Numerical Analysis of Potential Contributions of the Proposed Huangpu Gate to Flood Control in Taihu Lake Basin

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Abstract

The Taihu Lake basin, located in the hinterland of the Yangtze River Delta, Eastern China, is one of the most developed regions in China. The basin has experienced increasing flood risk. The largest flood in history occurred in 1999, with a return period estimate of 200 years, which is much higher than the current capacity of flood defense with a return period of 50 years. Due to its flat saucer-like terrain, the capacity of the flood control system depends on the flood control infrastructure and the peripheral tidal conditions. The Huangpu River is an important river in the basin. It connects the Taihu Lake upstream and the Yangtze Estuary downstream, and also drains two-fifth of floodwaters of the basin. The Huangpu River is strongly affected by the high tide conditions in the estuary. Therefore, the plan of an estuary gate, Huangpu gate, is considered as one of the most effective solutions to the flood mitigation in the basin. The main objective of this paper is to access the potential contributions of the proposed Huangpu gate to flood control capacity of the basin. To achieve this goal, various flooding scenarios are quantitatively analysed. Results show that the Huangpu gate is effective to evacuate the floodwaters. It can help to reduce the peak levels and the duration of high water levels in the upper portion of the Huangpu River. The flood risk of the Taihu Lake, the related surrounding areas along the Taipu Canal and the Huangpu River can be consequently reduced.

Keywords: Flood control; Huangpu Gate; Taihu Lake Basin; Numerical analysis;

1 Introduction

The Taihu Lake Basin, located in the hinterland of the Yangtze River Delta, Eastern China, is a region which is impacted by both marine, such as tides, waves and the influx of saline water, and river, such as flows of fresh water and siltation. Extensive urban development has contributed to increasing flood magnitude and flood frequency in this region. Major flood disasters, flooding more than 3000 km^2, have occurred more than ten times during the twentieth century (Yu et al. 2000). The largest flood disaster occurred in 1999 and it resulted in damages with direct economic loss of 16 billion USD (Wang et al., 2011). There are 239 typhoons affecting the basin from 1949 to 2013, averaging about 3 to 4 per year on average (Ye & Zhang, 2015). According to the report from The Intergovernmental Panel on Climate Change (IPCC), the flood control of coastal systems and low-lying areas is addressed, including the Yangtze River delta, which is identified as one of the highly vulnerable coastal deltas (2007).

The Huangpu River, located in the downstream part of the Taihu Lake basin, is the last significant tributary of the Yangtze River. The Huangpu River is not only the major river that drains the local floodwater of the Shanghai city but also one of the major rivers that drains the floodwater of the Taihu Lake Basin. With a length of 113 km, it flows through the urban core of Shanghai city, which is evaluated as one of the most vulnerable metropolises to extreme flooding in the world (Balica et al., 2012). The river embankments, which is an traditional flood defense infrastructure, has been built along the Huangpu River since the 1950s, however, its flood control capacity is decreased by increasing storm surges and extreme tides, man-made changes in the estuary, land subsidence and aging infrastructures. Currently, the river embankments need to be periodically raised to withstand the increasing water levels.

The designed return period of the Huangpu River 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 core, the water level reached the historical height of 5.72 m, 0.5 m higher than the second largest record in 1981 and only 0.14 m 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). In 2004 the standard of the 1000-year level was investigated to been reduced to a 100-year level because of sea-level rise and land subsidence (Tang et al. 2014), indicating the capability of flood protection was reduced. To enhance the current capacity of flood protection in Shanghai, the height of embankments needs to be raised to meet the standard of 1000-year return period. However, the continuously increase of its height will not only require huge economic cost but also affect the urban landscape and water environment. Another potential risk of high river embankment is that extreme dam-break flooding will be more devastating. Moreover, the reliability of the reinforced embankment is in question because of the aging foundation and core of the embankment, which was built in the 1950s (Zhou et al., 2016).

A combination of flood defense walls and estuary barriers has been used as an alternative flood control infrastructure in the low-lying regions in Japan, England, Netherland and other countries. The Thames barrier in UK, for instance, has been operated for more than 30 years with a considerable flood control capacity of the large city upstream. It can effectively mitigate the flood risk, which is caused by discharge from upstream areas and high tides caused by storm surges (EA, 2012). Inspired by that, the Shanghai Municipal Government proposed to build a storm surge barrier in the mouth of the Huangpu River so as to increase the city’s design flood with a return period of 1000 years (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; Shao and Yao, 1999). Chen (2002) presented an economic and efficiency analysis of the proposed tidal gate at the estuary of the Huangpu River. Chen (2001) and Shao (1999) carried out comparative studies based on previous experiences outside China. Chen (2002) analysed a rough estimate of the gate’s economic benefits based on the protected areas by the proposed gate. Most research on the importance and benefits of the proposed Huangpu gate is based on qualitative approaches, while little research focuses on the quantitative analyses of the potential benefits of the proposed Huangpu gate when fluvial flooding occurs. The main objective of this paper is to access the potential contributions of the proposed Huangpu gate to flood control capacity of the basin. To achieve this goal, through numerical simulations, various monsoon-induced floods scenarios are quantitatively analysed.

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. The Taihu Lake is located in the center of the basin, surrounded by the Yangtze River on the north, the Hangzhou Bay on the south, the East China Sea on the east, as shown in Fig. 1(a). This basin is not a sizable basin with total area of 36,895 km^2, which is only 0.4% of the national total (Hu & Wang, 2009). However, the Gross Domestic Product (GDP) is up to RMB 6.69 trillion by the end of 2015, accounting for about 10% of national total, and the regional per capita GDP being more than 2.5 times the national average. This region is of great significance for the social and economic development of China.

The Taihu Lake Basin is characteristic of a dense water web and a flat saucer-like landform, forming a complex hydro-system that includes interlaced rivers, dense water nets and dotted depression lakes of different sizes (Qin, 2008). 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 suffering 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 occurring due to excessive rainfall with long durations, which contributes to basin-wide floods. Meanwhile, 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 total rainfall in the 43-days monsoon period reached 670 mm, which was three times more than the long-term average precipitation in the 1954-2010 periods. The return period of 1999 flood event is estimated as 200 years (Evans & Cheng, 2010), much higher than the current capacity of flood control in the basin with 50-years return period and the planned capacity with 100-years return period (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 recorded (Wu, 2000). During this flood, the high water level in Taihu Lake set a new record of 5.08 m, which exceeded the previous record in the 1991 flood by 0.29 m.

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, as the only one without an estuary gate, flows into the Yangtze River estuary and experiences two high tides and two low tides each day (semi-diurnal tides), as shown in Fig. 1(a). For this reason, the tidal effect complicates the flow pattern of the Huangpu River. As a 'barrier effect', the high tide helps to keep the floodwater in the river. The river can, therefore, naturally drain floodwaters in the Taihu Lake and the middle of the floodplain only for 13-14 hours per day. The Huangpu River receives about 40.9 billion m^3 of tidal water from the Yangtze River (Zhang, 1997). The total tidal influx of the Huangpu River is about 47.47 million m^3 per year, and the total inflow from its upstream area is about 10.02 billion m^3 per year.

3 Methodology

3.1 Scenario description

The main methodology in this study is scenario analysis, which is a process of analysing 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.

