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Model Study on Potential Contributions of the Proposed Huangpu Gate to Flood Control in Taihu Lake Basin

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Abstract. The Taihu Lake basin, one of the most developed and dynamic regions, is located in the hinterland of the Yangtze River Delta, Eastern China. The largest flood in history is the 1999 flood event with a return period of 1 in 200 years, which is above the current capacity of flooding defense in the basin with a return period of 1 in 50 years. Due to its flat saucer-like terrain, the capacity of the flood control system is dependent on the flood defense infrastructure and the peripheral tidal conditions. The Huangpu River, connecting the Taihu Lake and the Yangtze River, is one of the major drains, which is strongly influenced by high tide conditions in the coastal waters of the Yangtze River. Hence, constructing an estuary gate is considered one of the effective solutions to the flooding problem in the basin. This paper aims to quantitatively analyze the potential contributions of the proposed Huangpu gate to flood control capacity of the basin under various flooding scenarios. It is concluded that the Huangpu gate is an effective mean to evacuate the floodwaters, by reducing peak levels in the upper part of the tide-affected river. Its beneficiaries include the Taihu Lake, the related surrounding areas along the Taipu Canal and the Huangpu River basin.

1 Introduction

An estuary is a partly enclosed body of water where freshwater from rivers, streams and groundwater flows to the ocean, and mix up with salty seawater. It is subject to both marine influences, such as tides, waves and the influx of saline water, and riverine influences, such as flows of fresh water and sediment. When its infrastructure cannot accommodate the drainage needs of land that is paved and highly developed, estuary flooding tends to become more frequent. The Intergovernmental Panel on Climate Change (IPCC) paid high attention to the flood control of coastal systems and low-lying areas, and estimated that 75% of the population affected live in Asia is mega-deltas and deltas. The Yangtze River delta is one of the highly vulnerable coastal deltas identified by IPCC (2007, 327).

To fight flooding, the traditional method of flood defense in an estuary is to build river embankments to a height greater than the maximum expected water level. More recently, an alternative method of flood defense, a combination of flood defense walls and estuary barriers, has been used in Japan, England, Netherland and other low-lying countries. The Thames barrier in UK, which has been successfully operating for nearly 30 years, can effectively mitigate the flood risk caused by heavy volumes of discharge from upstream areas and of high tides caused by storm surges, thereby raising the flood control capacity of the large city upstream (EA, 2012).

The Huangpu River, located in the downstream part of the Taihu lake basin, is the last significant tributary of the Yangtze River before it empties into the East China Sea. It is a river with a length of 113 km flowing through the heart of Shanghai city, which is the most vulnerable major city in the world to serious flooding (Balica et al., 2012). The Huangpu River is not only the major river to drain the local floodwater of the Shanghai city but also one of the major rivers to drain the floodwater of Taihu Lake and its surrounding areas. However, man-made changes in the estuary, land subsidence and embankments ageing are decreasing its flood control capacity, leading to a situation where the tidal river embankments have to be periodically raised to withstand the increasing water levels caused by storm surges and extreme tides.

The design return period of the Huangpu River against high tide is 1000 years, which was approved in 1985. The highest water levels recorded are caused by the 11th typhoon in 1997. At the Huangpu Park observation station in the city center, the water level reached the historical height of 5.72m, 0.5m higher than the previous record in 1981 and only 0.14m lower than the design water level at this location (Nai et al., 2004). Based on the revised hydrological analyses which extended the series of water levels from 1912-1983 to 1912-2002, the embankment height in its original design corresponds to less than 200 years return period due to the new record high tide (Shao, 1999; Yao, 2001; Lu, 2008). The flood protection of Shanghai city is currently not reflecting the current and expected social and economic importance of the area to China, and the potential hazards due to sea level rise in the foreseeable future. In order to meet the nominal construction standard, the embankments have to be raised again. However, it is expected that the height of the river wall will affect the urban landscape and water environment, and will incur huge costs of embankment reinforcement. Another limitation of high river embankment is that large events are more devastating if the defense is broken. Moreover, the reliability of the reinforced embankment is in question because there is not enough confidence in the quality of the original embankment constructed in the 1950s. For this reason, the Shanghai Municipal Government intends to raise the city's flood frequency to 1:1000 by a storm surge barrier in the mouth of the Huangpu River (Nai et al., 2004).

