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Water diversion and allocation for typical confined polder river-net in Taihu Basin

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Abstract

Hydraulic restoration in a confined polder river-net is a new issue under the concept of the Interconnected River System Network (IRSN) proposed by the Ministry of Water Resources (MWR) in China. This paper studies the typical hydrographic connection in the polder, and analyses the current situation of the hydrographic river-net in the typical area of Subaiwei in Changshu City by setting up a one-dimensional unsteady hydrodynamic model. The best water diversion-allocation schemes in the confined polder river-net are simulated and optimized in various scheduling rules. In order to recover the ability of hydro-connection and stream function, the effects of different scheduling rules and the duration time of water diversion under the ability of pump stations around polder boundary are compared. The results show that the optimized injects can enhance the total flow velocity and the exchange rate is more than 20% on average in various streams. This study is critical for the sustainable utilization of limited clean water in a confined river-net polder, and for quantifying the water ecological recharge for hydrodynamic connection.

Keywords: Confined river-net; Exchange rate; Hydrodynamic model; Optimization scheme; Water diversion-allocation

Introduction

National framework management for river-net regulation and control

The drainage system in the plain river network area is of great importance for the supply of water, the health of river-lake ecosystems and the resistance of flood and drought, which is the lifeline of regional development (Xie *et al.*, 2012; Xiang *et al.*, 2015). Nowadays, with the increasing acceleration of urbanization, on the one hand people put forward higher requirements on water quantity, water quality, flood control, domestic water and ecological environment water (Sun *et al.*, 2014). On the other hand, human

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economic and social activities have a severe influence on the drainage system, which lead to a series of problems such as the weak connectivity of river and lake system, the deficiency of water resources and environment carrying capacity, low flood drainage capacity and the increasing risk of water security, etc. (Wang *et al*., 2005; Lu *et al*., 2006).

Faced with such a stark reality, the Ministry of Water Resources (MWR) put forward a new concept of an Interconnected River System Network (IRSN), which currently has been regarded as a new water control strategy and attached great importance for water supply in a new situation (Li *et al*., 2011; Xiang *et al*., 2015). Therefore, in this paper, the structure and function of the river water system interconnection is discussed, which will be of great importance to the sustainable utilization of urban water resources, the healthy development of economic and society, and the construction of ecological civilization (Partheniades, 1965a, 1965b).

Local demand for water diversion from Yangtze river to Taihu Lake

Changshu is a Chinese city located in the northern part of Taihu Lake Basin, which is a river network in the low-lying plain region. With the development of urbanization, the river system inside the polder faces many problems, such as scattered drainage patterns, poor river network fluidity, serious silting conditions, and deteriorating water quality (Wu *et al*., 2013).

After years of water conservancy construction, especially with the implementation of water conservancy projects of Wangyu River, Haiyangjing, Huancheng River, and Zouma Pond (Han, 2008; Kang & Guo, 2011), the drainage in Changshu has been manually controlled as a rational layout of water network system, in which water diversion and drainage are very convenient for conservancy projects. The management capabilities of the water distribution control and the trunk channel have been significantly improved (Chen *et al*., 2013). However, influenced by local natural topography, social and economic constructions, as well as hydraulic engineering construction, part of the water in the dike is still experiencing poor river network fluidity, a high level of water environmental stress, etc. (Ji, 2010).

Therefore, the local government takes the Yangtze River as a natural tidal power source and regularly controls the connected drainage inside and outside the polder area, in order to import clear and pure water into the polder area to improve the water environment (Wang *et al*., 2005; Zhang *et al*., 2006). Therefore, it is essential to propose a heuristic method of water diversion and drainage to ensure good circulation of water systems on the basis of flood control in the polder area.

Regulation and control for confined river-net systems

Compared with natural open river network systems, most of the watercourses in Changshu polder area belong to a constrained or confined river network by flood control dykes. The scheduled plan mainly depends on water conservancy regulation and control, which has the ability to maintain the original function of the river network (Dai & Wang, 2005). Considering the sustainability of a watercourse function under limited situations, both traditional river network planning concepts and planning methods require updating (Zhu, 2013). Due to the complexity of the river network in the polder region and the limitations of actual project scheduling, this paper adopts a hydrodynamic model to simulate the regulation scheme of water diversion and drainage in a polder region (Fleurant *et al*., 2006); Zhu *et al*., 2013).