In order to analyse the potential contributions of the proposed gate to the flood control in the basin, five scenarios are used in this study (Table 1). Four scenarios are the cases with proposed gate with different operational rules, and one scenario is the case without gate for the comparison to others. All the scenarios are based on the 1999 flood event, the largest flood in history.

In 'Scenario base A': the estuary gate would not be constructed at the outlet of the Huangpu River. Thus, the water in the Huangpu River and the Yangtze River estuary can exchange naturally.

In 'Scenario A1': the proposed gate will be operated in the rising stage of the lake levels with a high possibility to create new record of the lake level based on weather forecast. In the simulation of 1999 flood event, it is operated seven days in advance before lake level reaches its peak value.

In 'Scenario A2': the proposed gate will be operated when large basin-wide floods occur with the lake level is higher than 4.50 m, which means the flood situation of the Taihu Lake is very severe and need to accelerate the drainage rate of the major draining rivers downstream, including Huangpu River.

In 'Scenario A3': part of tidal water intrusion will be blocked, and the gate will not be closed to prevent tide intrusion until the tide rises to the tide threshold. That is, the gate will not be closed to block tide intrusion every day, only for the case when the high water exceeds the tide threshold and is forecasted to rise.

In 'Scenario A4': the gate would prevent all the intrusion of tidal water during the flood period. It is a hypothetical extreme condition and is not practical due to the difficulty of frequently operating such a huge gate with a width of 400 – 500 m (i.e. to close twice every day). This scenario is just a case to calculate the potential maximum benefits to flood control of the basin. Furthermore, it is not necessary to prevent all tidal water intrusion, resulting in a stop of water exchange between the

Huangpu River and the Yangtze River networks. Under this condition, it is also likely to produce a negative impact on waterway transportation and water environment system.

Considering the time needed for decision making and gate construction, it is very likely that the Huangpu gate will start to work in 2025. For this reason, the proposed flood control projects in the Plan (MWR, 2008) are also simulated in the scenarios as the flood defense infrastructures. Also, parameters in the model are the same as those used in the Plan (MWR, 2008). Hu (2006) proposed the ehorage ground is the best site in the Huangpu River for the gate, because it is in the first regular bank and its influences to the shipping are much less. Cui (2012) and Lu (2008) proposed the similar gate site. In this study, the estuary gate is also simulated at the same place which is about 5-6 km from the river outlet.

3.2 Model description

The HOHY model, developed by the Hohai University, China, is used in this study. This model was tested for regional application since 1970s, and was applied to the whole basin in 1997. It is one of the main productions of a three-year water quality study in the Taihu lake basin supported by the World Bank loan, which were jointly undertaken by Hohai University and Delft Hydraulics, the Netherlands. The HOHY model can simulate the cycle of flood waters well. Meanwhile, the model provides, at a broad scale, a reasonable simulation of the Taihu lake basin flooding system. It can not only simulate complex hydro-systems with numerous interlaced rivers and lakes, complicated relationships between river nets, hilly areas and tidal boundaries, and also simulate complex operational rules of control structures, such as sluices, pumps and siphons. It has been used in a variety of fields, such as the preliminary demonstration-of-benefit stage of water works in the basin. In particular, the model has been successfully applied in the flood control planning of the Taihu lake basin, which was approved by the Minister of Water Resources of P.R.C in 2008 (MWR, 2008).

The model is composed of two parts: a hydrological part of runoff generation and routing, and a hydraulics part of simulating hydraulic procedure of channel flow. Each of them can run independently. The schematization of the model is shown in Fig. 2. More details of the model are discussed as follows (see Cheng et al. (2006) for additional details).

Runoff is generated when precipitation exceeds the capacity of infiltration, interception and depression storage. The basin land use 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, considering the store and drainage processes of reservoirs and large ponds. In plain areas, runoff curve number 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 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 intersections like the links among rivers. The operation of water-engineering works such as the simulations of gates, pumping stations and siphons will be simulated in the model.

The calibration data for the model are two consecutive years from 1984 to 1985 (Liang et.al, 1993), and the validation data are two years of 1995 and 1996. And the model is tested for three basin-wide floods in 1999. The simulation results of 1999 flood can be found in a reference by Ou & Wu (2001), which also contain detailed analyses by comparing model results with the observational data in the 1999 flood event. Fig.3 shows the water level differences between the model and observations in the 1999 flood at eight representative stations of various sub-areas. The names and positions of these eight representative stations are shown in Fig.1 (a). Fig.4 shows the discharge differences between the observation and the model at the Taipu Gate and Wangting Siphon, respectively. The positions of the Taipu Gate and Wangting Siphon are also shown in Fig. 1(a). The comparisons of water levels and discharges demonstrate that the HOHY model simulations are of sufficiently high accuracy for following analyses.

Among these five scenarios, the operational rules in 'Scenario A3' are the most complex to simulate since different operational rules of the gate will be applied for the flood tide and ebb tide, respectively. The operational rules are as follows. If the high water in flood tide is higher than the tide threshold, the gate will be closed. Once the gate is closed, it will not be re-opened until it has the natural water-expelling ability to drain floodwater in the ebb tide (until tide level falls to lower than the water level in the upstream of the gate). Hence, the model needs to be modified to enhance its capabilities for this purpose.

The model extension focuses on the flood routing part, related to the algorithms of unsteady open channel flow, and the inputs of control rules of the gates related to the tidal conditions. The main program was improved by adding a function to judge the stage of tide before running the gates (i.e. in flood or ebb tide), which makes the specification of the gate's control rules more flexible. The original program is modified based on the flowchart given in Fig. 2 with table gridlines.

The modified model is tested by using a simple case, where the tide threshold is assumed to be 4.0 m. The simulation results are illustrated in Fig.5 and Fig.6. The first graph describes the case when the gate keeps open because the high water in this tidal period is always lower than 4.0 m. The second graph, as a comparison, is the case that the gate should be closed when the rising tide is higher than 4.0 m. The gate will re-open to drain floodwater when the gate has natural water-expelling ability to evacuate floodwater in the ebb tide.

The model results includes the gate discharge, tide water level at the estuary and the difference of water levels between the upstream and downstream of the proposed gate, showing the logical relationship of the gate's operational rules. The results in Fig.5 demonstrate that the discharge at the gate seems like a sinusoidal curve affected by the tidal boundary. It is likely that the gate needs not to be closed as the high water in this tidal period is less the tide threshold of 4.0 m. Fig.6 is another case of the gate's operational rules of which the high water is about 4.70 m. At 2:30 am, 15 August 1999, the tide level at the river outlet in the flood tide slightly exceeds the tide threshold of 4.0 m, and the gate has to be closed. It is not re-opened in the ebb tide until 8:15 am, 15 August 1999 when water level in the upstream is higher than that in the downstream near the proposed gate, which means the gate has the natural water-expelling ability to drain floodwater at this moment (see the red bars in Fig.6). Overall, the modified model has the ability to simulate complex operational rules of the proposed gate.

4 Result analysis and discussion

Based on qualitative analyses from the topography and water system of this area, the Huangpu River receives the floodwater from the Taihu Lake and the related surrounding areas where the Taipu canal and the Huangpu River pass by, especially for those low-lying areas, including the southern part of the Yangchengdianmao catchment area, the northern part of the Hangjiahu catchment area, and the western part of the Puxi catchment area (Fig.7). Therefore, the potential contribution of the proposed gate is analysed from three aspects: the contributions to the flood control of the Taihu Lake, the related surrounding areas, and the Taipu Canal and the Huangpu River.

