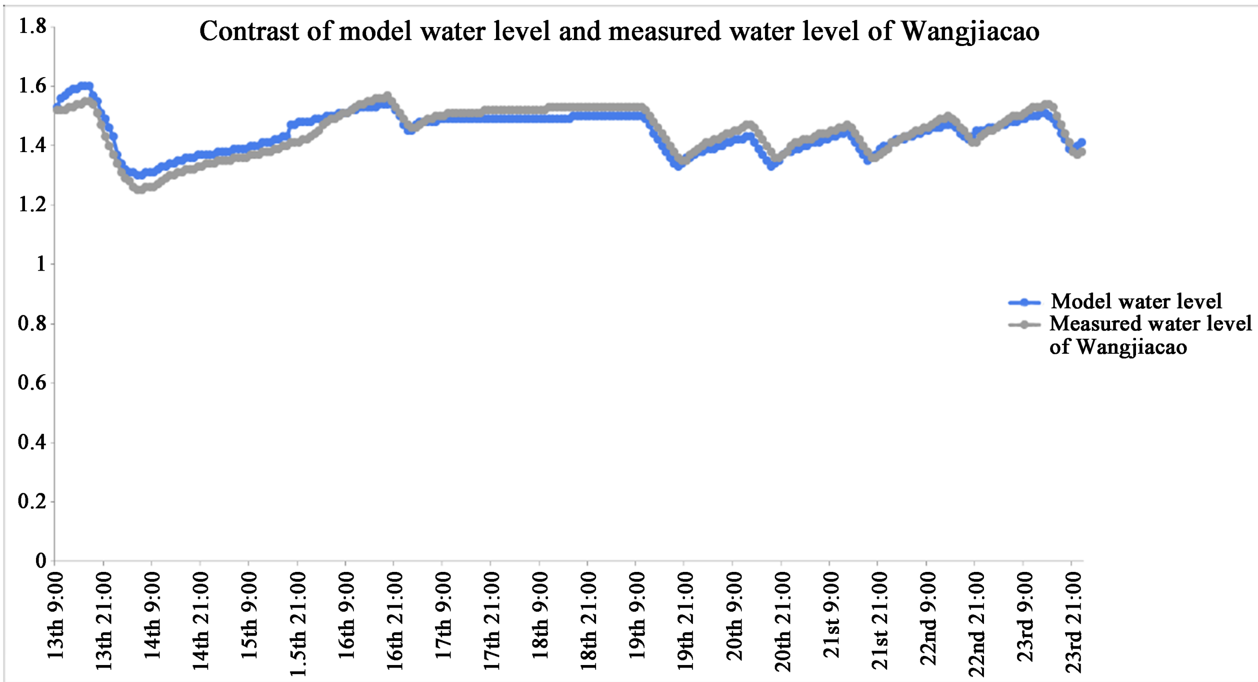

Figure 6. Contrast of model water level and measured water level of Wangjiacao.