The hydrodynamic model is a one-dimensional mathematical model for river networks, invented by the Danish Hydraulic Institute. In a confined river-net, the boundary for water supply is controlled by a hydraulic structure, and tidal streams are difficult to reach a steady state in the whole water allocation process. The unsteady flow condition and hydrodynamic model system can offer more procedural information, which is valuable for water management. Through model system tools, an optimal scheduling rule about water diversion and drainage in the polder region is offered to achieve the goal of connecting the drainage system inside and outside the dike, make the inside circulation into a system, effectively promote a virtuous cycle of the river network in polder and improve the water environment in the area.

Research area and methods

General situation survey of the target research area

Changshu is located in the southeast part of Jiangsu Province, China, at longitude 120°33′–121°03′ and latitude 31°31′N–31°50′N. Changshu borders on Taicang in the east, Kunshan and Xiangcheng in the south, Wuxi and Jiangyin in the west, Zhangjiagang in the northwest, and Yangtze River in the north. Changshu is on the alluvial plain of Yangtze delta, and the terrain slope is from the northwest to the southeast, and most of the ground elevation is between 3 and 7 m. Wangyu River and Yantie Pond run through the whole territory, which divides the city into three parts, namely, Yuxi, Yangcheng and Binjiang.

The typical research area is a confined polder in Changshu that is mainly surrounded by Zhangjianggang River, East Ring River, Dawen, and Baimao Pond, all of which are connected by sluice gates (Figure 1). This target area includes one river-basin watercourse, one regional watercourse, two municipal rivers, and 20 town-level or village-level rivers. The rivers in this water system of the polder area are interconnected with each other, but the overall connectivity is in poor condition. On account of the needs of city development, the water conservancy construction and its project scheduling, some rivers are blocked, while others are disconnected from the outside river dike, and the channels are seriously occupied by sand deposition. This has a strong impact on the drainage system connection and water cycle.

Schematic design and model of water cycle

Data collection. The schematic design requires information on the current status of the target research area, hence the researchers needed to conduct a detailed data collection and statistics which mainly included the current basic data of existing rivers, the existing flood control and drainage projects as well as their operation conditions.

Establishment of model system. According to the drainage system distribution, the current water diversion-drainage situation, and the characteristics of the drainage system inside the polder area in Changshu (Han *et al*., 2011), a hydro-dynamic model, which adapts to the complex hydrographic river-net system, was established. In the hydraulic module, the governing equations of one-dimensional unsteady water flow movement rules is described. The de Saint-Venant system of equations is composed of continuity equations of mass conservation as shown in the upper equation, and momentum equations of energy