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

Table 2 describes the peak value of the lake water levels (along with the durations) that exceed the various control levels among different scenarios from June to August, 1999. Fig.8 describes the simulated water level of the Taihu Lake from June 1st to August 31st occurred in 1999 flood event. The lake levels in Scenarios A1, A2, A3 and A4 are all lower than those in Scenario base A. Similarly, the durations are also shortened when the water level is higher than different control levels. Compared with the maximum lake water level in Scenario base A (5.03 m), those in other four scenarios decrease 0.04 m, 0.01 m, 0.03 m, and 0.12 m, respectively. It contributes to the flood control of the Taihu Lake and its western adjoining low-lying areas.

It should be noted that the difference in the design water levels is not significant with respect to different return periods for such a typical shallow lake located in low-lying plains. For instance, the design water level of 100-year return period is 4.80 m, 0.15 m higher than that of 50-year return period. For this reason, the decrease in the peak lake level by 0.04 m in Scenario A1 is relatively significant for the flood control of the lake, as well as the decrease of 0.12 m in Scenario A4. The western adjoining floodplain is also benefited from this proposed gate. Due to the relatively lower flood capacity of the western adjoining areas, the region is likely to be inundated when water intrusion from the lake to the adjoining areas not yet controlled by sluices if the lake level is too high. The flooding in western adjoining areas will be quite worse once the lake breaches the dike.

From the viewpoint 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 longer time the gate is operated, the more tidal water will intrude into the Huangpu River estuary. During its operation, the gate will reduce the amount of tidal water entering the upper estuary, which already has high water levels from high river flows. Clearly, the floodwater in the lake will be drained slowly by the Taihu canal and the Huangpu River if they have high water levels due to tide intrusion. 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 more effective to reduce flood risk in the lake by operating the estuary gate in advance. Even to run the gate by a relatively short period, such as one week in this study, the contribution to reducing peak value of lake level and slowing 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

Floodwater of the related surrounding areas, including the Yangchengdianmao catchment area, the Hangjiahu catchment area, the Puxi catchment area and the Pudong catchment area, is also drained into the Huangpu River (Fig.7). Therefore, the safety of these four areas against flooding is also closely linked to the capacity of the Huangpu River. Table 3 lists the peak values of water levels of representative stations which are illustrated by the symbol of star in Fig. 1(b). Fig.9 shows the simulated daily water levels in the related surrounding areas (stations 1-4).

Simulation results of these four stations (Fig.9) show the similar trends as that of the Taihu Lake. Scenario A4 represents the maximum potential contributions of the proposed gate, i.e., the maximum decrease of daily peak level in the related surrounding areas (stations 1-4) was 0.32 m, 0.19 m, 0.39 m, and 0.05 m, respectively. In contrast, the improvement of the flood control capacity in station 4 is relatively small among these four stations due to its terrain. The local floodwater in the Pudong catchment area that drains to the East China Sea has the priority over that to the Huangpu River due to its natural water-expelling ability. Generally, the flood capacity of Station 4 does not depend on the drainage capacity of the Huangpu River as much as the other three stations.

In contrast, in Scenario A1 of which the gate is operated in advance, the gate 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 in Scenario A2, the gate only decreases the peak value of water levels between 0.07 m and 0.15 m. However, Scenario A2 has more advantages in speeding up drainage rate of floodwater at the recession stage and shortening the waterlogging time.

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

Fig.10 shows the simulated daily water levels in the Taipu canal and Huangpu River (cross-sections 1-7), which are illustrated by the symbol of rectangular shape in Fig. 1(c). The daily water levels in the Taipu canal and Huangpu River decrease to various extents when the gate is in operation. Scenario A4 represents the potential maximum contributions with the prevention of all tidal water intrusion. In this scenario, the maximum reduction of the peak water level in the Taipu canal is 0.26 - 0.37 m, and that in the Huangpu River is 0.46 - 0.60 m.

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

In Scenario A1, the gate is operated in advance during the period of the rising stage of the lake level, and the peak flood level value in the Taipu canal and Huangpu River can be apparently decreased due to the enlargement of the drainage capacity of the Huangpu River. In Scenario A2, the gate is operated when the lake level is higher than 4.5 m, and its contribution to the peak water levels is less than Scenario A1, while the draining rate in the recession stage is rather faster. If the gate is operated by blocking high tide during the flood period (Scenario A3), the peak water levels in the Taipu canal and Huangpu River are decreased during the spring tides. This conclusion is completely consistent 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

Table 4 describes the inflow volumes from the Huangpu River upstream tributaries during the flood period. Except the Taipu canal, there are numerous upstream tributaries that originate from the sub-areas of the northwest and southwest of the Huangpu River (Fig. 7). In Scenario A4, the inflow volume from the southwest tributaries into the Huangpu River is up to 3.25 billion m^3, more than twice of that in Scenario base A (1.50 billion m^3). The inflow from the northwest upstream areas in Scenario A4 is about 1.05 billion m^3, increases by 78.0% in comparison to that in Scenario base A (0.59 billion m^3). The inflow from the Taipu canal is about 5.00 billion m^3, only increases by 27.2% in comparison to that in Scenario base A (3.93 billion m^3). In terms of the major inflows into the Huangpu River, the inflow from the southwest and northwest upstream areas increase significantly in comparison to that from the Taipu canal, suggesting that the Huangpu River plays a dominant role for these two sub-areas.

Table 5 describes 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 preventing the river from tidal water intrusion. Compared to Scenario base A, the net outflow volumes at the gate site during the entire flood period in other four scenarios are increased by 4% (Scenario A1), 8% (Scenario A2), 22% (Scenario A3) and 52% (Scenario A4), respectively. Fig.11 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 clearly reflects the difference of the drainage efficiency of the Huangpu River. Although the river discharge amount in Scenario A1 is only increased by 4% for the whole flood period (from 7.20 to 7.46 billion m^3). It should be noted that the influence on the flood control during the gate operation period is more distinct because the net outflow volume is nearly doubled by changing the bi-directional flow to unidirectional flow.

5 Conclusions

Compared to a natural channel, an estuary gate can prevent the tidal water from entering the upper estuary. This study shows that constructing an estuary gate in the Huangpu River is effective in terms of evacuating floodwaters and reducing peak levels in the upper part of the river. The potential contributions of the proposed gate are closely associated with its operation time. Regarding the maximum potential contribution, the net outflow at the site of the proposed gate is increased by 52% in the entire flood period of the 1999 flood, and hence the efficiency of the drainage district from the Taihu Lake to the Yangtze River estuary is significantly improved.

Constructing the proposed gate will benefit the Taihu Lake, the related surrounding areas and the two major rivers, the Taipu canal and the Huangpu River. The inflow volumes from the upstream tributaries into the Huangpu River is increased by 27% (the Taipu canal), 78% (the north part of Hangjiahu catchment area) and 117% (the south part of the Yangchengdianmao catchment area), respectively. The daily peak level of the lake is decreased by maximum 0.12 m, in related surrounding areas between 0.05 m and 0.39 m depending on different topographies, and in the two rivers 0.26-0.37 m and 0.46-0.60 m, respectively.

The potential contribution of the gate depends on the operating time of the gate. 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, reduce the duration of high water level and decrease the flood risk of the lake and its adjoining areas upstream. For Scenario A3, it appears that flood control is more effective during spring tides. Generally, the contribution of the gate is more distinct in August than other months.