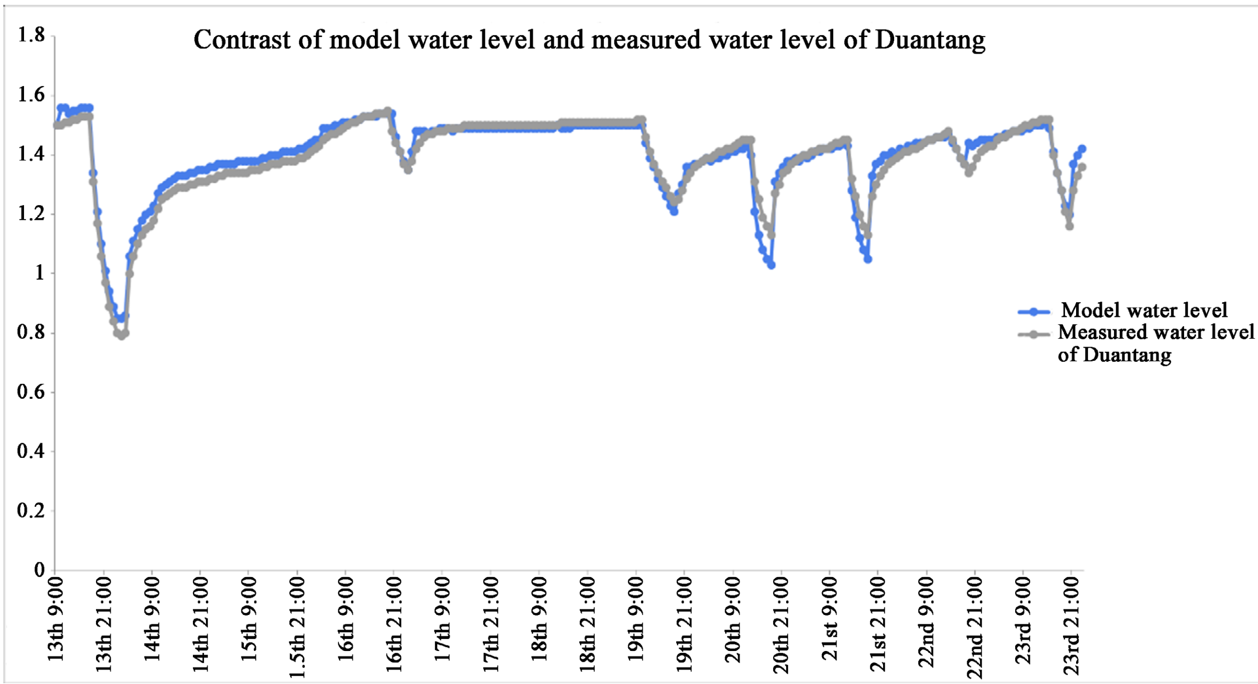

Figure 7. Contrast of model water level and measured water level of Duantang.

3. Planned Water Distribution Project and Scale Analysis

According to the analysis results of prototype test, it is still difficult to effectively improve the fluidity of some river sections under the existing water diversion projects. So, it is planned to increase water diversion sources, build new pumping station at Shaojiadu, Wujiangkou and Tujiayan, open the Xixia reservoir,