Since the 1990s, numerous studies have demonstrated the importance of constructing such an estuary gate to enhance the safety of Shanghai city, which is a metropolis in the upstream areas of the Huangpu River (Chen, 2001; Shao, 1999; Yao & Chen, 1999). Chen (2002) presented an economic and efficiency analysis of the proposed tidal gate at the estuary of the Huangpu River. However, most research to describe the importance and benefits of the proposed Huangpu gate is based on a qualitative analysis using comparative studies based on foreign experiences (Chen, 2001; Shao, 1999), and a rough estimate of the gate's economic benefits based on the protected areas by the proposed gate (Chen, 2002). Few researches focuses on the quantitative analyses of the potential benefits of the proposed Huangpu gate when fluvial flooding occurs, not to mention the occurrence of basin-level floods. This paper is to estimate the potential contributions of the proposed Huangpu gate to the flood control using numerical simulations when the basin suffers monsoon-induced floods.

2 Study Area

The Taihu lake basin, located in the hinterland of the Yangtze River delta, is one of the most developed areas in China. Around the basin, the Yangtze River is to the north, the Hangzhou Bay is to the south, the East China Sea is to the east, and Lake Taihu is situated in the center, as shown in Figure 1. This basin is not a sizable basin with total area of 36,895km^2, which is only 0.4% of the national territory. However, over 10% of the national Gross Domestic Product (GDP) is being produced, with its regional per capita GDP being more than 2.5 times the national average. It is of great significance for the social and economic development of China.

The Taihu lake basin is typified by a dense water web and a flat sauce-like landform, forming a complex hydro-system that includes interlaced rivers, dense water nets and dotted depression lakes of different sizes (Qin, 2008, 11). The water system and drainage system in the basin possesses individual properties: (1) it has a saucer-like landform, and the elevation of more than half of the floodplain is lower than the water level of flood control; (2) it is a typical river plain region with high river net density of 3.2 km/km^2 and the total river length is about 120,000 km; (3) the surface gradient is about 1/100,000 - 1/200,000, and the river flow velocity is only 0.3 - 0.5m/s in flood seasons; (4) the daily drainage time of peripheral outlets in the basin is about 13 - 14 hours due to semi-diurnal tides. Overall, the capacity of flood control system in the basin is dependent on the flood defense infrastructure and the peripheral tidal conditions to a certain extent.

This basin is prone to suffer both monsoon-induced and typhoon-induced floods. Generally, the basin is characterized by a monsoonal climate with the period concentrated in summer, from June to July, lasting several weeks or even months. Consequently, broad scale rainfall events are prone to occur due to excessive rainfall with long durations, which always bring out basin-wide floods. Worse still, the monsoon flood risks are exacerbated by the very low-lying topography and high tide conditions of peripheral outlets in the basin. The largest flood in history occurred in 1999 and the direct economic losses amount reached more than 13 billion RMB. The total amount of precipitation in the 43-days monsoon period reached 670 mm, three times more than long-term average, and was estimated to have a return period of 1 in 200 years (Evans & Cheng, 2010, 3), far from the current capacity of flood control in the basin (1 in 50 years) and the planned capacity (1 in 100 years)(MWR, 2008). Total average rainfall of 7-day, 15-day, 30-day, 45-day, 60-day and 90-day in 1999 all exceeded the historical values ever recorded (Wu, 2000). Obviously, the high lake level in this flood also set a new record of 5.08m, which exceeded the previous record in the 1991 flood by 0.29m.

