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Article

An Ecological Flood Control System in Phoenix Island of Huzhou, China: A Case Study

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Abstract: Traditional flood control systems always have a conflict with natural ones, *i.e.*, rivers in cities are usually straight and smooth, whereas natural ones are according to ecological mechanisms. Social and economic developments in the modern world require a new system combining ecological needs and traditional flood control system. Ecological flood control systems were put forward and defined as flood control systems with full consideration of ecological demands for sustainable development. In such systems, four aspects are promoted: connectivity of water system, landscapes of river and lakes, mobility of water bodies, and safety of flood control. In Phoenix Island, Huzhou, needs for ecological flood controls were analyzed from the four aspects above. The Water system layout was adjusted with the water surface ratio, which is the ratio of water surface area (including rivers, lakes, and other water bodies) to the total drainage area, and connectivity as controlling indicators. The designed water levels provided references for landscape plant selection. Mobility of the adjusted water system was analyzed, including flow direction and residence time. On the bases mentioned above, ecological flood control projects were planned with comprehensive consideration of the ecological requirements. The case study indicates that ecological needs can be integrated with flood control to develop ecological flood control systems that do not only prevent floods but also retain the ecological functions of water bodies.

Keywords: flood control system; water system; ecological function; mobility of water body; Phoenix Island; Huzhou

1. Introduction

The environment is the basis of socio-economic development. Protection of the former should be coordinated with the development of the latter to achieve harmony between humans and nature [1]. Socio-economic development has advanced, but at the expense of the anterior environment. Environmental degradation is serious [2], and protection of the environment has drawn increasing attention from local and foreign researchers [3–5]. In China, a corresponding strategy has been proposed: to develop a favorable natural ecosystem, to achieve coordinated development of humans and their environment, and to establish a perfect economic-social-natural ecosystem.

Researchers have mostly focused on the ecological restoration and assessment of rivers, lakes, and wetlands [6–9], analysis of ecological corridors [10,11], and investigation of the relationship between ecological footprint and urban development [12,13]. Prior studies have had significant effects on the protection and rehabilitation of the ecological environment.

China is a flood disaster-prone country. Flooding seriously restricts economic development, lessens the operational efficiency of the economic system, and threatens the ecological balance [14]. The water system is the carrier of floods and the center of flood control system construction. But the related results from ecological studies of the water system are not applied in the traditional flood control system, which overemphasizes on engineering measures that destroy the original ecological balance [15]. At present, the ecological aspects are chiefly considered in urban development. Selected non-engineering measures and low-impact development ones, with consideration of ecosystem protection, have been given more attention during the process of flood control system construction in recent years [16–21]. Wetlands, one of the most important ecological measures, can be engineered to provide three independent functions: flood control for existing and proposed developments, treatments for urban storm water runoff, and habitat for freshwater fish and wildlife [22–26]. However, few studies have shown the construction of an ecological flood control system.

The current paper proposes an ecological flood control system that combines the needs of the ecosystem and flood control measures. Ecological demands include connectivity of water system, landscapes of water bodies, mobility and safety. Measures are given based on the four aspects, with full consideration of ecological needs and flood control requirements. Phoenix Island, a pioneer in ecological civilization construction, is the research site to study the ecological flood control system.

2. Methods

An ecological flood control system should meet both the ecological functions, including connectivity of water system, landscapes and mobility of water bodies, and flood control requirements. Consequently, the designed system comprised traditional engineering and non-engineering measures for flood control and ecological functions. Specific tasks and methods were as follows:

(1) Connectivity of water system. A systematic approach was used to analyze the problems of the current water system, and then a new water system layout was planned in accordance with the requirements of the ecological health of the water system and landscape aesthetics.

(2) Landscapes of water bodies. Apart from the morphological characteristics of the water system, the landscapes depend on the selection of vegetation and living beings. Different vegetation and living beings, such as emergent plants, floating leaf plants, submerged plants and wetland plants, need different water levels. Therefore, the key point is to determine the different water levels per standard, which were obtained by statistical analysis.

(3) Mobility of water bodies. Mobility analysis included two aspects. One was the confirmation of flow directions, to locate the landscapes and maximize the wetlands and other vegetation. The other was the determination of residence time, which is the average time of water staying in the area, to verify rationalities of the water system layout and the water bodies' landscapes as well as to ensure water quality. Mobility was analyzed by the hydrological and hydraulic model to calculate the local water resources and discharge of each river to determine flow directions and residence time.

(4) Safety of flood control. When the three ecological functions above were achieved, verification of flood control was necessary. Unsteady flow calculation was used to obtain the water levels for different standards for flood control, on the basis of which targeted projects were proposed in accordance to the ecological requirements.