Overall, it is significant and effective to build an estuary gate at the outlet of Huangpu River to improve the flood capacity against basin-wide floods. The implementation of the gate needs further investigation, including the feasibility of economics, environment and navigation. When the operation rules of the proposed gate are formulated, much attention should be paid to the navigation in the river so as to mitigate the influence on the shipping.

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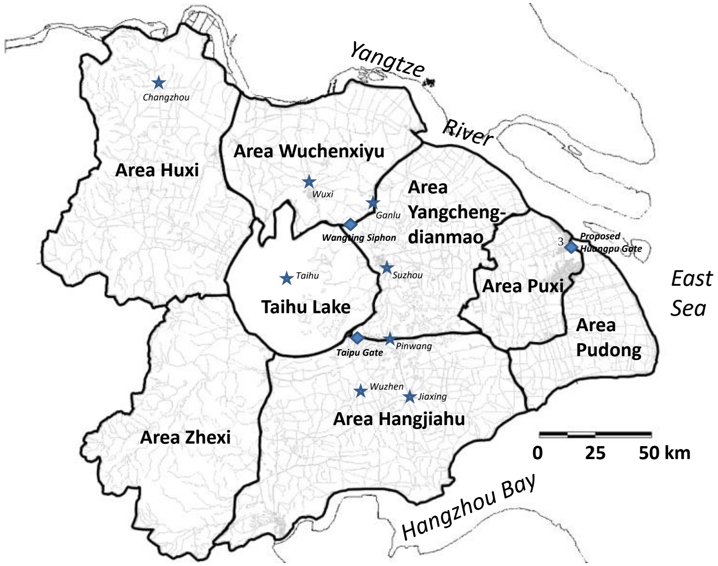


Figure 1(a): Location of the Taihu lake basin

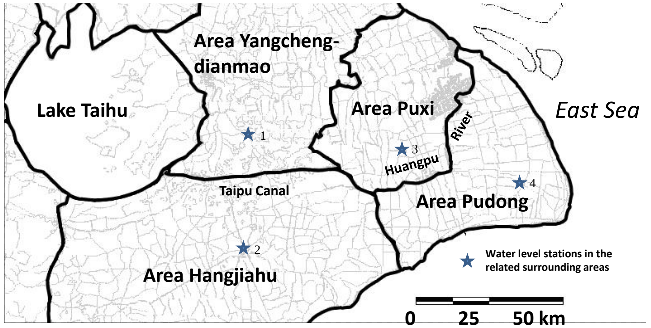


Figure 1(b): Location of water level stations in the related surrounding areas

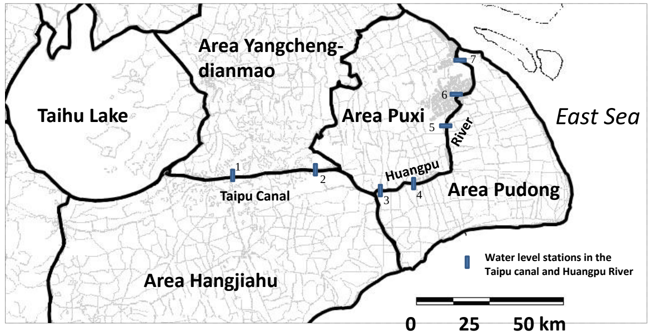


Figure 1 (c): Location of water level stations in the Taipu canal and Huangpu River

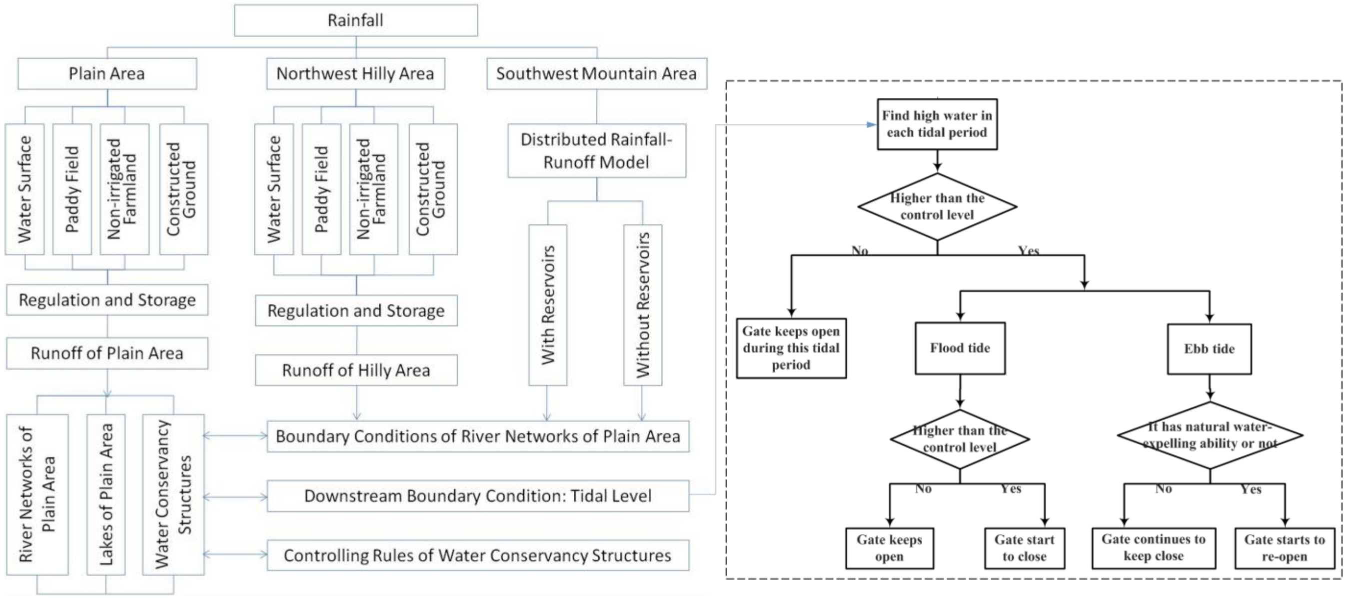
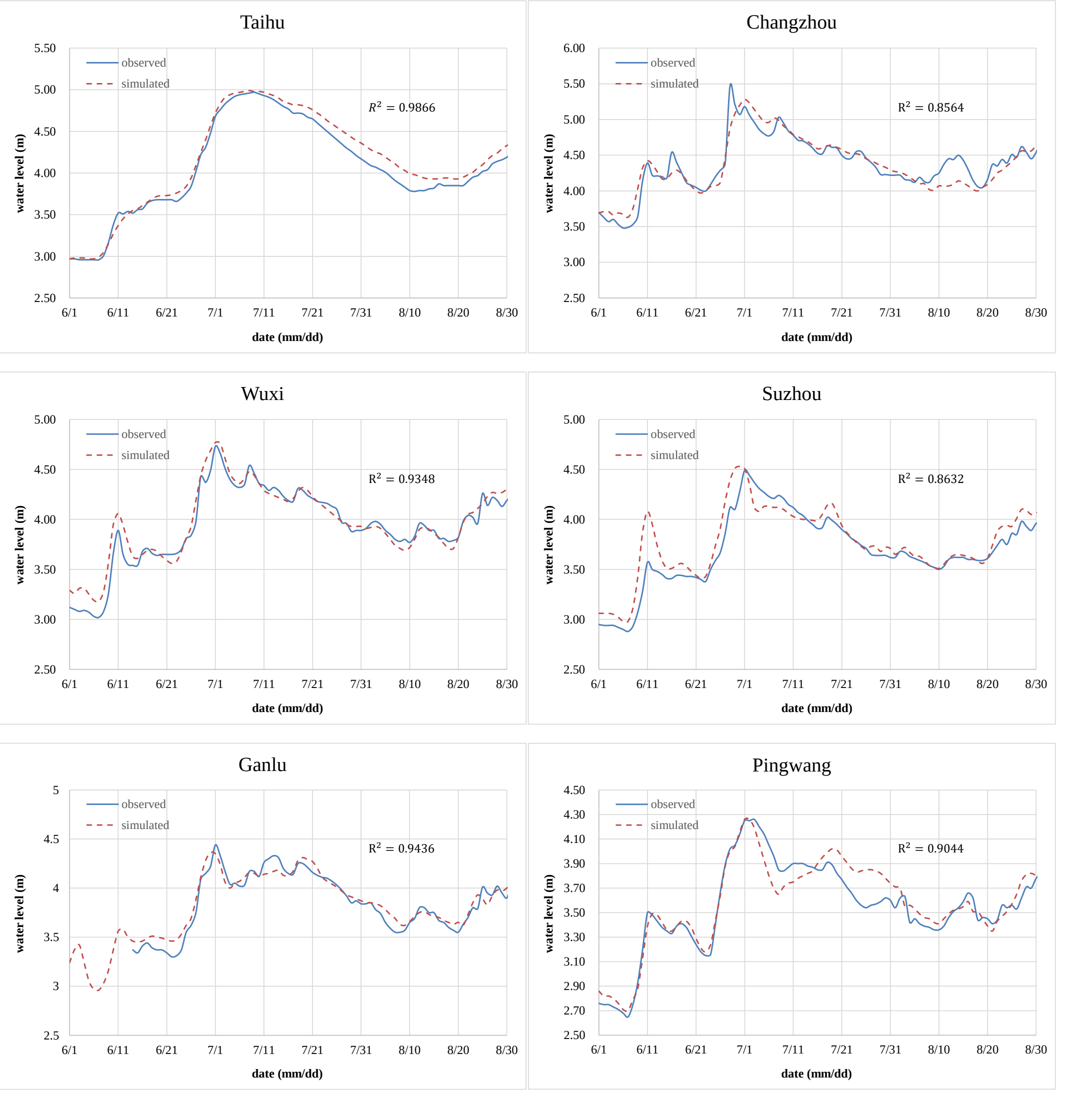


