Study on Flood Risk Characteristics and Disaster Prevention Countermeasures in the Taihu Basin

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Abstract. The Yangtze River Delta is the region with the strongest comprehensive strength in China. Taihu Basin is the economic core region in the Yangtze River Delta, and it plays a significant role in the economic development of the Yangtze River Delta, as well as in China. The basin is characterized by rapid urbanization, exploitation of natural resources and environmental pollution. After several decades of governance, the flood control system in the Taihu Basin has been significantly improved. Owing to exceptional weather conditions, geographical location and topographical features; the basin is extremely vulnerable to flood hazard. It presents a significant challenge for flood risk management when combined with global developments such as sea level rise. A comprehensive overview of flood management systems and considerations are of great value. In this paper, the characteristics of flood risk are summarized after the basin experienced dramatic development of urbanization over the last twenty years, and the existing problems and potential threats to the basin flood control system are analyzed. In view of a strategic perspective of disaster prevention, this paper presents various countermeasures to deal with the challenging situation in the Taihu Basin, including the structural systems and non-structural measures.

1. Introduction
Located in the delta region of the Yangtze River in East China, Taihu lake is the third largest water body in China with an area of 2 338 km\textsuperscript{2}. The Taihu Basin reaches to the Yangtze River in the north, East China Sea in the east, Hangzhou Bay in the south, and Mount Maoshan and Tianmu Mountains in the west, with an area of 36 895 km\textsuperscript{2}. There are numerous rivers and lakes in the basin, and the land slope is gentle. As such, it is famously know as plain river network area in China. Based on the characteristics of topography and water networks, the basin is divided into eight sub-areas, namely Huxi, Zhexi, Lake Taihu, Wuchengxiyu, Yangchengdianmao, Hangjiahu, Puxi, and Pudong (seen in Figure 1). Due to its flat saucer-like terrain, the ground level of low-lying areas in the plain is usually lower than the water level of rivers and lakes during flood seasons. When encountering heavy rainfall, upstream flood and local logging water converge in low-lying areas, making the area prone to flood disasters. In addition, the surged tidal backwater makes flood difficult to drain out, resulting in long duration of high water level [1][2]. When the local storm coincides with the astronomical high tides, the storm tide travelling into estuary areas can rapidly raise water level in rivers and possibly cause inundation of the downstream areas [3]. Due to the dramatic urbanization over the last twenty years in
the Taihu basin, the flood control and disaster mitigation are facing significant pressures. Affected by human activities, the basin’s flood prevention is an interdisciplinary problem, including water resources, water environment and other problems, which contributes to the significant changes of the features of flood risk [4]. In addition to exceptional weather conditions, geographical location and topographical features; the basin is extremely vulnerable to flood hazard. And it presents a significant challenge for flood risk management when combined with global developments such as sea level rise [5]. Therefore, the study on flood risk characteristics and disaster prevention countermeasures in the Taihu Basin is very meaningful.

Figure 1. Location map of the Taihu Basin in China.

