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, one of the most developed regions, is located in the hinterland of the Yangtze River Delta, Eastern China. In this basin, the largest flood in history occurred in 1999, which was estimated to have a return period of 1 in 200 years, much higher than the current capacity of flood defense (1 in 50 years). Due to its flat saucer-like terrain, the capacity of the flood control system is dependent on the flood control infrastructure and the peripheral tidal conditions. The Huangpu River is a quite important river that connects the Taihu Lake upstream and the Yangtze Estuary downstream, and two-fifth of floodwaters in the basin are drained by this river. However, it is strongly affected by the high tide conditions in the estuary. Hence, constructing an estuary gate is considered as one of the most effective solutions to the flooding problem in the basin. This paper aims to quantitatively analyse the potential contributions of the proposed Huangpu gate to flood control capacity of the basin under various flooding scenarios. The results show 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 and the duration of high water levels. It will benefit the Taihu Lake, the related surrounding areas along the Taipu Canal and the Huangpu River basin.

Keywords: Flood control; Huangpu Gate; Taihu Lake Basin; Tidal effect; HOHY model;

1 Introduction

An estuary is a partly enclosed body of water where freshwater from rivers, streams and groundwater flows to the ocean, and mixes 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 affected population live in Asia is mega-deltas and deltas. The Yangtze River delta is one of the highly vulnerable coastal deltas identified by IPCC (2007).

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, a combination of flood defense walls and estuary barriers has been used as an alternative flood control infrastructure in Japan, England, Netherland and other low-lying countries. The Thames barrier in UK, which has been successfully operating for more than 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 metropolises 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 aging 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 the high tide is 1 in 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 initial 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 lacks 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; Shao and Yao, 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). Little research 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. 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). By the end of 2015, the area of the basin including its relevant regions amounts to 36,895 km^2, accounting for only 0.4% of the national total, while the Gross Domestic Product (GDP) amounts to RMB 6.69 trillion, accounting for about 10% of national total. 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 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 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, which was three times more than the long-term average with a nearly sixty-year period 1954- 2010. It was estimated to have a return period of 1 in 200 years (Evans & Cheng, 2010), much higher than 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 the 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, 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. Statistically, 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 the upstream area is about 10.02 billion m^3 per year.

3 Methodology

3.1 Scenario description

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. Since then, they have been used in a variety of fields, such as the 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.

‘Scenario base A’ is the case that the estuary gate would not be constructed at the mouth of the Huangpu River. Thus, the water in the Huangpu River and the Yangtze River estuary can exchange naturally.

‘Scenario A1’ means 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.

‘Scenario A2’ means the proposed gate will be operated when large basin-wide floods occur, i.e. the lake level is higher than 4.50m, which means the flood situation of Lake Taihu is very severe and need to accelerate the drainage rate of the major draining rivers downstream.

‘Scenario A3’ is to block part of tidal water intrusion, 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 in flood tides and expected to continue to rise based on weather forecast.

‘Scenario A4’ is a hypothetical condition since the gate would prevent all the intrusion of tidal water during the flood period. It is obviously not practical due to the difficulty of frequently operating such a huge gate with a width of 400 - 500m (i.e. to close twice every day). This scenario is purely taken as 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 cutting off water exchange between the two river systems. It is also likely to produce a negative impact on waterway transportation and water environment system.

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). Also, parameters in the model are the same as those used in the Plan (MWR, 2008). Hu (2006) presented the an ehorage ground is the best gate site in the HuangPu River for it is in the first regular bank and its influences to the shipping are much less. Some studies about the potential contributions of the gate are also based on this site (Cui, 2012; Lu, 2008). In this study, the estuary gate will be constructed at the site of an ehorage ground which is about 6 kilometres from the river mouth.