In the basin, there are numerous tidal channels that link the lake and the coast (bay, estuary), and most outlets are controlled by floodgates subject to tide-locking. The Huangpu River, the only one not controlled by estuary gate, flows into the Yangtze River estuary and experiences two high tides and two low tides each day (semi-diurnal tides). For this reason, the tidal effect complicates the flow pattern of the Huangpu River, and it can naturally drain floodwaters in the lake and the middle of the floodplain only for 13-14 hours per day because the high tide acts as a ‘barrier effect’ to keep the floodwater in the river. At the estuary of the Huangpu River, the average influx of tidal water is about 58 million m^3, and maximum high tide flow is 12,100 m^3/s. Statistically, the total tidal influx of the Huangpu River from the Yangtze River is about 44.25

billion m^3 per year, and the total inflow from the upstream area is about 10.02 billion m^3 per year (Website: Local chronicles of Shanghai City).

3 Method

3.1 Methodology

Methodology in the study is scenario analysis, which is a process of analyzing possible future events by considering alternative possible outcomes. It is instructive to investigate the potential contributions of the proposed Huangpu gate to the flood control of the basin, which is still in the preliminary demonstration-of-benefit stage.

Scenarios were first used in World War II as part of military strategic planning to imagine possible strategies for battle. They have since been used in a variety of fields, such as a well-known example of the IPCC scenarios. Scenarios are made up of a set of explicit 'if-then' propositions that explore the consequences of a range of driving force assumptions. Duinker and Greig (2007) provide a summary of definitions of scenarios, including simple and more comprehensive definitions. The numerous definitions of scenarios are similar in that they are based on learning about potential alternative futures.

In this study, total five scenarios are given in Table 1 in order to analyze the potential contributions of the proposed gate to the flood control in the basin, using the 1999 flood event, the largest flood in history. One is the simulation of the natural channel, and the others are the cases with proposed gate which have the different operational rules. Taking into account the time needed for decision making and gate construction, it is of high possibility that the gate would be completed and come into use after 2025. For this reason, the flood defense infrastructures in scenario simulation include the proposed flood control projects in the Plan (MWR, 2008).

3.2 Model

The HOHY model, developed by the Hohai University, China, is chosen for scenario analysis. In order to simulate complex operational rules of the proposed estuary gate, and the main Fortran codes of the model is revised to accommodate additional capabilities needed for the purpose of this study. The model includes a hydrological part of runoff generation and routing, and a hydraulics part of simulating hydraulic procedure of channel flow, each of them can run stand-alone (Cheng et al., 2006).

Runoff is generated when precipitation exceeds the capacity of infiltration, interception and depression storage. The basin surface is classified into four types: water surface, paddy field, non-irrigated farmland and constructed land, each of them employs different methodologies for runoff-generation calculation. After that, runoff is routed according to basin topography. In hilly areas, an instantaneous unit hydrograph method is used, taking into account the store and drainage processes of reservoirs and large ponds. In plain areas, a unit afflux curve is used in each computed area.

After the runoff from the hilly and plain areas flows into water networks, the hydraulics method is applied for the simulation of river flow. The Saint Venant Equations are used as the governing equations for 1-D unsteady open channel flow, including the continuity on and momentum equations. Only those lakes with larger water surface are considered as possessing the function of storing floodwater, while the others are considered as a common junction like the linkages among rivers. The operation of water-engineering works such as the simulations of gates, pumping stations and siphons will be taken into account at the same time.

The calibration data for the model is four consecutive years from 1984 to 1987, and the verification data are two years of 1995 and 1996. And the model is tested for three basin-wide floods in 1954, 1991 and 1999. The simulation results of 1999 flood can be found in a reference by Ou & Wu (2001), which also contain detailed analyses by comparing simulation results with the observed data in the 1999 flood event. Figure 2 shows the differences between the simulated and observed water levels in the 1999 flood at eight representative stations of various sub-areas, and Figure 3 shows the differences between the observed and simulated discharges at the Taipu Gate and Wangting Siphon, respectively. As can be judged from these comparisons of water levels and discharges, the HOHY model simulations are of sufficiently high accuracy for scenario analyses.

4 Results and discussion

The analysis of potential contributions of the proposed gate is structured into three segments, i.e. the contributions to the flood control of Lake Taihu, the related surrounding areas, and the Taipu canal and Huangpu River.