2. Characteristics of flood risks in the basin

2.1. Special natural conditions making the water level of Taihu Lake rising quickly
The upper reaches of the basin are river systems of Area Huxi and Zhexi, which originate from mountainous areas. Their tributaries are arboriform and converge into the Taihu Lake. The characteristics of the river systems are near source, rapid flow, large gradient, fast confluence and prone to floods (see the location shown in Figure 1). In case of heavy rainfall in the upstream area, a large number of mountain torrents will discharge straightly into the Taihu Lake, which lead to rapid rising of the water level in Taihu Lake. The downstream plain river network area is a fanned decentralized drainage system, characterized by crisscrossed river network, connection with the east lake group, gentle gradient, and tidal backwater. As a result, the average falling rate of water level in Taihu Lake is about 0.6 times of the average rising, resulting in a long duration of high water level [6]. For example, during 1999 Catastrophic Flood in the Taihu Basin, the maximum daily inflow was up to 3098 m$^3$/s, while the outflow was only 702 m$^3$/s. The maximum daily rise of water level in Taihu Lake was 0.21 m [7]. The daily increase of the water level of the plain river network was about 7 times of the daily precipitation. The largest daily increases were 1.09 m in the water level station of Changzhou, 0.74 m in Huzhou, 0.59 m in Jiaxing, 0.64 m in Wuxi, 0.49 m in Qingpu and 0.26 m in Suzhou [6].
2.2. Difficult distinction between flood and waterlogging making duration of high water level longer
Besides the precipitation in the Taihu lake, the flood water and logging water in the upper reaches are also stored in the Taihu Lake, and in turn, discharged downstream through the main channels to form the Taihu Lake flood. It is difficult to distinguish flood and waterlogging in plain river network area when there is extensive and prolonged rainfall or local heavy rain. During the flood event, the upstream flood and the local waterlogging flood discharge together in the plain river channels, resulting in the rapid increase of the water level in river channels. It is likely to cause flooding due to the mixing effect caused by the local waterlogging and external flood. Obviously, the increase of the water level directly due to the flood upstream is likely to cause the embankment to overflow or break, which threatens the flood control of the polder area near the river. Meanwhile, the drainage water from the polder areas leads to high water level in the lower reaches of the river. As a result, it is difficult to discharge the flood water from upper reaches. The practice in 1999 and 2016 flood indicates that the discharge capacity of the Taipu Canal is obviously restricted due to the failure to control the entrance of some tributaries on the south bank of the Taipu Canal (shown in Figure1), which is evaluated as one of the most contributive river to drain the flood water from the lake and upstream areas.

2.3. Flood risk increasing due to the utilization of rain-flood resources
The available local water resources in Taihu Basin is about 17.6 billion m$^3$, while the actual average annual water consumption has reached 34.5 billion m$^3$ since 2002. It presents a big contradiction between supply and demand. Due to quality-induced water shortage, strengthening the utilization of rain-flood resources and implementing inter-basin water resources dispatching are the main and effective measures to resolve the water resources shortage and improve the regional water environment. According to hydrological analysis, the annual average water level of Taihu Lake rose from 3.17 m (the water level time series from 1986~2001) to 3.28 m (the water level time series from 2002~2017). There is the same trend in river networks. For example, Wuxi station, a regional representative station of the river network, has also seen its average water level rise by about 40 cm over the years. This means that the storage capacity of flood in the rivers and lakes is declining. Due to the interweaving of flood and drought in the Taihu Basin, it is quite frequent to have a sharp turn from drought to flood or from flood to drought. The flood risk accompanied by the utilization of rain-flood resources is obviously increased.

2.4. The increasing trend of flood losses due to the rapid economy and society development
In recent years, the continuous urbanization of Taihu Basin has promoted rapid increase of urban population, rapid accumulation of social wealth and significant improvement of urban ground hardening rate. The built-up area expanded from 2206.8 km$^2$ in 1995 to 11455.3 km$^2$ in 2015, an increase of 5.3 times. The urbanization rate rose sharply from 47.2% in 1990 to 81% in 2017. The large increase of urban permanent residents and migrant population has energized the urban social and economic development, while it also has aggravated urban flood risks, and brought huge challenges to basin flood risk management. Obviously, in case of flood disaster in Taihu Basin where the population and wealth are highly concentrated, the loss will be catastrophic. Since 1994, the establishment of People's Republic of China, there have occurred four severe regional floods in the Taihu Basin in 1954, 1991, 1999 and 2016, with direct economic losses of 1 billion yuan, 11.39 billion yuan [8], 14.125 billion yuan [7] and 7.53 billion yuan [9], respectively. There are, averagely, 3 to 4 typhoons per year affecting the Taihu Basin. According to an incomplete statistics, Typhoon Fitow caused direct economic losses of over 30 billion yuan in Zhejiang, Fujian, Shanghai, Jiangsu, Anhui and other provinces in 2013. In general, with the development of economy and society, the flood disaster loss of Taihu Basin shows an increasing trend.