3. Analysis of Demands of Ecological Flood Control

3.1. Overview of Phoenix Island

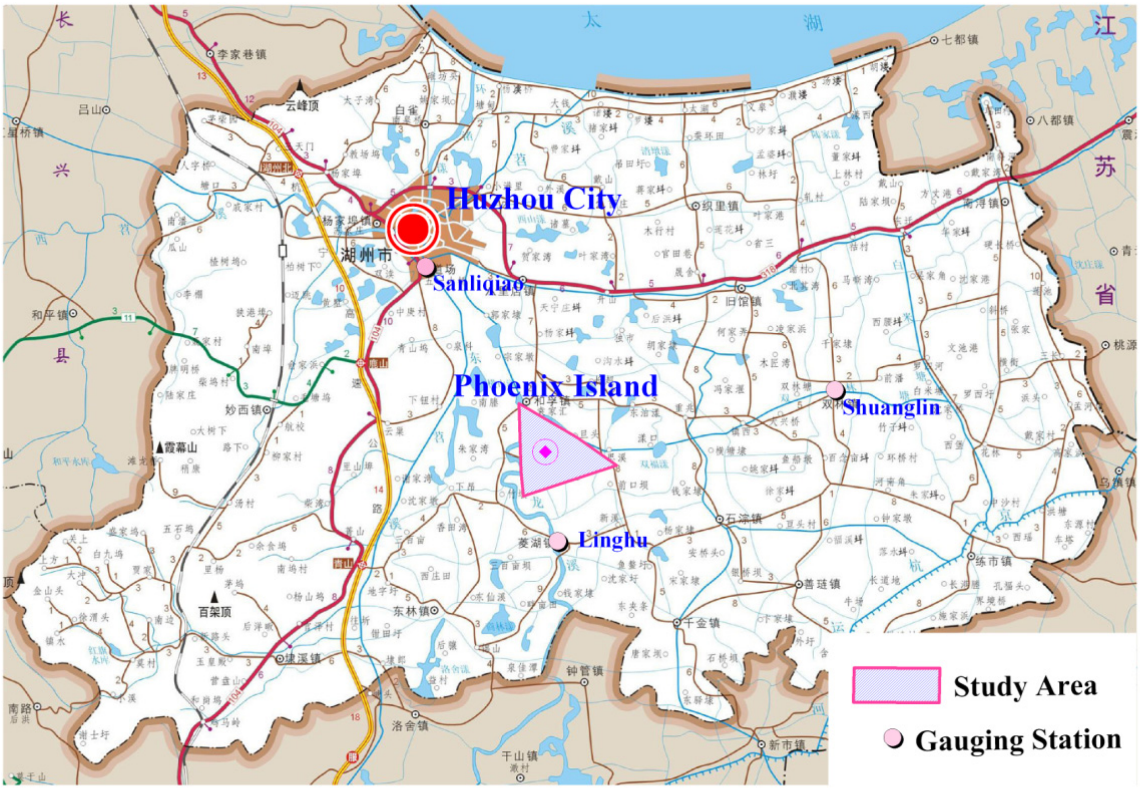
Phoenix Island in Huzhou City is located in the Taihu Basin with a dense river network. A large number of scenery spots are distributed in Phoenix Island. Flow velocity in these regions is slow, and the directions are flexible. Two main rivers, Dantou and Laolongxi-Linghutang Rivers, flow into Hefu Lake. These rivers are the chief drainage rivers in the region (Figure 1).

Given the numerous rivers and lakes in Phoenix Island, water should be chosen as the main element for ecological civilization construction with consideration for local characteristics. Meanwhile, the water brings frequent floods, hence the need for ecological flood control system.

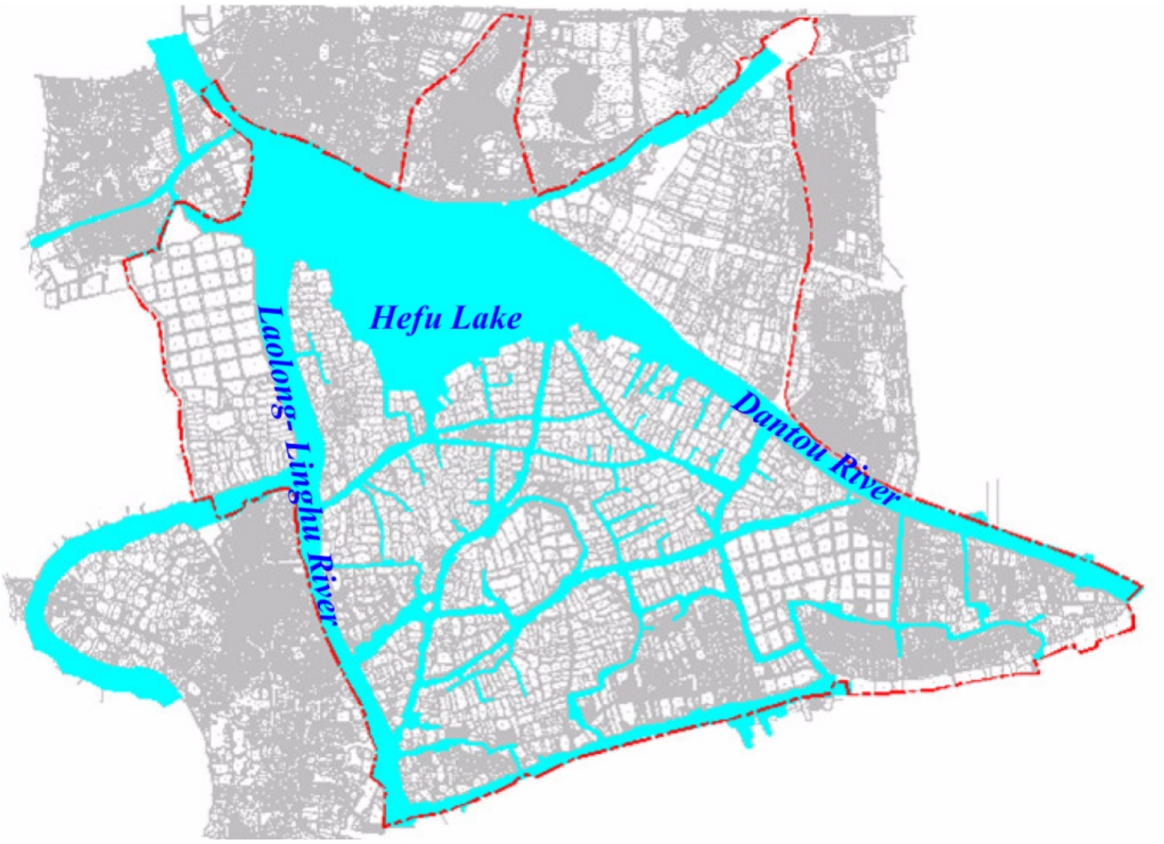
3.2. Demand for Connectivity of Water System