4.1 potential contributions of the proposed gate to flood control of Lake Taihu

Table 2 describes the peak value of lake level and the duration exceeding the various control levels. Figure 4 describes the simulated water level of Lake Taihu from June 1st to August 31st in 1999 flood event. It can be seen that the lake levels in scenarios A1, A2, A3 and A4 are all lower than that the scenario base A, and the durations of water levels higher than different control levels are also shortened accordingly. Compared with the peak lake-level in the scenario base A (5.03m), those in other four scenarios decrease 0.04m, 0.01m, 0.03m, and 0.12m, respectively. It is an effective outcome for the flood control of Lake Taihu and its western adjoining low-lying areas.

It should be noted that for such a typical shallow lake located in low-lying plains, the difference in the designed water levels is not too much with respect to different return periods. For instance, the design water level of 100-year return period is 4.80m, while that of 50-year return period is 4.65m, and the difference between them is only 0.15m. For this reason, the decrease in the peak lake level by 0.04m in the scenario A1 is rather significant for the flood control of the lake, needless to say by 0.12m in the scenario A4. On the other hand, the western adjoining floodplain is also benefited from this proposed gate. The flood capacity of the western adjoining areas is relatively low due to economy conditions there. Therefore, it is likely to be inundated due to water intrusion from the lake to the adjoining areas not yet controlled by sluices if the lake level were too high. Obviously, the western adjoining areas would be quite worse once the lake dike breaches.

From the point of view of the lake's flood control, it can be concluded that the Huangpu River with an estuary gate is much more effective than the natural river. The extent of contributions depends much on the total operation time and the period when the gate is operated. The more time the gate is operated, the more tidal water is intruded at the Huangpu River estuary, in effect reducing the amount of tidal water entering the upper estuary, which already has high water levels from high river flows. Overall, scenario A1 is a good example to examine the potential contributions of the proposed gate. In the simulation of the 1999 flood, the Huangpu gate is much effective to reduce flood risk in the lake by operating the estuary gate in advance. Even running the gate by a relatively short period, such as one week in this study, the contributions to reduce peak value of lake level and slow down the rising rate of lake level are rather distinct.

4.2 potential contributions of the proposed gate to flood control of related surrounding areas

As shown in Figure1, floodwater of the related surrounding areas, including the Yangchengdianmao area, the Hangjiahu area, the Puxi area and the Pudong area, is also discharged into the Huangpu River. So the safety of these four areas against flooding is also closely related to the capacity of the Huangpu River. Table 3 describes the peak values of water levels of representative stations which are marked in Figure 1 using symbol of circular cylinder. Figure 5 shows the simulated daily water levels in the related surrounding areas (stations 1-4).

From Figure 5, simulation results of these four stations show similar trends with that of Lake Taihu. The scenario A4 represent the maximum potential contributions of the proposed gate, i.e. maximum decrease of daily peak level in the related surrounding areas (stations 1-4) was 0.32m, 0.19m, 0.39m, and 0.05m, respectively. By contrast, the improvement of the flood control capacity in station 4 is relatively small because the local floodwater in this area draining to the East China Sea has the priority over that to the Huangpu River due to its natural water-expelling ability. In other words, the flood capacity of this station does not depend on the drainage capacity of the Huangpu River as much as the other three stations.

By contrast, for scenario A1 of which the gate is operated in advance, it can play a notable role in reducing the peak values of water levels between 0.15 m and 0.35 m except for station 4, while scenario A2 only decrease the peak value of water levels between 0.07m and 0.15m. Instead, the scenario A2 has more advantages in speeding up drainage rate of floodwater at the recession stage and shortening the waterlogging time as well.

4.3 potential contributions of the proposed gate to flood control of the Taipu canal and Huangpu River

Figure 6 shows the simulated daily water levels in the Taipu canal and Huangpu River (cross-sections 1-7), which are marked in Figure 1 using symbol of diamond shape. The daily water levels in the Taipu canal and Huangpu River are decreased to various extents if the tidal estuary gate was operated. The scenario A4 represents the potential maximum contributions due to its prevention of all tidal water intrusion, of which the maximum reduction of the peak values of water levels in the Taipu canal are between 0.26 m and 0.37 m, and those in the Huangpu River are between 0.46 m and 0.60 m.