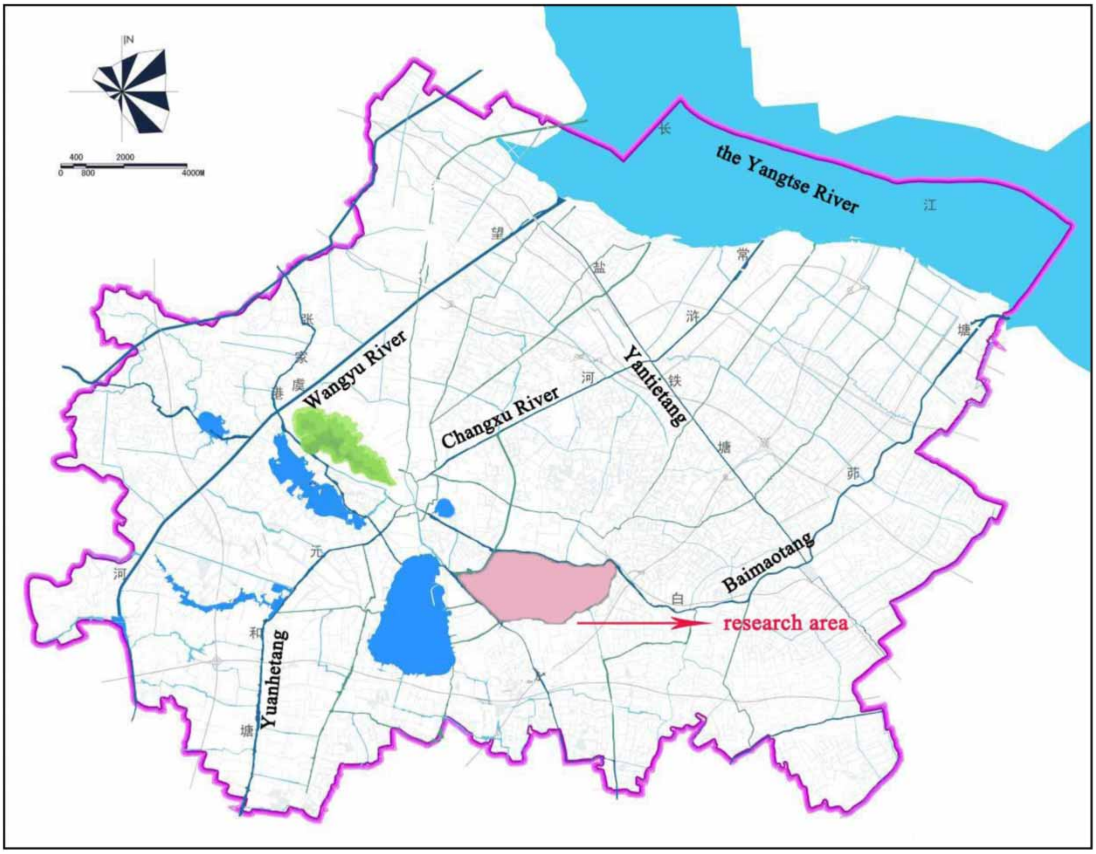

Fig. 1. The current hydrographic net in Changshu in Taihu basin.

conservation as shown in the lower equation. They are listed respectively as follows:

$$\begin{aligned} &\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \\ &\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial h}{\partial x} + g\frac{Q|Q|}{C^2 AR} = 0 \end{aligned} \tag{1}$$

In the above equations, x indicates distance coordinate; t indicates time; A indicates the cross section of water area; Q, and h indicates flow and water level, respectively; q indicates lateral inflow; C indicates Chezy coefficient; R indicates hydraulic radius; and g indicates gravitational acceleration (Li & Weng, 2001; Lai, 2009).

1. The generation of hydrographic net file

During the process of building the numerical generalization of the target model branch, the influence of main rivers on water diversion in the process of diversion and drainage in the target research area are fully considered. In the process of generalization, the connectivity of watercourses is consistent with the actual situation and the modeling scheme conditions (Wang & Bai, 2008). The overall model could generalize 14 watercourses, and the specific situation is shown in Figure 2.

2. The generation of cross-section file

The HD model fixes the calculative points of water level based on the data in the sectional data file. In the meantime, stake marks automatically branch the water level calculative points to the flow calculative points. In order to ensure the requirement of accurate modeling accumulation, the section distance should not be more than 100 m, and the data of cross section in a specific site (such as the river intersection) should be encrypted. All of the sections are derived from the census forms regarding watercourses in Changshu, which reflects the current status of watercourses.

3. The generation of boundary file

Incorporated with the status of polder, this research uses the inflows as a boundary and the design of flow in the model is based on the water diversion and drainage scheme in Changshu. In this process, it is because the target research area is a plain hydrographic river-zone net, the lateral flow is formed in a uniform side inflow which consists of rainfall runoff, then it becomes the internal boundary into the watercourse. All the water evaporation and rainfall are the observed data which are designed to guarantee the reliability of the results (Woodbine, 2004).