Water system is the transmission medium of energy and matter. In Phoenix Island, the water system is a complex spatial network composed of rivers, lakes, beaches, wetlands, and riverside areas. The total length of the rivers is 25 km, and the water surface area is 1.6 km^2. Apart from the main rivers, poor connectivity of the secondary rivers causes inferior mobility, deterioration of water quality and even eutrophication. A certain scale of each river channel is required to ensure the water system's connectivity, mobility, and ecological functions, especially that of river intake. Small-scale river channels result in too little and slow water inflow, making it difficult to protect water quality.

Figure 1. Location of Phoenix Island (**a**) and the current water system layout (**b**).



(**a**) Location



(**b**) Layout

3.3. Demand for Landscapes of Water Bodies

In the process of ecological civilization construction, the landscapes of rivers and lakes are important requirements. Phoenix Island is beside the two important routes of the Yangtze River Delta, namely, Hujiashen Route (Dantou River) and Hanghuxi Route (Laolong-Linghu River). At present, the inner rivers directly connect the outer routes without any control projects. Busy shipping brings more turbid water, poor landscape visions and inferior water quality.

3.4. Demand for Mobility of Water Bodies

Phoenix Island is a plain river network region with little mobility. Mobility is further hampered by overgrown reeds and water weeds, which result in poor water quality and even eutrophication.

3.5. Demand for Safety of Flood Control

Flood disasters may destroy the ecosystem developed arduously by human beings if a corresponding flood control system is not developed. Therefore, flood control demands must be analyzed to create an ecological flood control system.

In Phoenix Island, Dantou and Laoling-Linghu are the main rivers for flood control. Meanwhile, the soil embankments are poor in quality with substandard sections. Crops are planted near embankments, and passing ships bring large waves that severely damage revetments. Additionally, the average surface elevation of the area is 3.5 m to 4.0 m, lower than the water level for a two-year recurrence period. All of these factors imply a high risk for flood disasters.

4. Construction of Ecological Flood Control System

4.1. Adjustment of Water System Layout

The process is aimed to take full advantage of the existing rivers, ponds, and lakes, to maintain the integrity and mobility of the water system, and to enlarge the water surface ratio (WSR). In Phoenix Island, three parts were divided for the water system layout, which resembled the shape of a phoenix, according to the existing water system (Figure 2):

(1) Water system in the Central Lake Area. In this area, densely covered mulberry dyke fish ponds and rivers enlarge the water surface areas, but these serve few important roles in flood control because of the separate pond without flood-regulating functions. In the ecological flood control system, lakes provided ecological values, such as flood regulation, climate adjustment, water quality purification, and biodiversity maintenance. Therefore, a palm-shaped lake was formed easily by assembled ponds. Then an unobstructed water system was obtained by dredging and linking rivers and possibly keeping the natural and ecological attributes of the rivers, wetlands, and lakes. Hygrophytes, emergent plants, floating leaf plants and submerged plants along the various kinds of water bodies, provided the living environment for flora, fauna, and microorganisms in the region to maintain the multi-layer landscape and ecological balance.

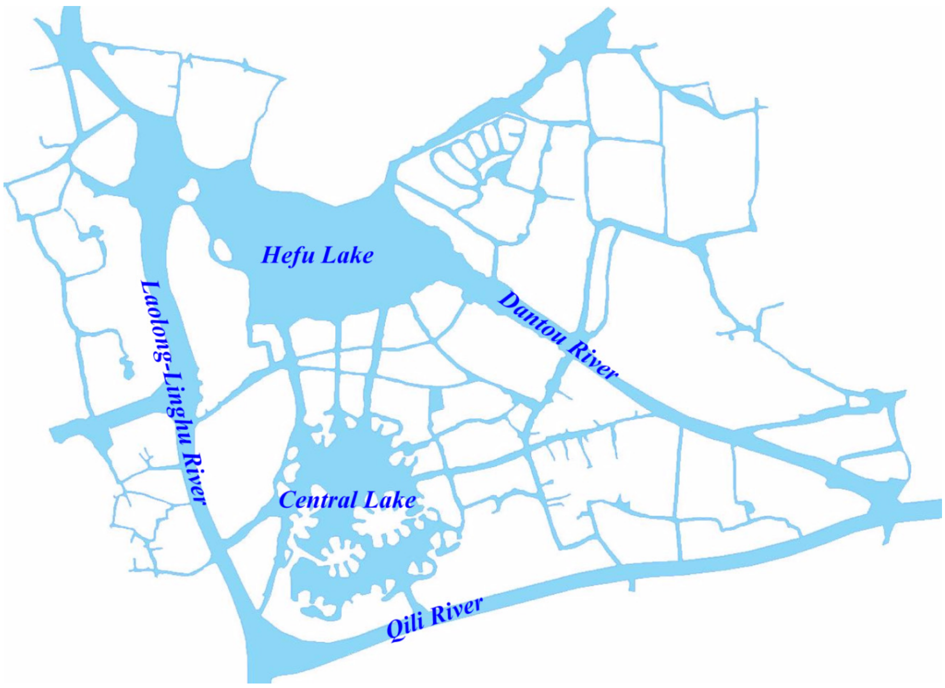
After adjustment, the water system in Central Lake Area had several functions such as flood control, water self-purification, ecological corridors, culture bearer, tourist attraction, and environmental values.