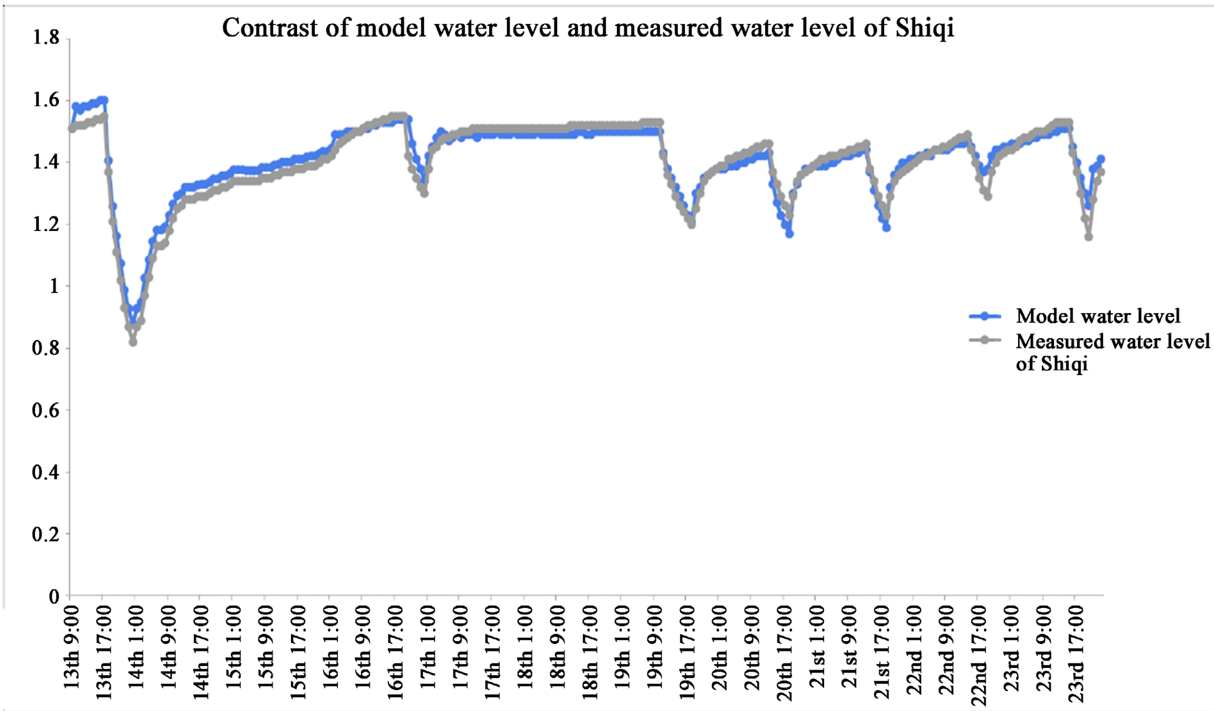

Figure 8. Contrast of model water level and measured water level of Shiqi.

build Fengpeng gate for water recession. The layout of planning projects, the scale of the new projects and the ecological discharge of reservoirs are determined through the simulation. The distribution of structures for water diversion and distribution is shown in **Figure 9**.

Several calculation conditions are set for comparative analysis to scientifically exam the scale and effect of the new diversion water projects. Three kinds of ecological discharge flows (0 m^3/d, 50,000 m^3/d and 100,000 m^3/d) are considered for Xixia reservoir, three kinds of diversion water flows (10 m^3/s, 15 m^3/s and 20 m^3/s) are considered for Shaojiadu pumping station, four kinds of diversion water flows (5 m^3/s, 10 m^3/s, 15 m^3/s and 20 m^3/s) are considered for Wujiangkou pumping station and three kinds of diversion water flows (5 m^3/s, 10 m^3/s and 20 m^3/s) are considered for Tujiayan pumping station. In addition, the effect of using Fengpeng gate to cooperate with water drainage is also analyzed. The conditions for analysis are shown in **Table 2**.

According to the analysis results of planning conditions 1 - 13, the ecological discharge of Xixia reservoir and the diversion scale of pumping station of Shaojiadu, Wujiangkou and Tujiayan are determined. The final scales of new water diversion projects are shown in **Table 3**.

Jiaokou reservoir discharges at the scale of 150,000 m^3/d and Xixia reservoir discharges at the scale of 50,000 m^3/d. Set 8-hour diversion time, the diversion flow of Shaojiadu pumping station is 15 m^3/s, of Wujiangkou pumping station is 10 m^3/s, of Gaoqiao pumping station is 13.44 m^3/s and of Huangjiahe pumping station is 1 m^3/s. Open Baofeng gate, Xingchun gate and Tujia weir for 4-hour drainage. During this water diversion time, the fluidity of Jishigang River, Wujiang