4. The generation of parameter file

In order to ensure a stationary start of the simulation, the numerical values of initial water level and flow are set in accordance with the actual hydrodynamic conditions in the beginning, as much as

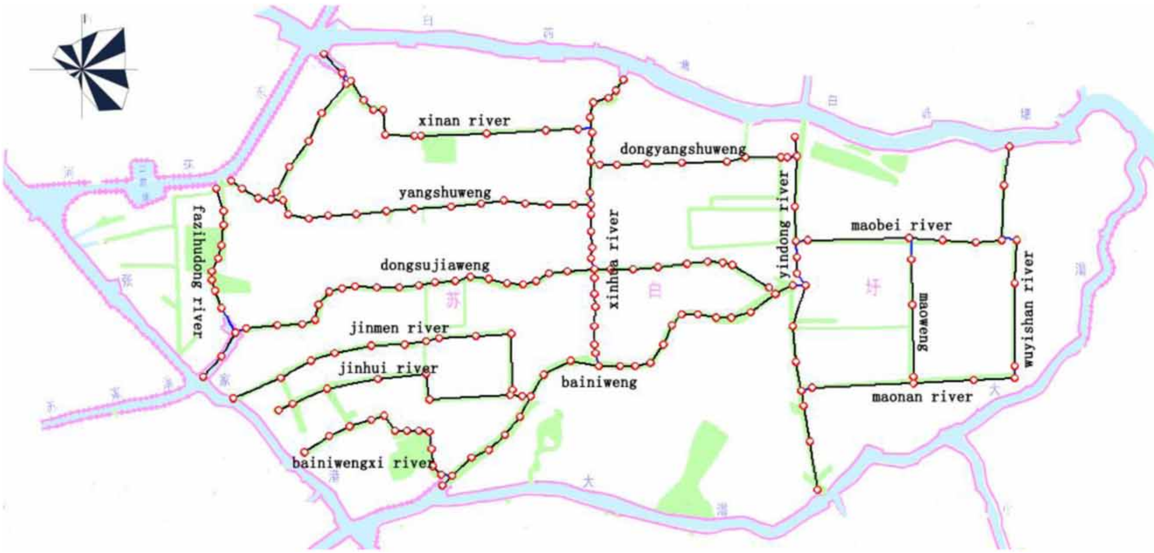

Fig. 2. Hydrographic net generalization in the target research area.

possible. In this model, the initial water level is set at 3.2 m, the river roughness is based on the actual flow data worked out by the Manning formula, and the roughness is 0.03 (Zheng, 2008; Valipour & Montazar, 2012; Valipour, 2016).

Hydrologic analysis and optimization of the scheme

Preliminary scheme simulation

The results found that the water quality and quantity in every river node is different by analyzing the current situation of discharge capacity. Xinan River, Dongsujiawen, Bainiwen and Maobei River were initially designed as steady inflow gates. Besides, the draining water mainly goes through the pumping stations in the north of Xinhua River and south of Yindong River and the free outflow creek such as Jinmen River. The specific amount of water diversion is shown in Table 1.

The drainage system of Changshu along the Yangtze River is remarkably sensitive to the tidewater, which is why the water division scheme should consider the stage-discharge changes of the peripheral rivers. Therefore, in the scheme, the diversion period was kept the same as the tidal cycle, i.e. 6 hours as a single water diversion period.

By simulating the polder in the scheme above, the variation of watercourse in the polder area during the process of water-diversion is obtained, see Figure 3. The effect of water circulation depends on the water exchange rate, whose main influential factors are diversion flow (Q), river section (A) and river length (L) (Mu & Zhang, 2007). The formula is as follows:

$$P = \frac{Q/A}{L} \times 100\% \tag{2}$$

The specific result of water changes is shown in Table 2.

After a preliminary simulation, it is obvious to determine that most water in the watercourses has been exchanged in the entire polder zone, whose water exchange rate is 20%. However, the water exchange rate in several rivers is still unsatisfactory. According to Figure 3, the river flow at the ends of Yinhuan River and Yangshuweng is slow, at only 0.2 m^3/s, and about 90% water diversion from Xinan River is discharged directly through Xinhua River, and barely no fresh water enters the Yangshuweng. What is more, there is a large difference between Dongsujiaweng River and Bainiweng, whose water exchange rates are 32 and 12%, respectively.

Table 1. Flow of water-diversion in each polder area.