(2) Water system in the Ecological Agriculture Area. The mulberry dyke fish pond complex is the base agricultural form in Phoenix Island, containing two interrelated systems of dyke (land ecosystem) and pond (water ecosystem) [27]. A virtual cycle is formed by the mulberry, silkworm, fish and mud. In other words, the mulberry dyke fish pond complex structures a three-dimensional utilization network of waste products, enhances agricultural output efficiency, and reduces pollution and flood risk, which can be called the model of the ecological agriculture.

On the base of the traditional mulberry dyke fish pond complex, a boutique ecological agriculture demonstration area was built based on management specification and technological improvement. In the area, straight rivers were preferred, and dredging was required to meet the irrigation demand for ecological agriculture and flood control. Meanwhile, the density of rivers was not high to keep a larger area for large-scale agriculture and thereby increase agricultural production.

(3) Water system in the Residential Island. In the rapidly urbanized area, WSR descends and storage capacity of water decreases rapidly associated with lakes, branches, wetlands. Floodplains are buried. In addition, land surface impermeability enhances runoff coefficients and runoff velocity. Urban flood, with higher peak discharge, larger volume, and shorter concentration time, brings higher risk than rural area flood. In an ecological flood control system, urbanization should have the lowest impact on hydrological response compared with pre-development. Low-impact development (LID) is recognized as an effective way to minimize negative influences in urbanized areas.

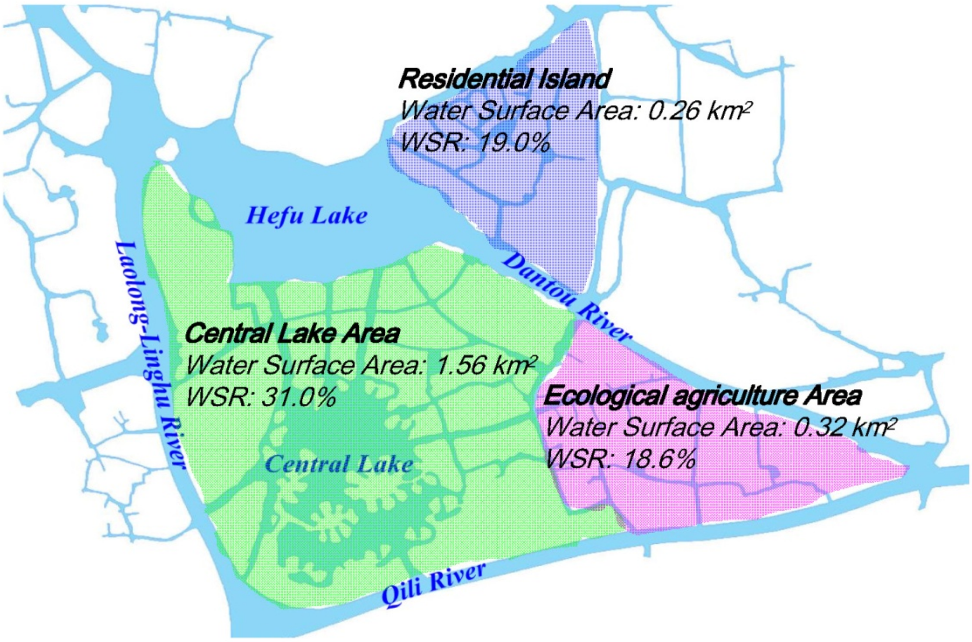
Figure 2. Adjusted water system layout.



According to the LIDs, bioretention ponds, ecological ditches, green squares sinks, and wetlands were used for the storage, retention, and infiltration of rainwater in the area. Diversity and waterside were the bases for adjusting the water system layout. To enhance water system mobility, certain density and smooth values were preserved, and then bridges and pump stations were constructed on the rivers. Meanwhile, routine maintenance of water landscapes was emphasized to prevent the water body from releasing bad odor.

After the adjustment, the ecological water system layout was completed with the newly excavated Central Lake as the core. The adjustment enhanced the hydraulic connection of the river network in Phoenix Island, especially in the Residential Island. The WSR increased (Figure 3), which helped control flood. The scales of the rivers connecting the Central Lake and the two main outer rivers were enlarged to smooth the river, increase flow into the lake, and improve water quality. The disconnected rivers were repaired to keep the rivers straight, and then reeds and weeds were removed to reduce the roughness, which helped improve water flow and shortened the residence time of the water system.

Figure 3. Water surface ratio (WSR) in the three parts.



4.2. Determination of the Controlled Water Levels for Landscapes

Guarantee rate is defined as the annual excess in probability of flows; a flow stage with a guarantee rate of 25% represents a flow that is exceeded 25% of the time. Water level values of different guarantee rates are helpful to meet the need of shipping, to confirm the height of bridges, and ascertain the ground elevations and areas of islands. For wetlands, the duration of inundation can be derived to choose appropriate plant varieties.