The Huangpu River benefits more from the proposed gate than the Taipu canal because the latter is relatively farther from the gate. The potential contributions of the gate are attributed to the reduction of tidal water intrusion during flooding.

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Generally the tidal intrusion is mainly concentrated on the lower reach of the Huangpu River, although the intrusion can propagate upward as far as more than 100 km from the estuary. The water level will rise in the upstream reach of the Huangpu River if the gate is closed, and then the discharge rate will increase when the gate re-opens due to the relatively larger difference in water levels between the upstream and downstream near the gate. Therefore, the gate decreases water levels of the Huangpu River more distinct than the Taipu canal.

In the scenario A1 of which the gate is operated in advance in the rising stage of the lake level, the peak value of flood levels in these two rivers can be apparently decreased due to the enlargement of the drainage capacity of the Huangpu River in this period. In the scenario A2 of which the gate is operated when the lake level is high than 4.5m, its contribution to the peak value of water levels is less than scenario A1, while the draining rate in the recession stage are rather faster. If the gate is operated by blocking high tide during the flood period (the scenario A3), the peak values of water levels in these two rivers are decreased during the spring tides. This conclusion is completely in line with those discussed in the previous sections on the contributions of the proposed gate to flood control of the lake and the related surrounding areas.

4.4 analyses of the inflow and outflows in the Huangpu River

Tables 4 describe the inflow volumes of the tributaries in the upstream of the Huangpu Rivers during the flood period. Except the Taipu canal, there are numerous tributaries in the upstream areas, which originate from the sub-areas of the northwest and southwest of the Huangpu River upstream. Compared with the scenario base A, the inflow volume of the tributaries in the southwest areas upstream into the Huangpu River is up to 3.25 billion m^3 (scenario A4), more than twice of that in the scenario base A (1.50 billion m^3). The inflow northwest areas upstream in the scenario A4 is about 1.05 billion m^3, increased by 78.0% compared to the scenario base A (0.59 billion m^3), while the inflow from the Taipu canal is about 5.00 billion m^3, only increased by 27.2% compared to the scenario base A (3.93 billion m^3). By comparing the major inflows into the Huangpu River, it suggests that the inflow from the southwest and northwest areas upstream are increased significantly compared to that from the Taipu canal, and the Huangpu River plays an extremely crucial role for these two sub-areas.

Tables 5 describe the tide intrusion and outflow volume at the site of the proposed gate during flooding. The proposed gate is helpful to improve the drainage efficiency of the Huangpu River by blocking tidal water intrusion. Compared with the scenario base A, the net outflow volumes at the gate site in other four scenarios are increased by 4%, 8%, 22%, and 52%, respectively during the entire flood period. To illustrate this point, Figure 7 shows the comparison of simulated river discharges at the site of the proposed gate between the scenarios base A and A1 from June 27th to July 3rd. The discharge difference between these two scenarios is clearly shown to reflect the difference of the drainage efficiency of the Huangpu River. Although the river discharge amount in the scenario A1 is only increased by 4% for the whole flood period (from 7.20 to 7.46 billion m^3), the impacts on the flood control during the gate operation period is much distinct, where the net outflow volume is nearly doubled by changing the bi-directional flow to unidirectional flow.

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5 Conclusions and discussion

The Huangpu River with an estuary gate is more effective than a natural channel in evacuating floodwaters, reducing peak levels in the upper part of the tide-affected river by reducing the amount of tidal water entering the upper estuary. The potential contributions of the proposed gate are proportional to its operation time. Regarding the maximum potential contribution, the net outflow volume at the site of the proposed gate is increased by 52% in the entire flood period of the 1999 flood, and hence the drainage efficiency is effectively improved from the lake to the Yangtze River estuary.