River name	Diversion flow at inject station (m^3/s)	Diversion cycle (h)	Total water (m^3)
Xinan River	$q_{1in} = 2$	6	43,200
Dongsujiaweng	$q_{2in} = 3.2$	6	69,120
Bainiweng	$q_{3in} = 3$	6	64,800
Maobei River	$q_{4in} = 1$	6	21,600
Tatal	9.2	–	198,720

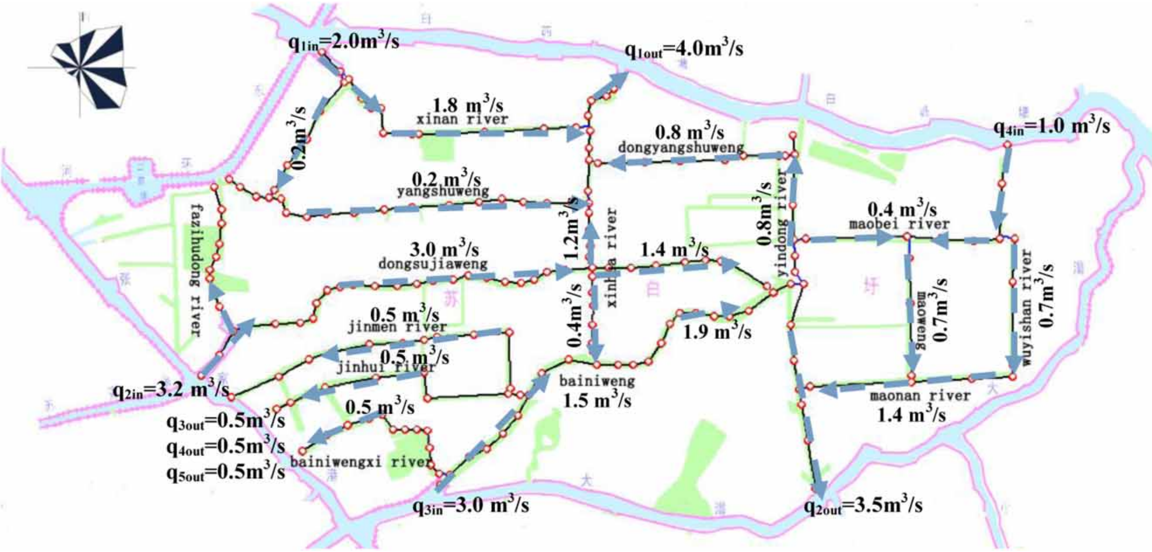

Fig. 3. Flow distribution of main node in preliminary scheme.

Table 2. The water exchange rates of major river-net in Subaiwei.

River name	Analog flow (m^3/s)	Water exchange rate (%)
Yinhuan River	0.2	19
Xinan River	1.8	96
Yangshuweng	0.2	0
Maobei River-Maoweng	0.3	22
Dongsujiaweng	3	32
Bainiweng River	1.5	12
Wuyishan River–Maonan River–Yindong River	0.7	24
Jinmen River	0.5	17
Jinhui River	0.5	19
Bainiwengxi River	0.5	26

Scheme optimization

According to the results of the aforementioned simulation, this research adjusts the scheme of water-diversion. Several statistical indices (the lowest and highest water exchange rate, average water exchange rate and coefficient of variation for whole simulation branches) were used to optimize the parallel schemes by the criterion mentioned in Equation (2). The water-diversion flow of Dongsujiaweng decreases to 2.7 m^3/s, and increases the water-diversion flow of Bainiweng to 3.5 m^3/s. In order to solve the low water exchange of Yangshuweng, the water diversion port of Xinan River was replaced with Yangshuweng, whose diversion flow was 2 m^3/s, as shown in Table 3. The simulation result is shown in Figure 4.

After adjusting the estuaries and flow of water diversion, the water allocation of Dongsujiaweng and Bainiweng tends to be reasonable. However, the effect of water exchange at Yangshuweng's estuary is

Table 3. Water diversion flow in major river-net.