3.2 Model development

The HOHY model, developed by the Hohai University, China, is chosen for scenario analysis. This model for local area application was started in 1970s, began to cover the whole basin in 1994, and completely finished in 1997. It is one of the outcomes 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. Not only can it simulate complex hydro-systems with numerous interlaced rivers and lakes, and complicated relationships between river nets, hilly areas and tidal boundaries, it also can simulate complex operational rules of control structures, such as sluices, pumps and siphons. It has been used in 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 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 independently. The schematization of the model is shown in Fig. 2. More details of the model are discussed as follows and from the reference by 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 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 1985 (Liang et.al, 1993), 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. Fig. 3 shows the differences between the simulated and observed water levels in the 1999 flood at eight representative stations of various sub-areas. Fig. 4 shows the differences between the observed and simulated discharges at the Taipu Gate and Wangting Siphon respectively, and the positions of the Taipu Gate and Wangting Siphon are as shown in Fig. 1(a). As can be judged from these comparisons of water levels and discharges, the HOHY model simulations are of sufficiently high accuracy for scenario analyses.

Among these five scenarios, the operational rules in ‘Scenario A3’ are the most complex to simulate using the HOHY model, where different operational rules of the gate will be applied for the flood tide and ebb tide, respectively. Specifically, the operational rules are as follows: If the high water in flood tide is higher than the tide threshold, the gate will be closed; otherwise it keeps open for water transportation. 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 main Fortran codes of the model are revised to accommodate additional capabilities needed 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 according to the flowchart given in Fig. 2 with table gridlines.

The modified model is tested by using a simple example, where the tide threshold is assumed to be 4.0m, with the simulation results 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 4.0m, so the gate does not need to be closed to prevent high tides. For a comparison purpose, the second graph is the case when the gate has to be closed due to rising tide higher than 4.0m. And then the gate will re-open to drain floodwater as long as the gate has natural water-expelling ability to evacuate floodwater in the ebb tide.

Here, three computed results, including the gate discharge, tide water level at the estuary and the difference of water levels between the directly upstream and downstream of the proposed gate, are used to explain the logical relationship of the gate’s operational rules. It can be seen in Fig.5 that the discharge at the gate seems like a sinusoidal curve affected by the tidal boundary. The reason lies in that the gate needs not to be closed due to the high water in this tidal period less the tide threshold of

4.0m. On the other hand, Fig.6 is another case of the gate's operational rules of which the high water is about 4.70m. At the moment of August 15th 2:30 am, the tide level at the estuary in the flood tide slightly exceeds the tide threshold of 4.0m, and the gate has to be closed. It was not re-opened in the ebb tide until at August 15th 8:15 am when the difference of water levels between the upstream and downstream near the proposed gate shows positive, which means the gate has the natural water-expelling ability to drain floodwater at this moment. The red bars of gate discharges also agree with this conclusion (Fig.6). Overall, the model after modification has the capacity to be used for complex operational rules of water-engineering works.

4 Results 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, as shown in Fig.7. Therefore, the potential contribution analysis 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 the Huangpu River.

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

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 Lake Taihu from June 1st to August 31st occurred in 1999 flood event. It can be observed that the lake levels in Scenarios A1, A2, A3 and A4 are all lower than that in Scenario base A, meanwhile the durations when the water level is higher than different control levels are also shortened accordingly. Compared with the peak lake-level in 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 the difference in the designed water levels is not too much 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 4.80m, 0.15m higher than that of 50-year return period. For this reason, the decrease in the peak lake level by 0.04m in Scenario A1 is rather significant for the flood control of the lake, needless to say decrease of 0.12m in Scenario A4. Moreover, 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 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 more time the gate is operated, the more tidal water will intrude into the Huangpu River estuary. It will reduce 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 more 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 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

As shown in Fig.7, 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 discharged into the Huangpu River. Therefore, the safety of these four areas against flooding is also closely related 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).