Figure 2: Schematization of the extended HOHY model (modified from Jin et al., 2008)


Taihu
water level (m)
date (mm/dd)
observed
simulated
R² = 0.9866
5.50
5.00
4.50
4.00
3.50
3.00
2.50
6/1 6/11 6/21 7/1 7/11 7/21 7/31 8/10 8/20 8/30
Changzhou
water level (m)
date (mm/dd)
observed
simulated
R² = 0.8564
6.00
5.50
5.00
4.50
4.00
3.50
3.00
2.50
6/1 6/11 6/21 7/1 7/11 7/21 7/31 8/10 8/20 8/30
Wuxi
water level (m)
date (mm/dd)
observed
simulated
R² = 0.9348
5.00
4.50
4.00
3.50
3.00
2.50
6/1 6/11 6/21 7/1 7/11 7/21 7/31 8/10 8/20 8/30
Suzhou
water level (m)
date (mm/dd)
observed
simulated
R² = 0.8632
5.00
4.50
4.00
3.50
3.00
2.50
6/1 6/11 6/21 7/1 7/11 7/21 7/31 8/10 8/20 8/30
Ganlu
water level (m)
date (mm/dd)
observed
simulated
R² = 0.9436
5
4.5
4
3.5
3
2.5
6/1 6/11 6/21 7/1 7/11 7/21 7/31 8/10 8/20 8/30
Pingwang
water level (m)
date (mm/dd)
observed
simulated
R² = 0.9044
4.50
4.30
4.10
3.90
3.70
3.50
3.30
3.10
2.90
2.70
2.50
6/1 6/11 6/21 7/1 7/11 7/21 7/31 8/10 8/20 8/30

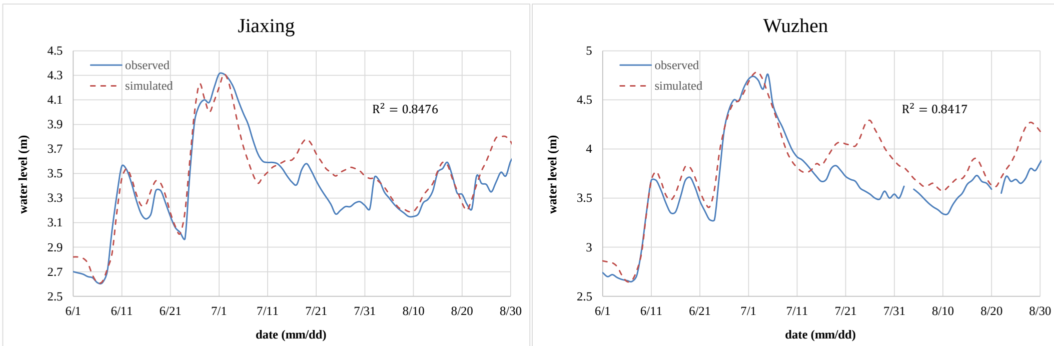


Figure 3: Comparison between water levels for the 1999 flood event at eight representative stations (from Ou& Wu, 2001)

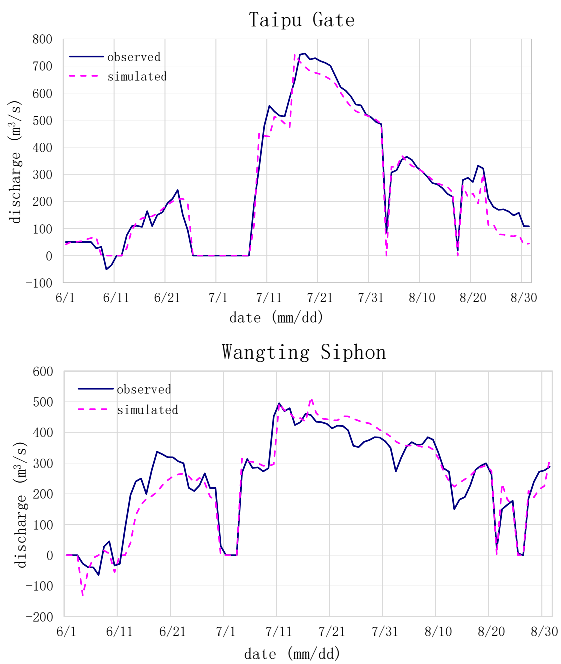


Figure 4: Comparison between daily discharges for the 1999 flood event at the Taipu Gate and Wangting Siphon (from Ou& Wu, 2001)