River name	Diversion flow at inject station (m^3/s)	Diversion cycle (h)	Total water m^3)
Yangshuweng	$q_{1in} = 2$	6	43,200
Dongsujiaweng	$q_{2in} = 2.7$	6	58,320
Bainniweng	$q_{3in} = 3.5$	6	75,600
Maobei River	$q_{4in} = 1$	6	21,600

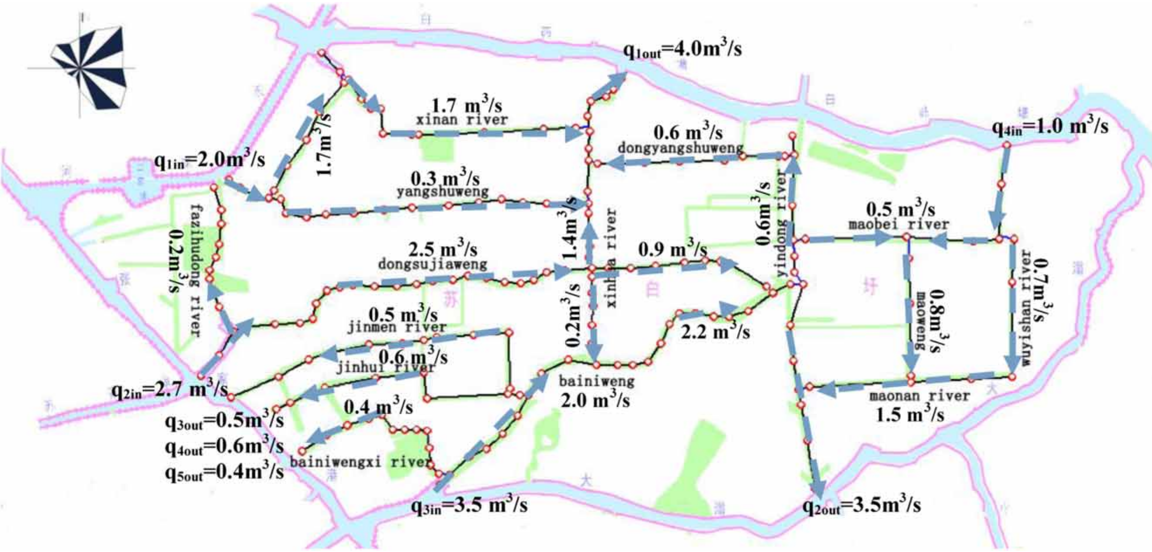

Fig. 4. Flow distribution of main node in optimized scheme.

limited. The average flow rate has only increased from 0.2 to 0.3 m^3/s, and most of the water is still discharged from Xinan River. From the adjustments of the scheme above, changing the water entrance in the polder area is not enough to solve the problem of the insufficient water allocation of Yangshuweng. Therefore, the scheme is changed to solve the current situation of uneven distribution of water allocation by controlling the switch of gates in the polder area. From the simulation above, it may be clear that the effect of water exchange is more ideal in the east of the polder area. Except for the water entrances and outfalls of Xinan River (Kuncheng Floodgate), Yangshuweng (Yantian Floodgate), Xinhua River (Xinhua Floodgate), and Yindong River (Baigu Floodgate), other entrances are unchanged. In this way, the optimal scheme is finally determined. After calculating the different results, the statistical analysis is shown in Table 4.

After different adjustment calculations of water diversion and drainage gates, the measures of only adjusting the scheduling rules of water diversion and drainage have no obvious effect on the average water exchange rate in the whole polder area. However, it is appropriate for scheduling rules which has significantly improved the water exchange rate in several areas. From Table 4, in terms of the water diversion entrance, it can be determined that water diversion from Yantian Gate could solve the problem of poor water exchange of Yangshuweng, changing its rate from zero to 9–30%, and it has obviously controlled the distribution amount of water diversion of Yinhuan River and Xinan

Table 4. Different result analysis of water diversion schemes.