The beneficiaries attributed to the proposed gate include Lake Taihu, the related surrounding areas, and the Taipu canal and the Huangpu River. The inflow volumes of tributaries upstream from the Taipu canal, the north of the Hangjiahu area, and the south of the Yangchengdianmao area into the Huangpu River are increased by 27%, 78%, and 117%, respectively. The maximum decrease of daily peak level of the lake is 0.12m, in related surrounding areas between 0.05 and 0.39 m depending on the different topographies, and in the two rivers 0.26-0.37m and 0.46-0.60m, respectively.

The potential contribution of the gate depends on the time when the gate operates. For scenario A1, it is beneficial to decrease the peak flood level and slow down the water level rise during the rising stage. For scenario A2, it is helpful to speed up the drainage rate during the recession stage and reduce the duration of high water level and decrease the flood risk of the lake and its upstream adjoining areas. For scenario A3, it appears that flood control is more effective during spring tides. Thus the gate's contribution is more distinct in August than in other periods.

In a word, it is significant and effective to build an estuary gate at the mouth of Huangpu River to improve the flood capacity against basin-wide floods, but its implementations needs further investigation into its economic, environmental and navigation feasibility. It is to be noted that the river's navigation should be paid high attention when the operation rules of this proposed gate is formulated, which make less trouble to the navigation as soon as possible.

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Figure 1: Location map of the Taihu lake basin

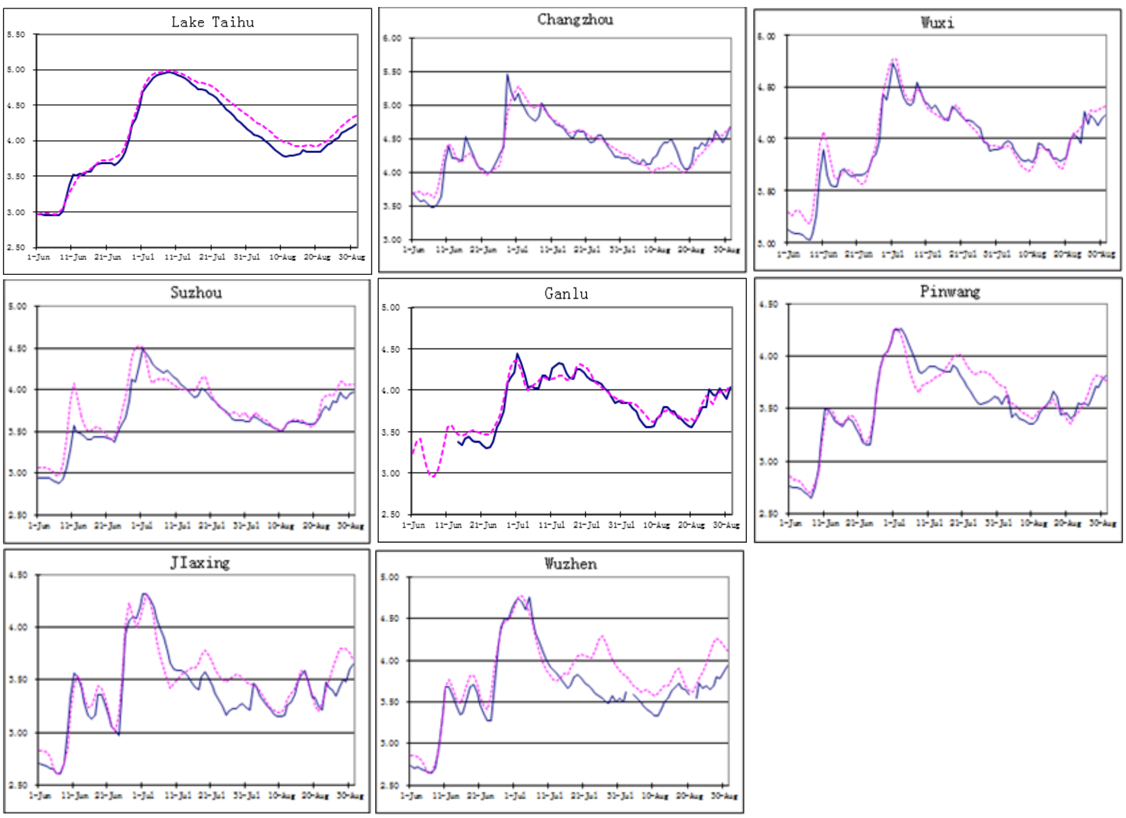

Figure 2: Comparison between observed (solid line) and simulated (dash line) water levels at eight representative stations (from Ou & Wu, 2001)