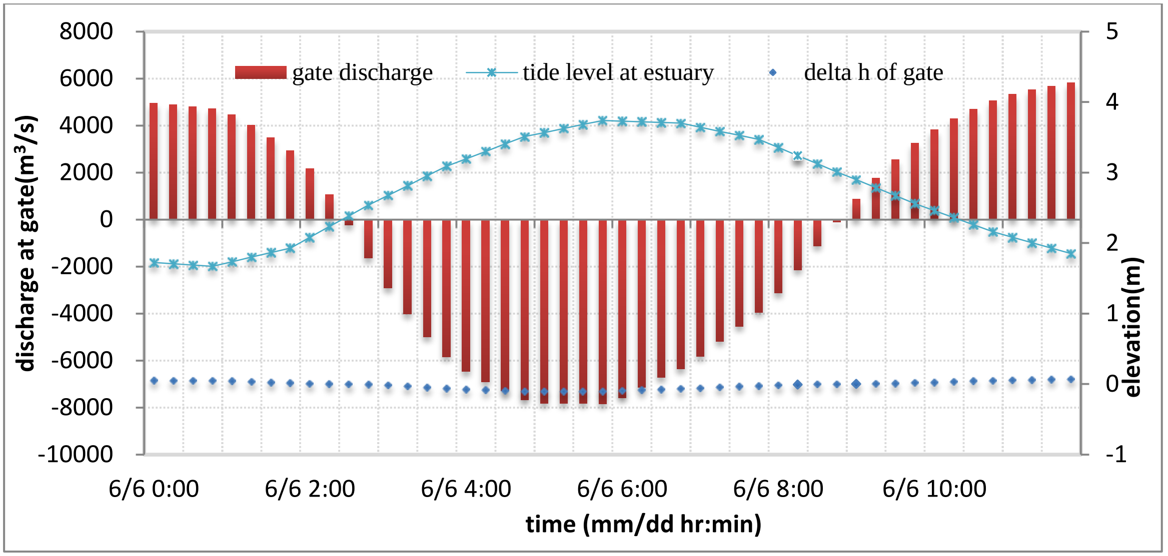


Figure5: A test example when the gate keeps open due to the high water lower than tide threshold in this tidal period (t.l.: tide level; w.l. water level; a negative discharge indicates the tidal water intrusions)

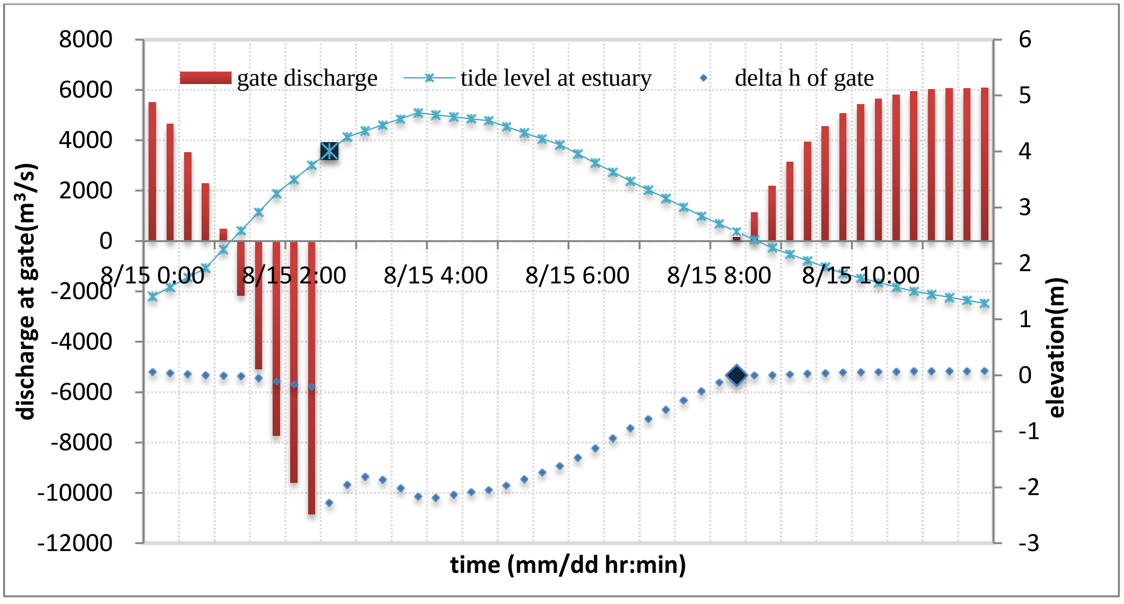


Figure6: A test example when the gate needs to be closed due to the high water higher than tide threshold in this tidal period (t.l.: tide level; w.l. water level; a negative discharge indicates the tidal water intrusions)

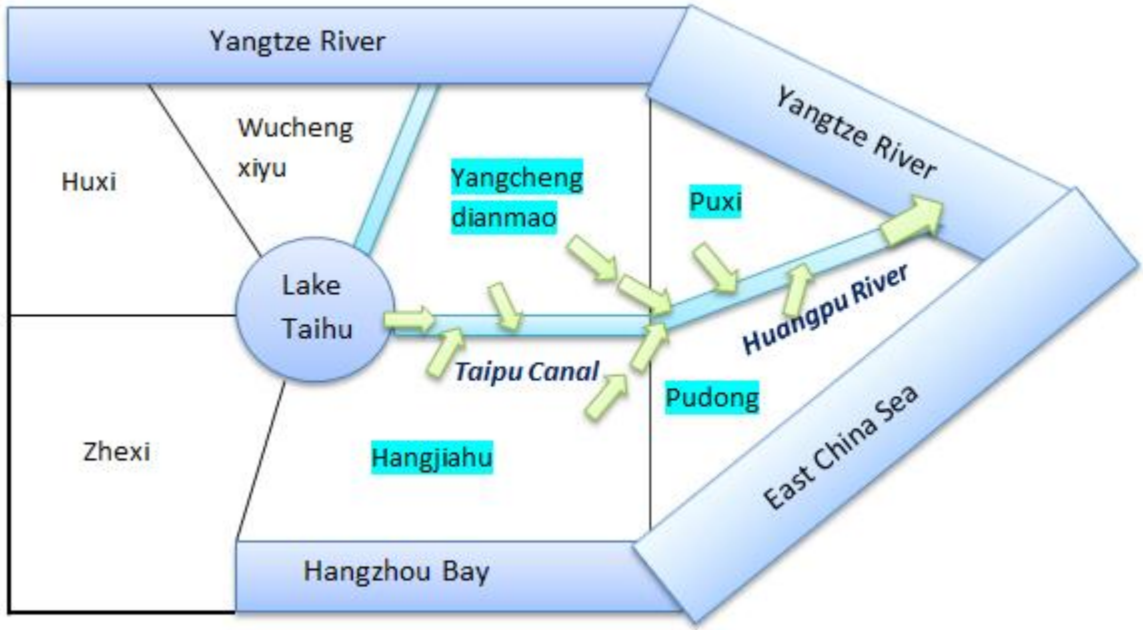


Figure 7: Conceptual drainage system along Lake Taihu – the Taipu Canal – the Huangpu River – the Yangtze River Estuary

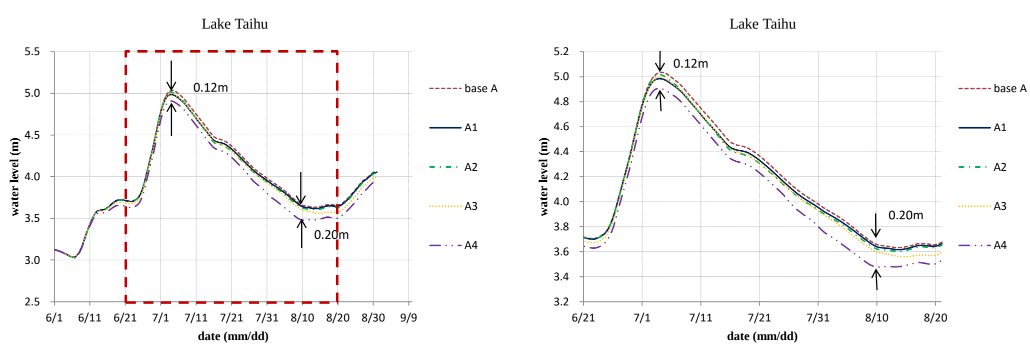


Figure 8: Comparison of the simulated daily lake levels among various scenarios from June to August, 1999