3. Engineering system of flood control in the basin
In 1991, a great flood event occurred in the Taihu Basin, causing heavy economic losses. In that year, the State Council held the first meeting on the governance of the Huai River Basin and the Taihu
Basin, and decided to implement the key hydraulic engineering projects identified in the Comprehensive Regulation Planning Scheme for the Taihu Lake Basin. In the winter of the same year, constructions began on four key projects, including the embankment around the Taihu Lake, the Taipu Channel, Wangyu Channel and South drainage project of Hangjiahu region. Subsequently, three regional projects in Area Huxi, Wuchengxiu and Zhexi, as well as four interprovincial boundary flood control projects in Hangjiahu, Hongqitang, Lanlu Harbor and the upper reaches of Huangpu River, had been begun construction [10][11]. By the end of 2005, these eleven key projects had been completed and put in use one after another (see Figure2 for their locations). Since 2007, according to Water Environment Comprehensive Regulation Planning Scheme for Taihu Lake Basin, Flood Control Planning for Taihu Basin, and other river basin plannings, key projects of water environment comprehensive regulation planning in Xinmeng River, Xingou River, Taijia River, Pinghuangtang River and other rivers had begun construction successively. Flood control engineering system gradually perfected and the discharge capacity enhanced, so as to improve the flood control capacity of the basin. The key projects of comprehensive flood control in the Taihu Basin have played an important role in preventing floods, typhoons and rainstorms in the basin, especially in preventing the catastrophic flood in 1999 and the flood in 2016.

Figure 2. The Established Flood Control System including 11 key Projects in the Taihu Basin

In the upper reaches of Taihu Basin, 26 large and medium-sized reservoirs have been constructed with a total storage capacity of 1.58 billion m$^3$, and 640 million m$^3$ for flood control. The total length of the seawalls and dike of Yangtze River around Taihu Basin is 512.3 km, which basically meets the protection standard of adding category 11 wind to the once-in-50-year tide, and part of it has reached the protection standard of adding category 12 wind to the once-in-100-year and once-in-200-year tide. The flood control capacity of large and medium-sized cities has basically met the planning standard of preventing 100 -200 year return period floods. The main embankments of the Huangpu River in Shanghai have basically met the standard of protecting against 1000-year return period floods. The polder area is about 16,200 km$^2$, accounting for 55% of the plain area of the whole basin. The discharge capacity of the polder areas is over 14,000 m$^3$/s. Through the construction of various hydraulic engineering projects, the Taihu Basin has formed a pattern of flood storage and discharge focusing on the storage of Taihu Lake and discharge of rivers connecting the lake and Yangtze River in the north, Huangpu River in the east and Hangzhou Bay in the south.

4. Problems in basin’s flood protection system
The Taihu Basin has developed economy, dense population and crisscrossed low-lying water networks. The flood protection system in the basin cannot meet the needs of rapid economic and social development. The main problems are as follows.

(1) The flood protection standard of the basin is not suitable for economic and social development. Population and wealth of the Taihu Basin is highly concentrated in the cities. Economic and social
development requires a more solid foundation for flood protection. On the other hand, great changes on basin water or rain conditions have taken place, and the required rainy days causing flood disasters reduced from 60 - 90 days to 30 - 40 days. The spatial and temporal distribution of rainfall is more concentrated, and rainfall patterns in the basin became unfavorable for flood protection. The current flood control capacity has not reached the standard of preventing 50-year return period floods with different spatial and temporal distribution of rainfall. However, in 1999, the 30 days maximum rainfall of actual flood exceeded 200-year return period [5][12]. Compared with the rapid development of economy and society, the construction of flood protection engineering system in basin is still lagging behind, and disaster reduction capacity is not adequate.