No hydrometric station is located in Phoenix Island. Three gauging stations collect water level data in the area, Sanliqiao, Shuanglin and Linghu (Figure 1). The daily average water level of Phoenix Island was obtained using geographic interpolation.

According to frequency analysis, the water levels of different guarantee rates were computed. Table 1 provides a reference for shipping and for landscape plant selection such as wetlands.

Table 1. Water level in different guarantee rates.

Guarantee Rate	Water level (m)
25%	3.31
50%	3.05
75%	2.83
95%	2.59

4.3. Analysis of Water System Mobility

4.3.1. Flow Directions

An ecological water system should be mobile for certain ecological functions. Flow directions were analyzed to locate wetlands or water treatment devices around the gates of water diversion. Data were used to purify the inflows, install sluice gates at river junctions that control the inflow and ensure water quality, and establish lifting pump stations for water bodies with poor mobility to speed up the water flow.

To obtain the main flow directions of the water system in Phoenix Island, the water level differences for every 10 days from 1971 to 2010 between the three gauging stations were calculated by statistical analysis.

In determining the main flow directions, the following definitions were referred.

When $Z_{sq} \geq Z_{lh}$,

$$\begin{cases} \dfrac{Z_{sq} - Z_{lh}}{Z_{sq} - Z_{sl}} \geq 2 & \text{Flow to South} \\ 0.5 \leq \dfrac{Z_{sq} - Z_{lh}}{Z_{sq} - Z_{sl}} < 2 & \text{Flow to Southeast} \\ 0 \leq \dfrac{Z_{sq} - Z_{lh}}{Z_{sq} - Z_{sl}} < 0.5 & \text{Flow to East} \end{cases} \quad (1)$$

When $Z_{sq} < Z_{lh}$,

$$\begin{cases} 0 \leq \dfrac{Z_{lh} - Z_{sq}}{Z_{lh} - Z_{sl}} < 0.5 & \text{Flow to East} \\ 0.5 \leq \dfrac{Z_{lh} - Z_{sq}}{Z_{lh} - Z_{sl}} < 2 & \text{Flow to Northeast} \\ \dfrac{Z_{lh} - Z_{sq}}{Z_{lh} - Z_{sl}} \geq 2 & \text{Flow to North} \end{cases} \quad (2)$$

where Z_{sq} is the water level of Sanliqiao, Z_{lh} is that of Linghu, and Z_{sl} is that Shuanglin.

According to the definitions above, the relationships of the flow directions among the three gauging stations were calculated in every 10 days per year (Figure 4). The main flow directions were from the west to east, north–south directions were unsteady, with more directions from north to south. Most water levels of Sanliqiao in the north were slightly higher than those of Linghu in the south, and those of Shuanglin in the east were the lowest.

To determine further flow directions of the adjusted inner river network, the hydrodynamic model of Phoenix Island was established. Results showed that the flow directions were almost from west to east, and those of a few rivers were unsteady, which might have important influences on the selection of ecological measures (Figure 5).

Figure 4. Main flow directions in a year.

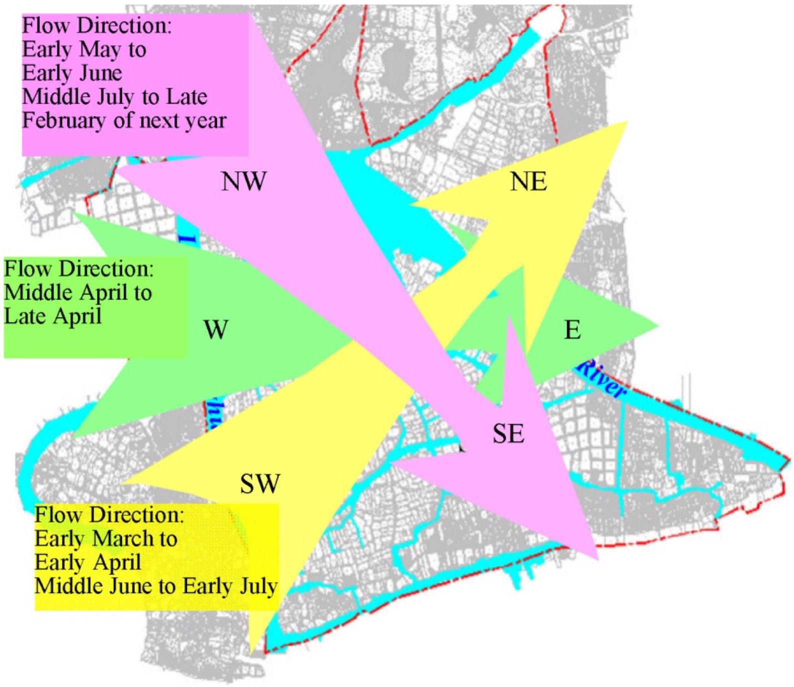
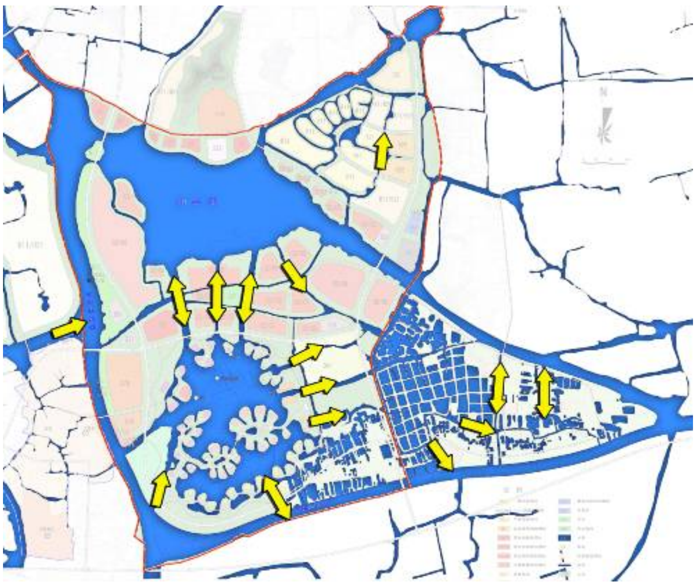