As shown in Fig.9, simulation results of these four stations show the similar trends as that of Lake Taihu. 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 0.32m, 0.19m, 0.39m, and 0.05m, respectively. In contrast, the improvement of the flood control capacity in station 4 is relatively small among these four stations due to its terrain, and the local floodwater in the Pudong catchment 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 Station 4 does not depend on the drainage capacity of the Huangpu River as much as the other three stations.

In 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, 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

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 if the tidal estuary gate is operated. Scenario A4 represents the potential maximum contributions due to its prevention of all tidal water intrusion, in which the maximum reduction of the peak water level 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. 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 distinctly than the Taipu canal.

In Scenario A1, the gate is operated in advance in the rising stage of the lake level, and the peak flood level value in these two rivers can be apparently decreased due to the enlargement of the drainage capacity of the Huangpu River in this period. In Scenario A2, the gate is operated when the lake level is higher than 4.5m, 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 these two rivers 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, as shown in 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 an extremely crucial 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 increase by 4% (Scenario A1), 8% (Scenario A2), 22% (Scenario A3) and 52% (Scenario A4), respectively. To illustrate this point, 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 only increases 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, constructing an estuary gate in the Huangpu River is more effective in terms of evacuating floodwaters and reducing peak levels in the upper part of the river because the gate can prevent the tidal water from 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 at the site of the proposed gate increases by 52% in the entire flood period of the 1999 flood, and hence the efficiency of the drainage district from the lake to the Yangtze River estuary is effectively improved.

Constructing the proposed gate will benefit Lake Taihu, the related surrounding areas and the two major rivers of the Taipu canal and the Huangpu River. The inflow volumes from the upstream tributaries into the Huangpu River increase 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 decreases 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. Thus the gate's contribution is more distinct in August than other months.

Overall, 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 the feasibility of economics, environment and navigation. When the operation rules of the proposed gate is formulated, much attention should be paid to the navigation in the river to mitigate the influence on the shipping as less as possible.

Acknowledgements

This study was sponsored by the Chinese National Science & Technology Pillar Program (No. 2014BAL05B02) and the program of the National Natural Science Foundation of China (No. 41672230).

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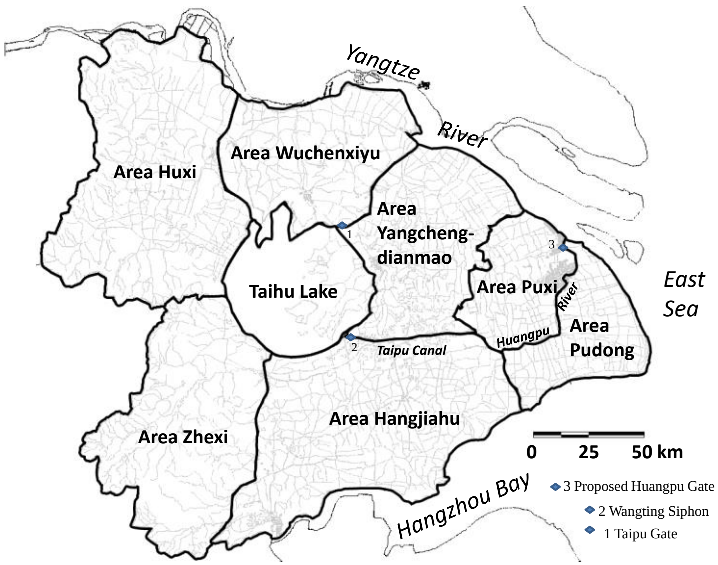