2. The main channels of the basin have insufficient flood discharge capacities. In view of the rapid development of urbanization, it not only improves the flood protection and discharge capacity of cities and low-lying areas, but also cuts off the river channel connections with lakes, reduces the storage capacity for rain and flood. The drainage modulus of the polder areas in the whole basin is about 1.4 m³/s · km², and that in Area Hangjiahu is now twice that of the past twenty years. It means the floodwater pumped outside are getting more and more. According to statistics, the designed discharge volume of the main gateways along the Yangtze river and Hangzhou bay is about 8600 m³/s, which is only half of the total drainage capacity in the polder areas and urban areas [13]. More seriously, restricted by factors such as high water (tide) level in the outer river and mismatch between the river channel and floodgate, it is difficult to give full play to the capacity of the estuary gate along the Yangtze river and Hangzhou bay.

3. The contradiction between flood and waterlogging is prominent in river plain. Taipu canal and Wangyu canal (seen in Figure1) are the main channels to discharge flood from Taihu lake, and are also the main channels to discharge waterlogging from the low-lying surrounding areas. The flood discharge of these two rivers is affected by the water level in the lower reaches and the tidal backwater; therefore, it is difficult to give full play to the flood discharge capacity, especially the contradiction between the flood discharge of Taipu River and the drainage of Area Hangjiahu. For example, in 2016 April 1 to July 8, the water level of Taihu lake was from 3.09 m to 4.87 m, 0.22m higher than the design water level. However, the average flow at the Taipu Gate station is about 241 m³/s, only 31% of its design discharge, and that of Wangting Siphon station is about 155 m³/s, only 39% of its design discharge. With the construction of flood protection projects in urban and polder areas, the discharge capacity of logging water in the region is enhanced, the discharge pressure of main channels is further increased, and the contradiction between flood and waterlogging is more prominent.

4. The Grand Canal has become a new weak part for the basin’s flood control, and the coordination between upstream and downstream becomes very difficult. There are several important cites and low areas need to be protected along the Grand Canal by increasing pumping capacities. The Grand Canal, which was not supposed to undertake the task of drainage, has become the main channel for regional flood discharge and drainage of the adjoining areas after the big surroundings for urban flood protection projects are completed. Currently, the total discharge capacity of the three major cities along the canal is about 1100 m³/s, considerably larger than the current capacity of the canal with 400-500 m³/s. The application of urban flood control projects has led to the rapid uplift of the water level, which has brought great pressure to the flood protection of the areas along the Grand Canal. From 2015 to 2017, the Grand Canal had experienced a series of floods and set a new record of water level [14], with problems of "fast rising water, slow retreating water and high water level". The record of the most rapid rise in water level was about 2m in the 24-hour in the upstream section of Grand Canal in the July of 2017.

5. Potential threats of basin flood protection
The main potential threats of flood control in the Taihu Basin are climate change and sea level rise. The assessment report of the Intergovernmental Panel on Climate Change (IPCC) shows that the climate has been undergoing significant changes with global warming as the main feature in the past
100 years. Global warming will make billions of people around the world face shortages of water and food and frequent occurrence of natural disasters such as floods, droughts and typhoons. Relevant research results show that the possibility of the adverse combination of rainstorm, flood, tide and typhoon, i.e., "four encounters", is increasing in Taihu Basin and the economic and social impact is also more severe [15]. Sea level rise is considered slow-motion disaster. According to the China Sea Level Bulletin in 2017, from 1980 to 2017, the average sea level rise rate was 3.3 mm/a, higher than the global average. It is predicted that in the next 30 years, the sea level along the east China sea will continue to rise by 75 – 160 mm [15].

During flood season, it is mainly used to discharge Taihu Lake flood into the Yangtze River, into the sea and into Hangzhou Bay by taking advantage of the low tide at the surrounding entrances. Its discharge capacity is closely related to the water situation around the basin. In general, the rise of sea level elevates the low-tide level around the entrances of the basin, reduces the discharge capacity of the river and the coast (Hangzhou Bay), and further increases the flood risks. Meanwhile, the storm surge disaster in coastal areas will be further intensified, the shoreline will be eroded and changed, and the degree of salt water intrusion and soil salinization will be aggravated. Researchers from the State Oceanic Administration believe that human economic activities will accelerate the rise of sea level, and the sea level in the developed areas tends to rise more rapidly; as a result, the potential flood threats in the Taihu Basin will increase significantly.