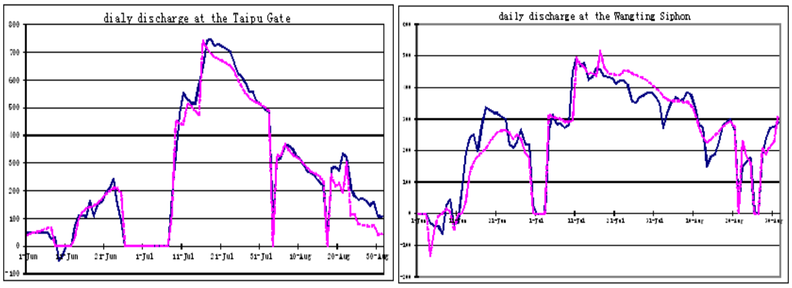

Figure 3: Comparison between observed (solid line) and simulated (dash line) daily discharges at the Taipu Gate and Wangting Siphon (from Ou & Wu, 2001)

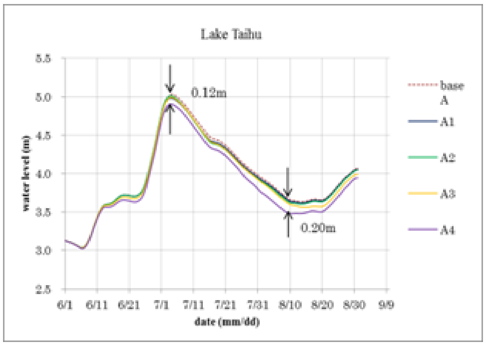

Figure 4: Comparison of the simulated daily lake levels among various scenarios

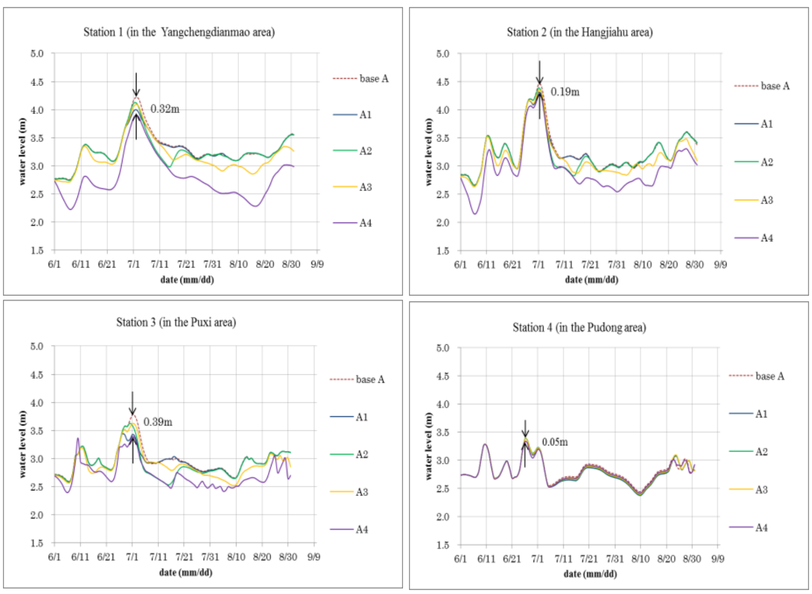

Figure 5: Comparison of the simulated daily water levels in the related surrounding areas among various scenarios

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Figure 6: Comparison of the simulated water levels in the Taipu canal and Huangpu River from June to August, 1999