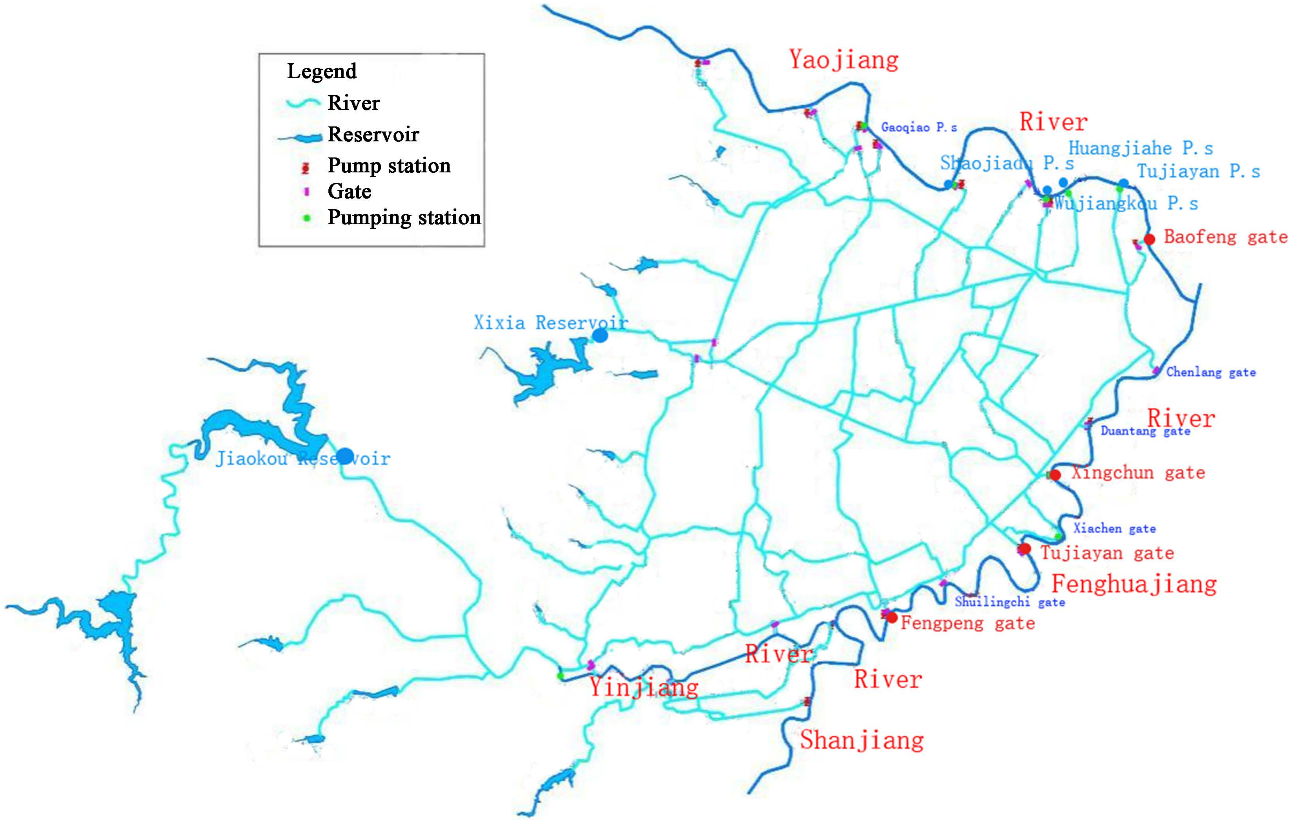

Figure 9. The distribution of structures for water diversion and distribution under the planning condition.

Table 2. The calculation and analysis of new engineering working condition.

Working Condition	Water diversion							Water drainage				Note
	Reservoir		Pumping station					Water gate				
	Xixia reservoir 10^4 m³/d	Jiaokou reservoir 10^4 m³/d	Gaoqiao pumping station 13.4 m³/s	Huangjiahe pumping station 1 m³/s	Wujiangkou pumping station m³/s	Shaojiadu pumping station m³/s	Tujiayan pumping station m³/s	Baofeng gate	Xingchun gate	Tujiayan gate	Fengpeng gate	
1		15	√	√				√	√	√		Ecological drainage analysis of Xixia reservoir
2	5	15	√	√				√	√	√		
3	10	15	√	√				√	√	√		
4		15	√	√		10		√	√	√		Water diversion analysis for Shaojiadu pumping station
5		15	√	√		15		√	√	√		
6		15	√	√		20		√	√	√		
7		15	√	√	5			√	√	√		Water diversion analysis for Wujiangkou pumping station
8		15	√	√	10			√	√	√		
9		15	√	√	15			√	√	√		
10		15	√	√	20			√	√	√		

Continued

11		15	√	√	5	√	√	√		Water diversion analysis for Tujiayan pumping station
12		15	√	√	10	√	√	√		
13		15	√	√	20	√	√	√		
14	5		√	√		√	√	√		Drainage Analysis Of Fengpeng water gate
15	5		√	√		√	√	√	√	

Table 3. The scale of new water diversion project.