6. Major flood protection countermeasures
Some countermeasures and Suggestions are put forward from the aspects of improving the flood control system and strengthening the adaptation and tolerance of climate change. As for the future flood control risks in the basin, we should focus on prevention, take precautions, strengthen monitoring and prediction, and properly handle the relationship between economic construction and flood control. The major flood protection countermeasures are as follows:

1) Perfecting engineering measures to improve the flood protection capacity of the basin
   It needs to further strengthen the construction of seawalls and dike of Yangtze River. The Taihu Basin is one of the areas seriously affected by typhoons in China, with an average of 3 – 4 typhoons every year [4]. It has been reported that along with global climate change, the frequency and intensity of typhoons have increased substantially [16]. The seawalls and dike of Yangtze River are the first line of protection for the Taihu Basin. Further strengthening the construction of the embankments and seawalls, and appropriately raising the standards of key embankments can effectively prevent the attack of typhoons and high tides.

2) It needs to further improve the discharge capacity of the basin. There are numerous tidal channels linking Lake Taihu and the coast (bay, estuary) in the basin. It can directly drain the basin’s floodwater as soon as possible. New or expanded drainage channels can directly lower the flood level of the lake and rivers, and reduce the duration of high water level in river plain. By making full use of the advantages of topography and tidal range, the flood discharge capacity of the hydraulic engineering projects along the river and the coast (Hangzhou Bay) can be brought into full play. It might also be a good idea to build a barrier at the estuary of the Huangpu River, which is evaluated as one of the most vulnerable metropolises to extreme flood disasters in the world [3][17].

3) The storage capacities of Taihu Lake and river networks should be improved. In case of regional flood, it is necessary to pay attention to the roles of lakes, rivers, reservoirs, temporary water storage regions and even polder areas. According to statistics, in 1999, the storage capacity of water surface was basically the same as that of the river network [18]. Taihu Lake is the center of flood protection, which plays an important role in historical floods. Each 0.1m rise in the lake's water level can increase storage capacity by 240 million m³. However, when the flood water level of Taihu Lake is too high in flood season, it will increase the difficulty for the upstream area to discharge water into Taihu Lake. Therefore, it is necessary to moderately improve the storage capacity of Taihu Lake by strengthening its embankment. In the dispatching practice of 2017 flood, experts realized that the storage capacity of river network within the protected areas is not fully used [11].
(2) Strengthening non-structural measures to make flood protection more orderly

1) It needs to formulate super-standard flood prevention plan. With global climate change, extreme weather events have occurred frequently in recent years. For instance, during the influence of Typhoon Fitow in 2013, the adverse combination of rainstorm, flood, tide and typhoon, occurred in the coastal area. The super-standard flood prevention plan of Taihu Basin should be revised and improved continuously in combination with the new situation, so as to continuously improve the flood management emergency capacity of the basin. In case of super-standard flood, the flood control projects within the basin should be arranged scientifically according to the principle of "upstream interception, middle reaches storage and downstream discharge", so as to ensure the safety of the great embankment around Taihu Lake, important cities and critical infrastructures, and minimize the casualty loss caused by the flood.

2) It needs to strengthen monitoring and early warning system. Through strengthening the coordination and communication with meteorological departments and the research on the characteristics of rainstorm and flood in the basin, the flood prediction and early warning level can be further improved. We will strengthen monitoring and forecasting of sea-level changes by comprehensively using tide surveys and advanced satellite surveys. In combination with the calibration of the geoid and the construction of levelling facilities in the basin, the monitoring network system covering the land subsidence areas in the basin and the land subsidence prediction research should be perfected.