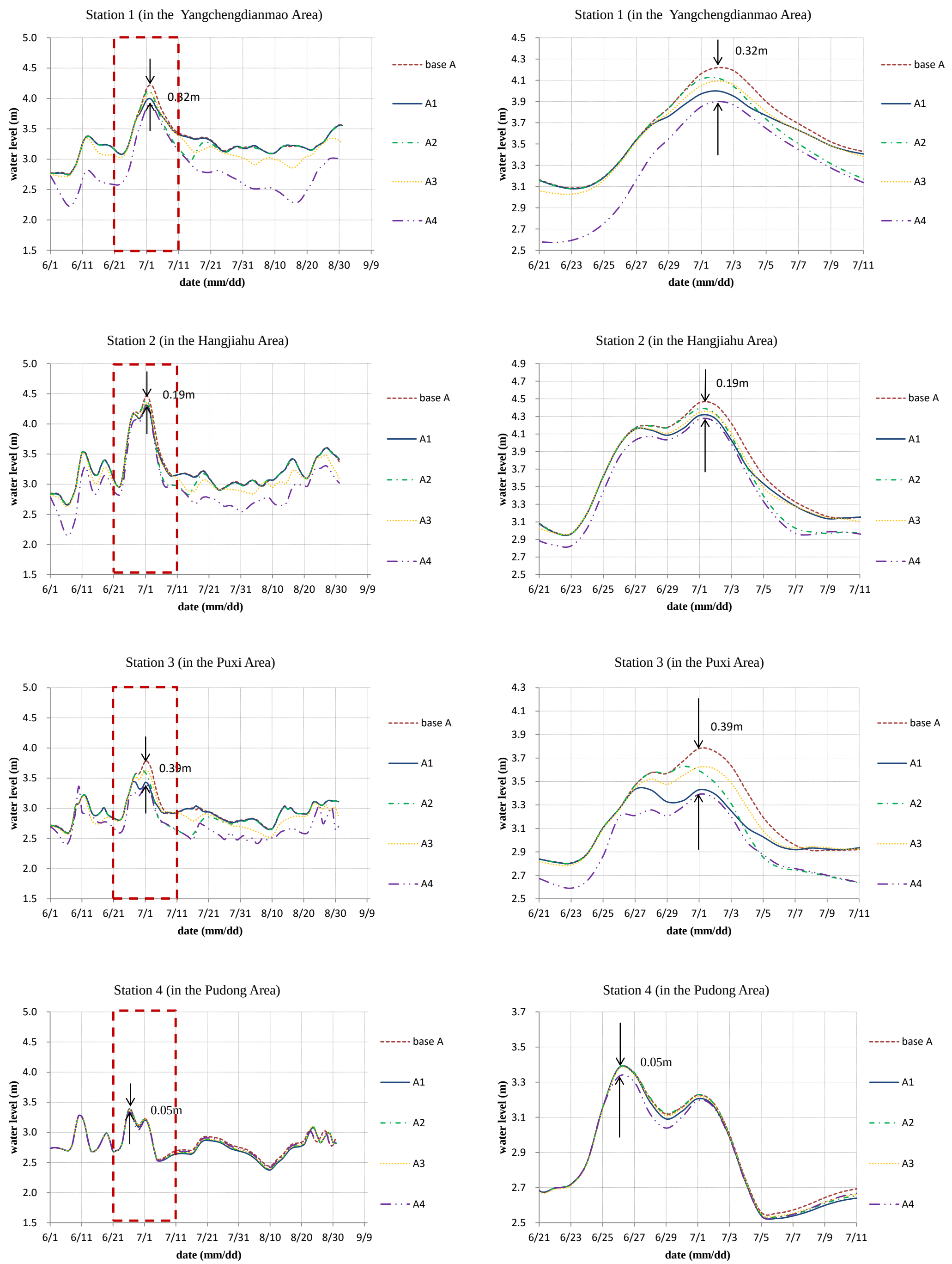
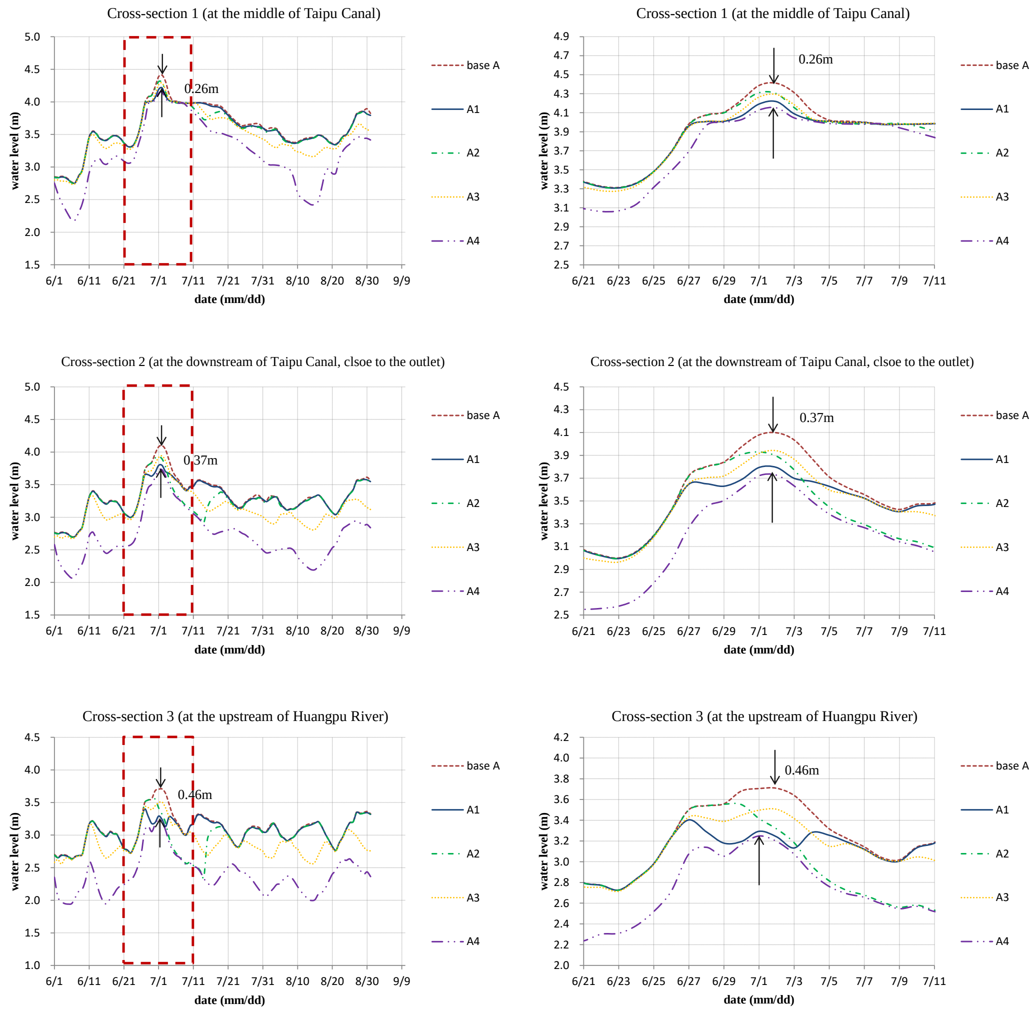