Project name	Water transfer scale
Xixia reservoir	5×10^4 m^3/d
Shaojiadu pumping station	15 m^3/s
Wujiangkou pumping station	10 m^3/s
Tujiayan pumping station	canceled

River, city moat and some river sections of Yuejin River is excellent, their flow velocities exceed 0.10 m/s. Hupo River, Xiyangang River, the North section of Fengpengqi River, Shaojiadu River, Buzheng River, some river sections of Yejiaqi River, Xiangjiangang River, the North section of Yuejin River, the midstream and downstream of Xitang River, some river sections of Zhongtang River and Nantang River (the river sections between Dahuangjia River and Nanxintang River) have good fluidity, their flow velocities are between 0.05 m/s and 0.10 m/s. Huangjia River, Qiantang River, the South sections of Yuejin River, the South sections of Fengpengqi River, the upstream and downstream of Nantang River, Nanxintang River, the North sections of Meiliangqiao River, Xiaoxigang and Lilonggang River have general fluidity, with flow velocities between 0.02 m/s and 0.05 m/s. The South sections of Meilianggang River, Qianzhangjing River, Zhaotiangang and Nantang River (river sections between Lilonggang River and Fengpengqi River) have poor fluidity and their flow velocity less than 0.02 m/s. The velocity gradient of river network mentioned above is shown in **Figure 10**.

During water drainage, Jishigang River, Xiyangang River, Shaojiadu River, the North section of Fengpengqi River, Buzheng River, Yejiaqi River, Xiangjiangang River, some river sections of Yuejin River, Beidou River, city moat, Dahuanjia River, the midstream and downstream of Xitang River, Nanxintang River, Nantang River (the river sections between Fengqi River and Duantangqi River) and the downstream of Qianzhangjing River have excellent fluidity, their flow velocities exceed 0.10 m/s. The upstream of Xitang River, the most river sections of Zhongtang River, Qianzhangjing River (the river sections between Xiaoxigang and Fengpengqi River), Meiliangqiao River, the South section of Fengpengqi River, some river sections of Yuejin River, Nantang River (the river sections between Lilonggang River and Fengpengqi River and the river sections between Duantangqi River and city moat) have good fluidity, with flow velocities between

Figure 10. The velocity gradient of river network during the water diversion time of the planned water distribution scheme.

0.05 m/s and 0.10 m/s. The fluidity of Hupo River, Huangjia River, Qiantang River, Xiaoxigang, the upstream of Nantang River and Zhaotiangang is general, the flow velocities are between 0.02 m/s and 0.05 m/s. The flow velocity of Lilonggang river is less than 0.02 m/s, which is poor. The velocity gradient of river network mentioned in this paragraph is shown in **Figure 11**.

4. Conclusion

In this paper, the hydrodynamic model of river network was used to simulate the water diversion evolution process at Haishu Plain. The verification results of the water diversion test process of Haishu Plain river network in Ningbo from December 11, 2018 to December 23, 2018 show that the model has high accuracy. Under the planned water distribution scheme, the flow velocity of most rivers in the river network can reach 0.10 m/s, which increases the fluidity of river network, improves the self-purification capacity of river network and allows the introduced water body to flow widely in the river network of Haishu District. The main water diversion and distribution scheme of Haishu district planning project takes the North part of the Yaojiang River and the reservoirs in the upstream hilly area as water sources, introduces external clean water sources by pumping stations along Yaojiang River like Gaoqiao pumping station, Shaojiadu pumping station, Wujiangkou pumping station and Huangjiahe pumping