Program	Kuncheng Floodgate	Yantian Floodgate	Xinhua Floodgate	Baigu Floodgate	Lowest water exchange rate	Highest water exchange rate	The average water exchange rate (%)	Coefficient of variation
1	Open (2 m^3/s)	Off	Off	Open (4 m^3/s)	Yangshuweng (0%)	Yinhuan-Xinan River (59%)	23.30	0.62
2	Open (2 m^3/s)	Off	Open (4 m^3/s)	Off	Yangshuweng (0%)	Yinhuan-Xinan River (67%)	23.69	0.70
3	Off	Open (2 m^3/s)	Open (4 m^3/s)	Off	Yangshuweng (9%)	Yinhuan-Xinan River (47%)	22.98	0.43
4	Off	Open (2 m^3/s)	Off	Open (4 m^3/s)	Bainiweng (17%)	Yangshuweng (31%)	23.34	0.19

River reach. While as for the water drainage of Xinhua Station, Baigu River Station is a better choice. The location of Baigu River Gate Station is east of Xinhua Station, which increases the length of the water diversion path from the west in the polder area. Hence, the water can be finally split at Yantian Station, which completely solves the problem of poor water exchange of Yangshuweng. For the four schemes mentioned, the coefficient of dispersion of the fourth scheme, which is only 0.19, is significantly better than the other three schemes. It indicates that the scheme can basically ensure the water exchange rate of a single watercourse of the polder in an optimal range, thus it would solve the problem of poor water exchange of a single watercourse.

To compensate for the lack of that scheme, after adjusting and simulating repeatedly, we finally determined a scheme of water diversion and drainage in the polder area. The specific water flow results from the simulation are shown in Figure 5, and the water exchange rates of the watercourses are shown in Table 5.

Through repeated simulation and verification, the best water diversion duration of Subaiwei is 6 hours. The scheduling rules are shown in Table 6. The scheme basically makes the water exchange rates of the main channel up to a normal level of 20% in the polder area, and keeps the water flow up to more than 0.4 m^3/s during the process of water exchanging, which guarantees a good effect of water exchange in the polder area.

The impact analysis of the period of water diversion-allocation on the effects of water diversion-allocation

The periodical length of a single water diversion cycle is critical after determining the optimal scheme of water diversion-allocation, especially for the effects of water diversion. On the basis of the water scheduling rules in Table 6, the water diversion with different durations (1, 3, 6, 9, 12, 15, 18, 21

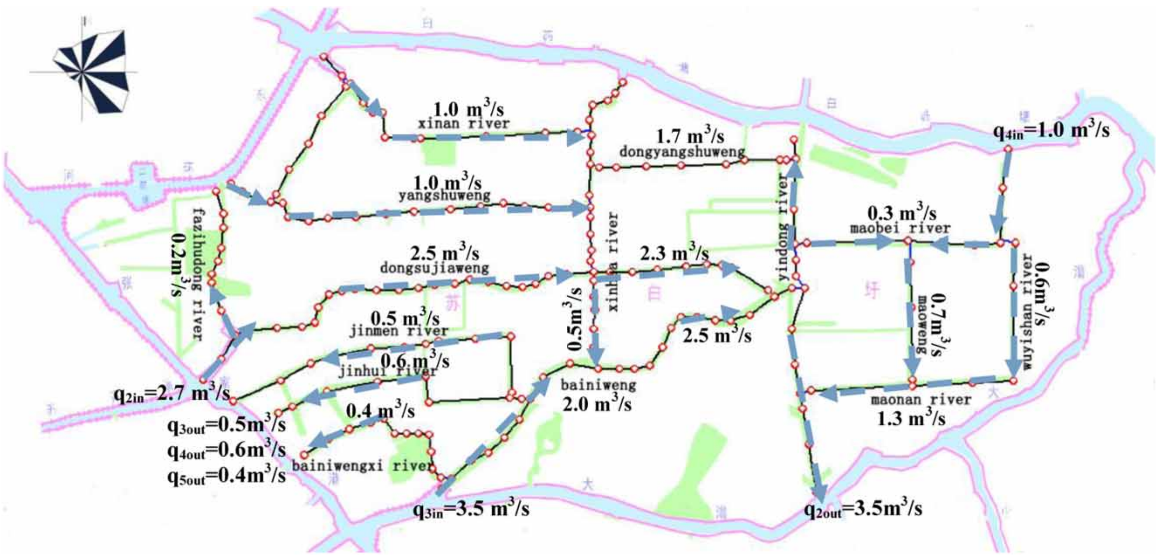

Fig. 5. Flow distribution of main node in the final scheme.