3) It needs to improve the accuracy of the weather forecast. Through the combination of GIS technology, cloud analytics, satellite radar and other advanced technologies; the accuracy of the forecast should be improved and the forecast period should be extended, especially to strengthen the local and sudden disaster monitoring and forecasting, such as the refined forecast of urban rainstorm areas, mountain-flood-prone areas and the areas affected by typhoon. When the forecast information is confirmed, the media such as television, text messages and the Internet should be used to inform the public to take precautions.

Acknowledgments
This study is supported by Projects in the National Key Research and Development Program during the Thirteenth Five-Year Plan Period (No. 2018YFD1100401).

References
[1] Qin, B. Q. (ed.) 2008 Lake Taihu China Dynamics and Environmental Change  Springer Science + Business Media B. V. pp1-5
[2] Gao J Chen Y Takara K Cluckie I and Smedt H 2005 Impact of land use changes on runoff of the Taihu basin, China  International Conference of GIS and Remote Sensing in Hydrology pp219 – 226
[3] Zhang H Liu S Ye J and Pat J 2017 Model simulations of potential contribution of the proposed Huangpu Gate to flood control in the Lake Taihu basin of China  Hydrology Earth System Science 21 pp 5339–55
[4] Ye J and Zhang H 2015 Practices and thinking of flood risk management in Taihu Lake Basin  Advances in Science and Technology of Water Resources 35 pp 136 – 141
[5] Harvey G Thorne C Cheng X Evans E Han S Simm J and Wang Y 2009 Qualitative analysis of future flood risk in the Taihu Basin, China  Journal of Flood Risk Management 2 pp 85–100 https://doi.org/10.1111/j.1753-318X.2009.01024.x
[6] Xu Q 2002 Research on the Strategy of Flood Control and Disaster Mitigation in China (Beijing: China Water & Power Press) pp 185
[7] Ou Y and Wu H 2001 1999 Catastrophic Flood in the Taihu Basin (Beijing: China Water Power Press) pp71-73, 154-156
[8] Wu H and Guan W 1999 The Flood of Taihu Basin in 1991 (Beijing: China Water Power Press) pp 130-131
[9] Mei Q Li P Jin K and Huang Z 2016 Flood prevention work and thinking about the flood of Taihu Basin in 2016 China Flood & Drought Management 5 pp 22-25
[10] Wang T 2006 Flood Control and Water Resources Management in Taihu Basin (Beijing: China Water Power Press) pp 45
[11] Zhang H and Li C 2014 Analysis on the Flood Control Situation and Countermeasures in the Taihu Basin China Flood & Drought Management 24 pp 4-6
[12] Cheng X Evans E Wu H Thorne C Han S Simm J and Hall J 2013 A framework for long-term scenario analysis in the Taihu Basin, China Journal of Flood Risk Management 6 pp 3–13 https://doi.org/10.1111/jfr3.12024
[13] Wu Y Sun H Feng D and Zhang H 2016 Practice and thinking on flood dispatching of Taihu basin in 2016 China Flood & Drought Management 15 pp 15-17[14] Zhang C Song Y Tao N and Bai J 2018 Practice and thinking of joint dispatching along the canal in south jiangsu province China Flood & Drought Management 28 pp 4-6
[15] State Oceanic Administration 2018 China Sea Level Bulletin in 2017 http://gc.mnr.gov.cn/201806/t20180619_1798298.html
[16] Qin D Chen Y and Li X 2005 Chinese climate and environment evolution (Beijing: Science Press)
[17] Balica S F Wright N G and F van der Meulen 2012 A Flood Vulnerability Index for Coastal Cities and its use in Assessing Climate Change Impacts Nature Hazards doi: 10.1007/s11069-012-0234-1
[18] Wu T 2000 1999 Catastrophic Flood in Taihu Basin and the Consideration for Taihu Flood Control Planning Journal of Lake Science 12 pp 6-11