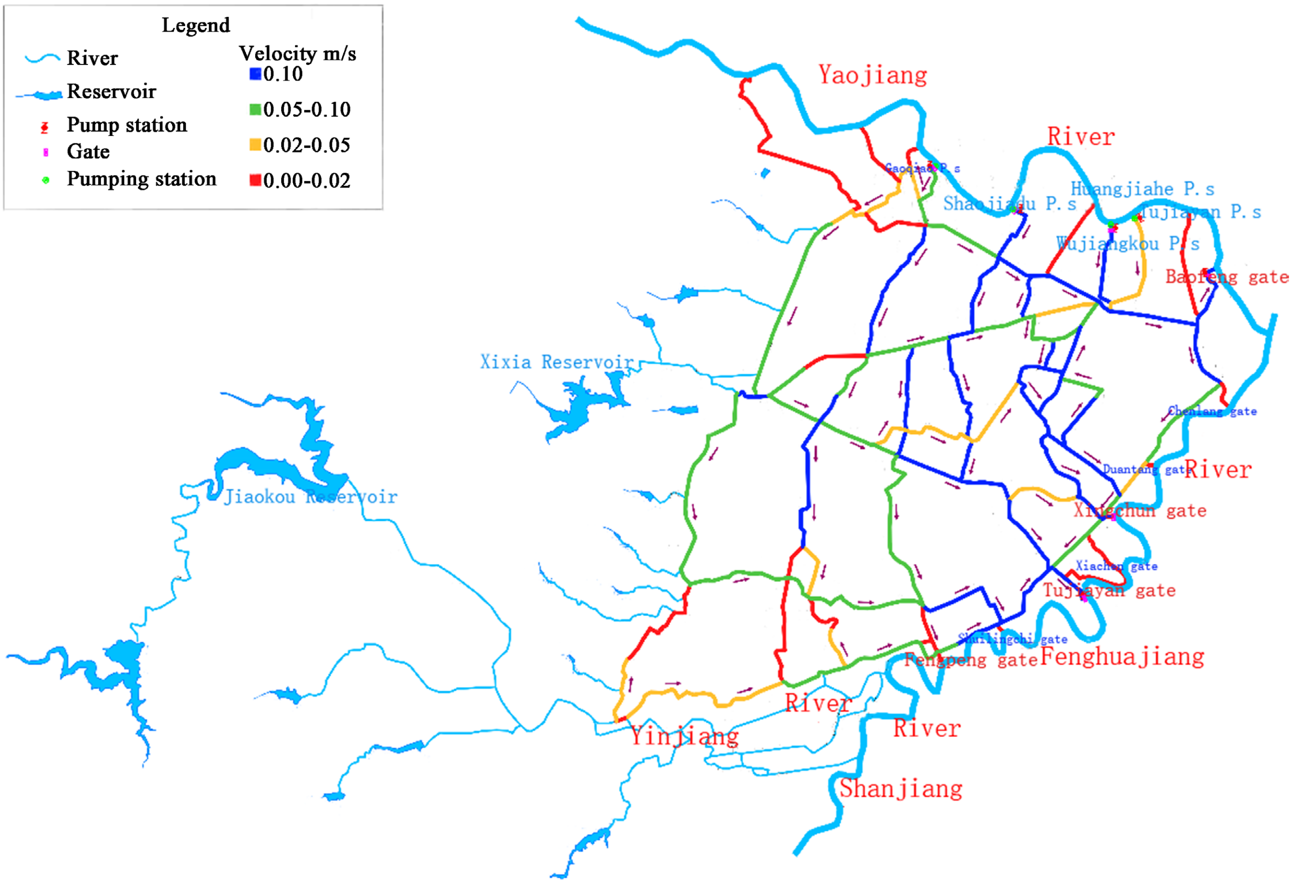

Figure 11. The velocity gradient of river network during the water drainage time of the planned water distribution scheme.

station, Xixia reservoir and Jiaokou reservoir based on the study of regional ecological water transfer mechanism under the condition of multiple water sources. The discharge scale of Jiaokou reservoir is 150,000 m^3/d and of Xixia reservoir is 50,000 m^3/d. The diversion flow of Gaoqiao pumping station is 13.44 m^3/s, and of Huangjiahe pumping station is 1 m^3/s. Shaojiadu pumping station and Wujiangkou pumping station are newly opened for water diversion, their diversion flow is 15 m^3/s and 10 m^3/s. Baofeng gate, Xingchun gate, Tujia weir and Fengpeng gate are opened for water recession. Under this water diversion and distribution mode, the river network shows good fluidity in the whole region and the clean water can flow through each main river section, thus, the plain water environment is effectively improved and the human settlement quality in Haishu Plain is also promoted.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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