Figure 5. Flow directions of the inner river network in a year.



4.3.2. Determination of Residence Time

Residence time of a water system is a very important ecological requirement, and is calculated as follows: residence time = water volume/flow rate. Linghu station was chosen as representative, with a series of high quality and complete rainfall data from 1971 to 2007. Typical years in different frequencies were selected after statistical analysis. By the hydrological model and the hydrodynamic model to get the amount of water volume through the area in different frequencies, residence time of the water system was obtained according to flow rate and storage capacity (Table 2).

Table 2. Residence times for the typical years ensured by the frequency of rainfall.

Typical Year	25%(1998)	50%(1997)	75%(2007)	95%(2003)
Rainfall (mm)	1384.9	1226.9	1109.4	947.6
Water Volume through the Area (million m^3)	552.33	453.94	595.21	628.55
Local Runoff Volume (million m^3)	4.85	4.36	4.11	2.36
Local Storage Volume (million m^3)	16.00	16.00	16.00	16.00
Residence Time (day)	10.5	12.8	9.7	9.3

Table 2 shows that the residence time of 95% was shorter than that of 25%, which implied that the typical year ensured by frequency of rainfall could not reflect the truth of residence time. Water volume through Phoenix Island had a significant impact on the residence time because the area was a bit small with less local runoff. In consideration of the water level mainly caused by the passed water recourses, the typical year should be confirmed by the frequency analysis of the average water level.

According to the frequency of the water level, the typical year of different frequencies (25%, 50%, 75% and 95%) were confirmed, the rainfall frequency of which were calculated as well. Then, the residence times were determined by the method mentioned above (Table 3). Results indicated that the frequency of water level and that of rainfall in typical year were close, and the residence times corresponded with the frequency of water level and rainfall.

Table 3. Residence times for the typical years ensured by water level frequency.

Frequency of Water Level	25%	50%	75%	95%
Corresponding water level (m)	3.22	3.09	2.97	2.80
Typical Year	1975	1990	2004	1972
Water level of Typical Year (m)	3.23	3.11	2.96	2.82
Rainfall of Typical Year (mm)	1393.5	1240.3	1091.5	1052.9
Frequency of Rainfall in Typical Year	26%	50%	76%	83%
Water Volume through the Area (million m^3)	831.75	560.75	537.82	536.06
Local Runoff Volume(million m^3)	4.30	2.97	2.65	2.23
Local Storage Volume (million m^3)	16.00	16.00	16.00	16.00
Residence time (day)	7.0	10.4	10.8	10.9

4.4. Verification of Flood Control

Constructions should meet the need of flood control. According to the requirements of ecological civilization construction, several land types distributed in Phoenix Island, including residential, agricultural, ecological landscape, and wetlands area, followed different flood control standards.

Flood control standards were as follows: recurrence was 100 years for residential areas, 20 to 50 years for agricultural areas, 10 to 20 years for ecological landscape areas, and 5 years for wetlands.

In the study, the hydrological model was established according to Xin'anjiang Model to calculate runoff generation and overland flow concentration. Based on Saint-Venant equations, the hydrodynamic model was developed to compute the water level in different recurrence periods.

$$\begin{cases} B\dfrac{\partial Z}{\partial t} + \dfrac{\partial Q}{\partial x} = q_s & \text{Continuity Equation} \quad (3) \\[2ex] \dfrac{\partial Q}{\partial t} + \dfrac{\partial}{\partial x}\left(\alpha \dfrac{Q^2}{A}\right) + gA\dfrac{\partial Z}{\partial x} + gAS_f = 0 & \text{Momentum Equation} \quad (4) \end{cases}$$

where, x is the longitudinal distance along the river, t is the time interval, A is the cross section area of the flow, Z is the water level, B is the width of the river, Q is the discharge of the cross section, g is the acceleration of gravity, S_f is the slope of energy grade line, and q_s is the inflow of river sides.

Preissmann four-point implicit scheme was used to disperse the Saint-Venant equations. The inner river network was simplified by preparing the unsteady flow calculation. In the simplification, main inner rivers with high capacity of transportation were fully considered, whereas subordinate ones were neglected; the storage capacity was considered in WSR [28].

The river network of Phoenix Island was simplified as 82 inner rivers, seven outer rivers, 410 inner rivers' sections, 14 outer rivers' sections and 50 nodes (Figure 6). According to the vegetation located on the rivers, different hydraulic roughness values were given for each river. Then, the water level of each node was obtained by the established hydrodynamic model. The water levels of the four main nodes were shown in Table 4 to find the applicable measures for flood control.

Figure 6. Simplification of inner river network in Phoenix Island.