Table 5. The statistical analysis of water exchange rates in main watercourses.

River name	Analog flow (m^3/s)	Water exchange rate (%)
Yinhuan River–Xinan River	1	27
Yangshuweng	1	31
Maobei River-Maoweng	0.4	25
Dongsujiaweng	2.5	24
Bainiweng River	2	17
Wuyishan River–Maonan River–Yindong River	0.6	21
Jinmen River	0.5	17
Jinhui River	0.6	22
Bainiwengxi River	0.4	21

Table 6. The statistical analysis of scheduling rules for Subaiwei's river-net.

	River name	Diversion flow (m^3/s)	Diversion cycle (h)
Diversion	Yangshuweng	$q_{1in} = 2$	6
	Dongsujiaweng	$q_{2in} = 2.7$	6
	Bainniweng	$q_{3in} = 3.5$	6
	Maobei River	$q_{4in} = 1$	6
Drain	North of Yindong River	$q_{1out} = 4$	6
	South of Yindong River	$q_{2out} = 3.5$	6
	Jinmen River	$q_{3out} = 0.5$	6
	Jinhui River	$q_{4out} = 0.6$	6
	Bainiwengxi River	$q_{5out} = 0.4$	6
	Fazihudong River	0.2	6

and 24 h) was simulated and the relationship between the diversion cycle and the average water exchange rate was determined. The results are shown in Figure 6.

Figure 6 determines that the average water exchange rate and the time diversion remains a linear positive correlation. However, the efficiency of river water exchange shows a significant decline with the extension of the water changing period. The reason may be that the river flow hedge phenomenon occurs due to a continuous diversion of different entrances in polder, and the effect of polder water changes will be affected when the rivers have completely changed the water in advance and drains the fresh water directly. Thus, in terms of engineering economics, moving too far is not effective for the water diversion cycle. It is better to control the single water diversion cycle within 6–9 h to ensure the optimal effect of polder water changes.

Conclusion

For executing the water policy of Interconnected River System Network (IRSN) proposed by the Ministry of Water Resources (MWR) in China, this study applies a one-dimensional flow model of hydrographic net to the optimized scheme of water diversion-drainage in a confined river-net system. This research simulates the effects of various factors in the river system of the polder area under the same conditions as standard flood

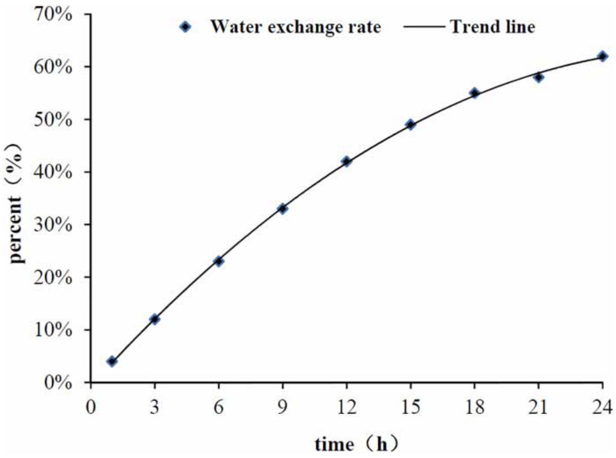

Fig. 6. The relationship curve between average water exchange rates and water diversion durations under optimized pumping scheme.

control and water-logging control. These different factors include the layouts of the sections of water diversion and drainage, the duration time of water diversion and drainage, and the potential influence of water diversion and drainage system. Through multiple analysis and comparison, this study confirms the stream direction of fresh water diversion, measures the dynamic connectivity of hydrographic net, and designs the optimal planning scheme of water diversion and drainage across the polder region. The results have been verified by our simulations. Therefore, it could provide an ideal reference for actual project construction and water allocation. The above-mentioned scheme is on the basis of the existing hydraulic scheduling that focuses on flood control and water-logging control, hence the flow of water diversion and drainage is the same, and it does not increase the pressure of flood control. This work will be valuable for testing an Interconnected River System Network (IRSN), which can offer more practical experience for further execution of the river system's protection and restoration.

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