Station 1 (in the Yangchengdianmao Area)
Station 2 (in the Hangjiahu Area)
Station 3 (in the Puxi Area)
Station 4 (in the Pudong Area)
0.32m
0.19m
0.39m
0.05m
water level (m)
date (mm/dd)
base A
A1
A2
A3
A4

Figure 9: Comparison of the simulated daily water levels in the related surrounding areas among various scenarios from June to August, 1999



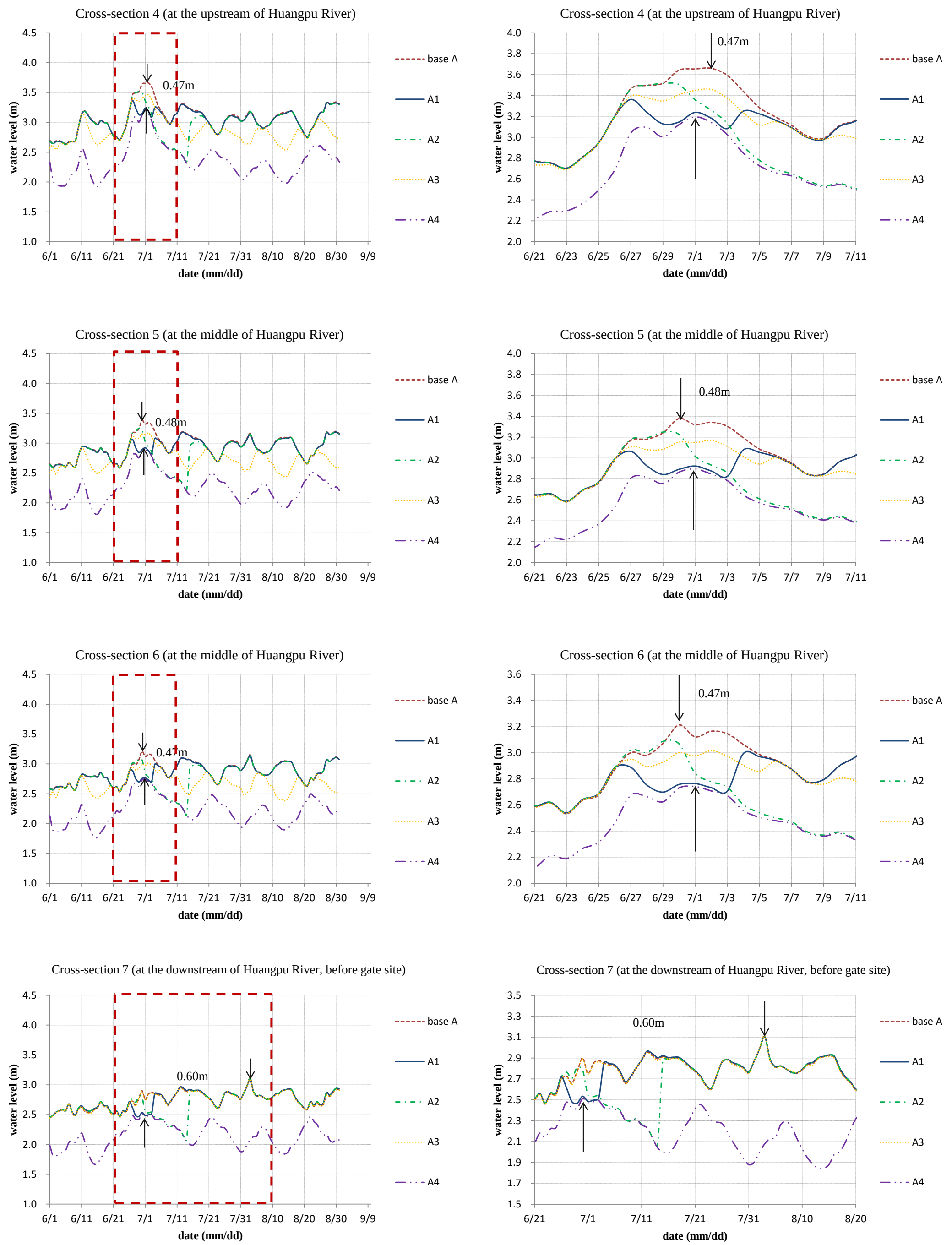

Cross-section 4 (at the upstream of Huangpu River)
0.47m
Cross-section 4 (at the upstream of Huangpu River)
0.47m
Cross-section 5 (at the middle of Huangpu River)
0.48m
Cross-section 5 (at the middle of Huangpu River)
0.48m
Cross-section 6 (at the middle of Huangpu River)
0.47m
Cross-section 6 (at the middle of Huangpu River)
0.47m
Cross-section 7 (at the downstream of Huangpu River, before gate site)
0.60m
Cross-section 7 (at the downstream of Huangpu River, before gate site)
0.60m
water level (m)
date (mm/dd)
base A
A1
A2
A3
A4

Figure 10: Comparison of the simulated water levels in the Taipu canal and Huangpu River from June to August, 1999

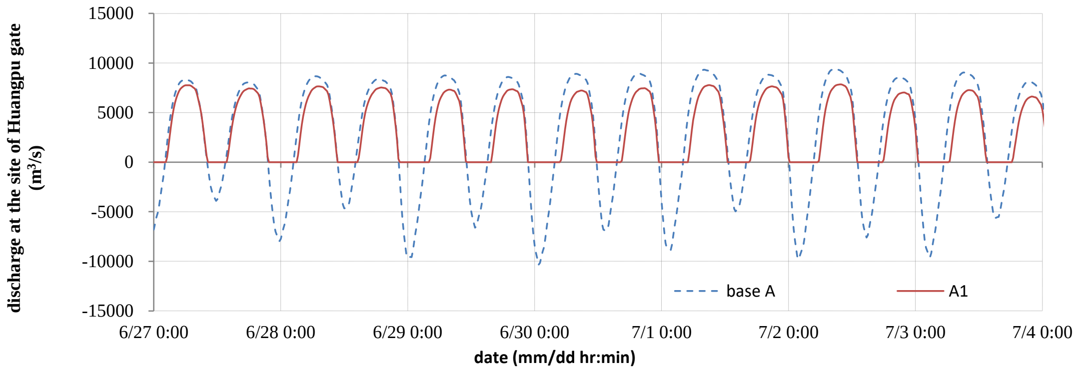


Figure 11: Comparison of discharges at the site of the proposed gate between the scenarios base A and A1 from June 27th to July 3rd, 1999 (negative discharges means the tidal water intrusion)

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 meanthatlake 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 to4.0m)
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, 1999

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 (unit: m)

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**

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	7.45	14	from Jun. 27th to Jul. 3rd
A2	14.14	21.94	7.80	30	from Jun. 30th to Jul.14th
A3	10.78	19.58	8.80	74	until high tide rises up to 4.0m
A4	0	10.95	10.95	184	from Jun. 1st to Aug. 31st