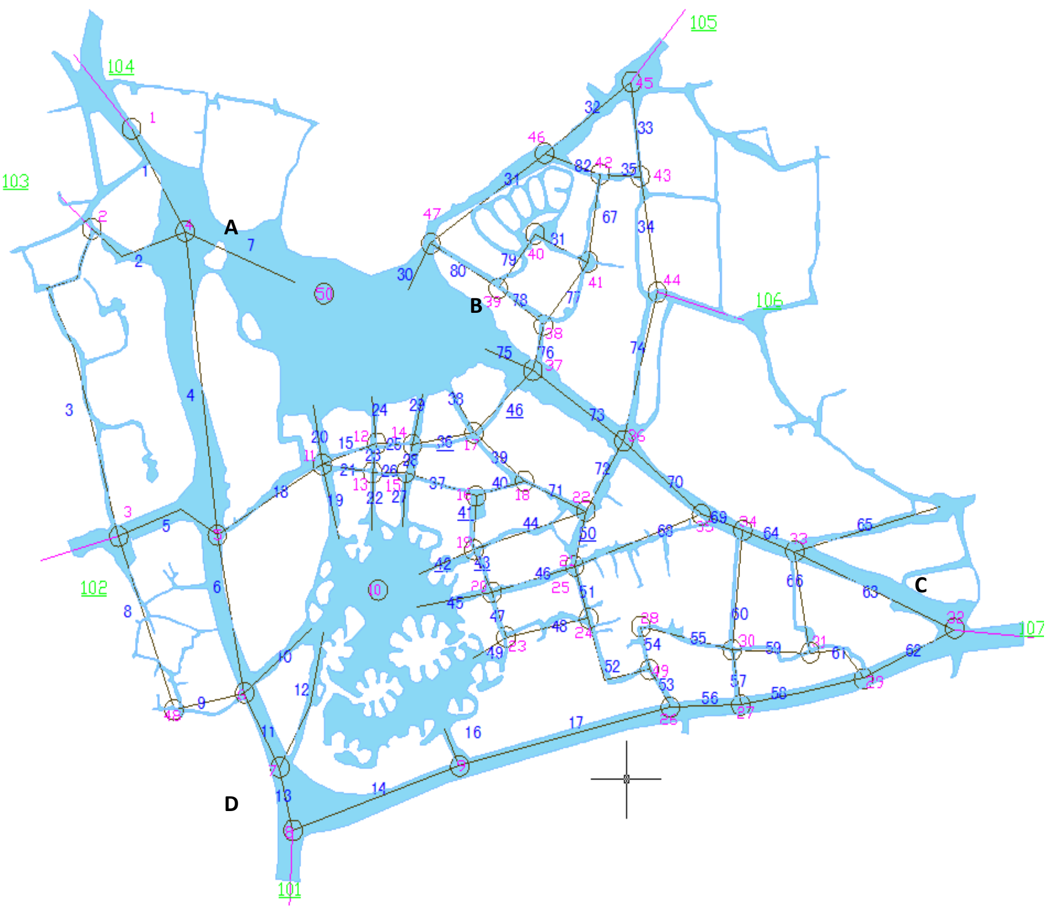
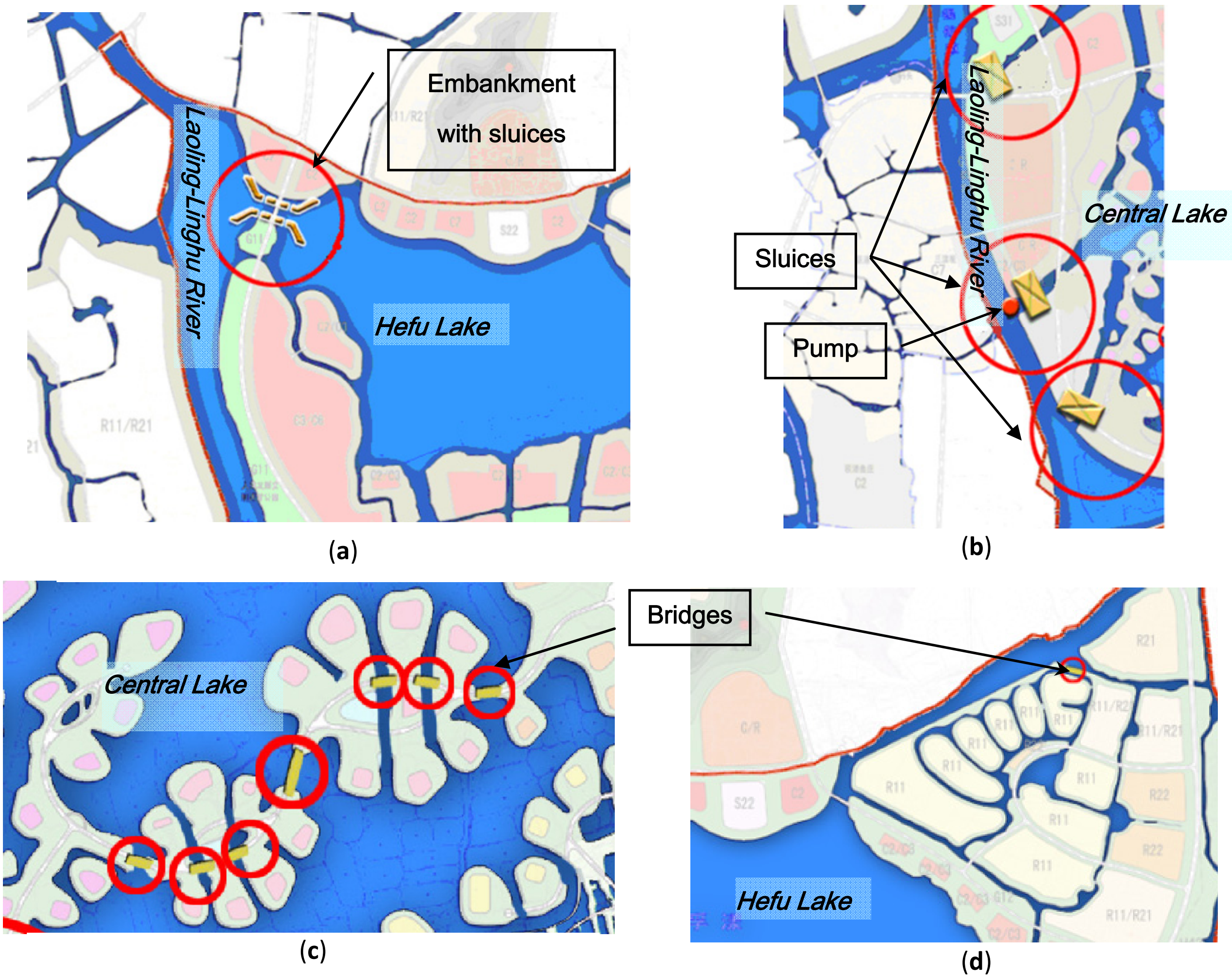