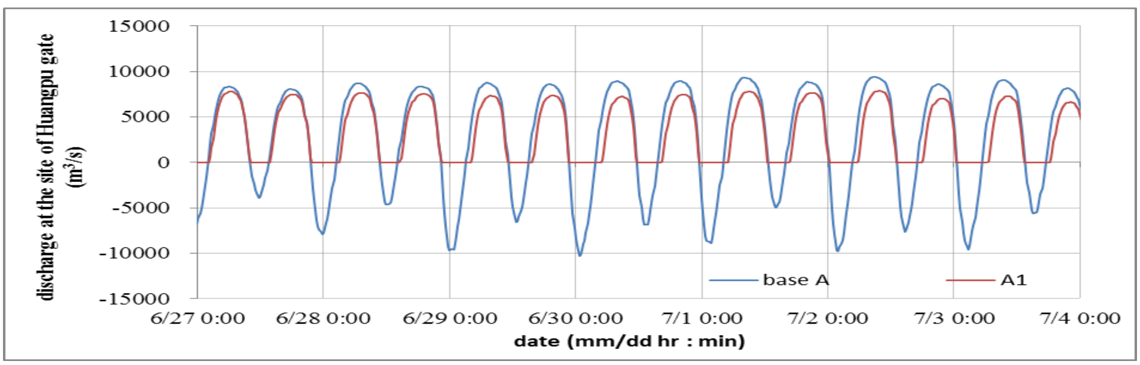

Figure 7: Comparison of discharges at the site of the proposed gate between the scenarios base A and A1 from June 27th to July 3rd (negative discharges means the tidal water intrusion)

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Table 1: Scenario design

Scenario	Description
base A	without the proposed estuary gate at the estuary of the Huangpu River
A1	with the gate, and it will be operated to prevent tidal intrusion 7 days in advance before the lake level reaches the peak value
A2	with the gate, and it will be operated to prevent water intrusion when large basin-wide floods occur (large basin-wide floods here mean that lake level is higher than 4.50m)
A3	with the gate, and it will not closed to prevent tidal water intrusion until the tide rises to the tide threshold (the tide threshold here equal to 4.0m)
A4	with the gate, and it will be closed whenever tidal water intrudes

Table 2: Peak value of lake levels and number of days when lake levels are higher than a certain control level among different scenarios from June to August

Scenario	peak value. (m)	flood control level 3.5m	high water level 4.0m	design water level (1/50) 4.65m	design water level (1/100) 4.8m
base A	5.03	81	37	12	8
A1	4.99	81	35	11	8
A2	5.02	81	34	11	8
A3	5.00	81	31	11	8
A4	4.91	70	28	10	6

Table 3: Peak value of water levels of representative stations in various scenarios

Scenario	Station 1	Station 2	Station 3	Station 4
base A	**4.22**	**4.46**	**3.78**	**3.38**
A1	**4.00**	**4.31**	**3.43**	**3.38**
A2	**4.12**	**4.39**	**3.63**	**3.38**
A3	**4.09**	**4.35**	**3.62**	**3.37**
A4	**3.90**	**4.27**	**3.39**	**3.33**

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Table 4: summary of the inflow volumes of the tributaries in the upstream areas of the Huangpu River from June to August in 1999 among various scenarios (unit: billion m^3)

Flow Volume\Scenario		base A	A1	A2	A3	A4
Tributaries in the upstream area of the Huangpu River	outlet of the Taipu canal	3.93	3.99	4.11	4.43	5.00
	tributaries from the sub-area, northwest of the Huangpu River	0.59	0.62	0.64	0.77	1.05
	tributaries from the sub-area, southwest of the Huangpu River	1.50	1.63	1.83	2.24	3.25

Table 5: Summary of tide intrusion and outflow volume at the site of the proposed gate from June to August in 1999 among various scenarios (unit: billion m^3)

Scenario	Outflow volume at the gate site			Times to close the gate	Special explanation about the gate close rules
	tide intrusion	total outflow volume	net outflow volume		
base A	17.49	24.69	7.20	/	
A1	15.58	23.03	7.46	14	from Jun. 27th to Jul. 3rd
A2	14.14	21.94	7.81	30	from Jun. 30th to Jul.14th
A3	10.78	19.58	8.79	74	until high tide rises up to 4.0m
A4	0	10.95	10.95	184	from Jun. 1st to Aug. 31st