Table 4. Water levels of four main nodes in Figure 7 in meters.

Recurrence Period (year)	A	B	C	D
100	5.33	5.32	5.32	5.35
50	5.16	5.14	5.14	5.17
20	4.90	4.89	4.89	4.91
10	4.68	4.67	4.67	4.70
5	4.43	4.42	4.42	4.44

Figure 7. Projects for ecological functions: (**a**) Embankment with sluices at the junction of Laoling-Linghu River and Hefu Lake; (**b**) Sluices and pump at the junctions of the Laoling-Linghu River and the Central Lake; (**c**) and (**d**) Bridges in the Central Lake and the Residential Island.



4.5. Other Projects in Ecological Flood Control System

In traditional flood control system, projects, such as embankments, polders, and others, are planned according to the water levels of different flood control standards, without consideration for ecological requirements. However, in an ecological flood control system, ecological projects are not separated from flood control ones. In other words, the projects planned should meet ecological requirements, such as connectivity, mobility, and ecological landscape of the water system, and also control flood.

Based on the above analysis on ecological functions and flood control requirements, the projects in Phoenix Island included:

(1) An embankment with sluices at the junction of Laoling-Linghu River and Hefu Lake (Figure 7a). The embankment was built for ecological functions rather than for flood control, which separated the river and the lake relatively to ensure the water quality of Hefu Lake. Sluices connected the outer river and the lake to assure certain inflow to the lake. Meanwhile, the top of the embankment was built as a landscape road.

(2) Sluices and pumps at the junctions of the Laoling-Linghu River and the Central Lake (Figure 7b). Three inner rivers connected the lake and the outer river. According to the flow directions mentioned above, from west to east, the three junctions were flow inlets. Sluices were used to control inflow and ensure water quality. Wetlands were located near flow inlets to purify the inflow. Regards of the limited wetlands area and inadequate purification ability, the wetlands were coordinated with sluices to control inflow and enhance purification for the Central Lake. Pumps were operated to ensure regular water diversion and exchange, increase flow velocity of the lake and improve water quality.

(3) Bridges to connect the islands (Figure 7c,d). In the central lake area and the residential island, water systems were adjusted to have very beautiful shapes. These disconnected the rivers, which had a small flow velocity and larger residence time compared with the connecting rivers. Water quality did not meet the standard. Therefore, bridges were used to connect the small islands and lessen the brooking branches, thereby enhancing the connectivity of water systems and reducing residence time.

(4) Filling the ground elevation to prevent flood of the design standard without the construction of embankments. The connectivity, landscapes and ecological functions of the water system were not influenced by sluices, pumps and other projects. Soil source was needed. For areas with high demand for ground control elevation, the bottom of buildings could be erected in the air, which could also enhance air flow and reduce humidity within buildings.

5. Conclusions

In an ecological flood control system, four steps are necessary: (1) Adjusting of the water system layout will maintain the integrity and mobility of water system, and enlarge WSR, with the full consideration of ecological landscapes; (2) Determining of the controlled water levels for different frequencies can provide references for the construction and operation of wetlands, shipping, and appropriate ecological landscapes; (3) Flow directions and residence time are the two important aspects for mobility. They decide the location of the landscapes and ensure water quality; (4) Verification of flood control is helpful to plan certain projects and choose measures according to flood control demands and ecological requirements.

In Phoenix Island, three water systems were completed with three functional areas according to the different characteristics and planning positions. In addition, the water levels of four frequencies (25%, 50%, 75% and 95%) were obtained. After the analysis on mobility, the results show that the main flow directions were from the west to east, and the residence time depended on water volume through the area because of the less local runoff. A typical year should be ensured by conducting frequency analysis of the water level under this circumstance. According to the actual conditions, many other projects were proposed to complete the ecological flood control system.

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Conflicts of Interest

The authors declare no conflict of interest.

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