Figure 1(a): Location map of the Taihu lake basin

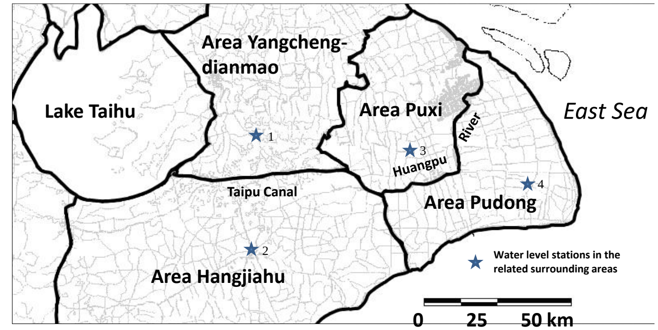


Figure 1(b): Location of water level stations in the related surrounding areas

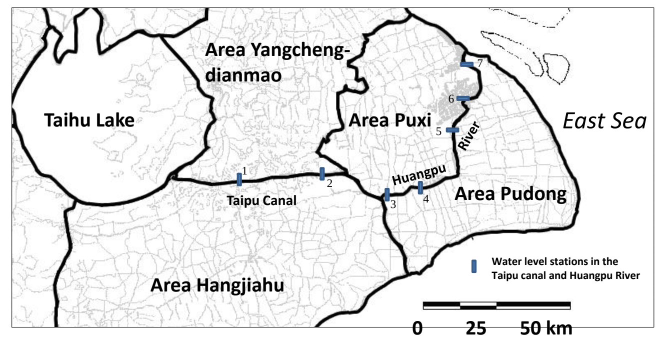


Figure 1 (c): Location of water level stations in the Taipu canal and Huangpu River

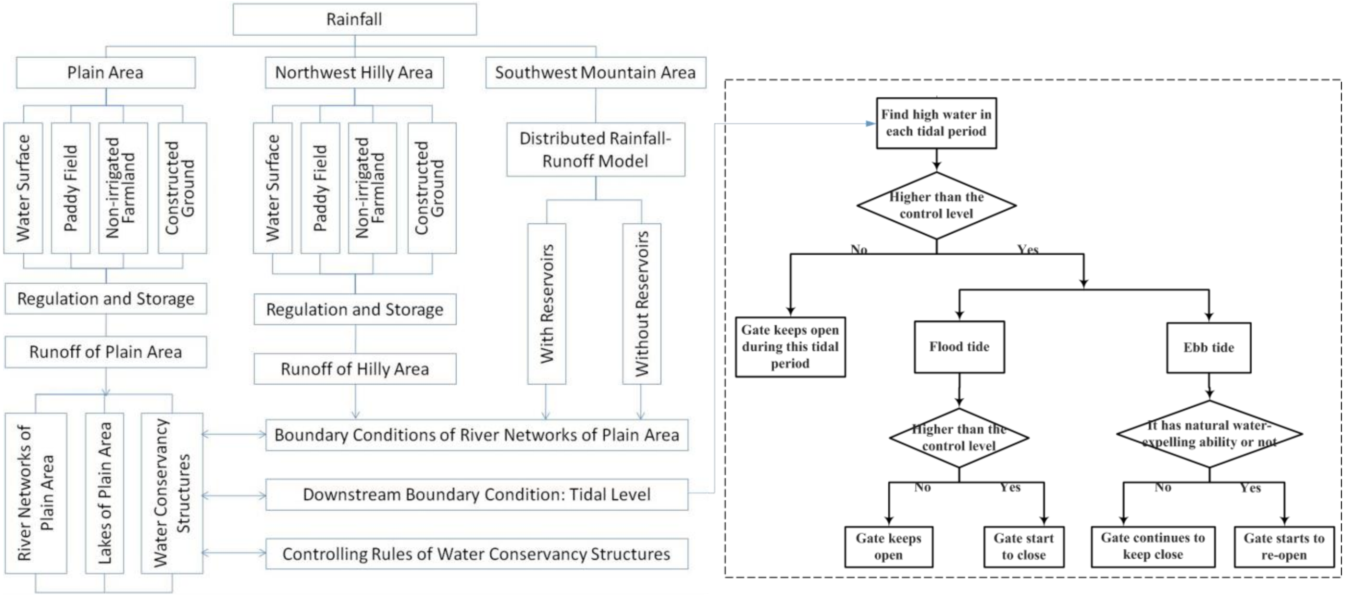
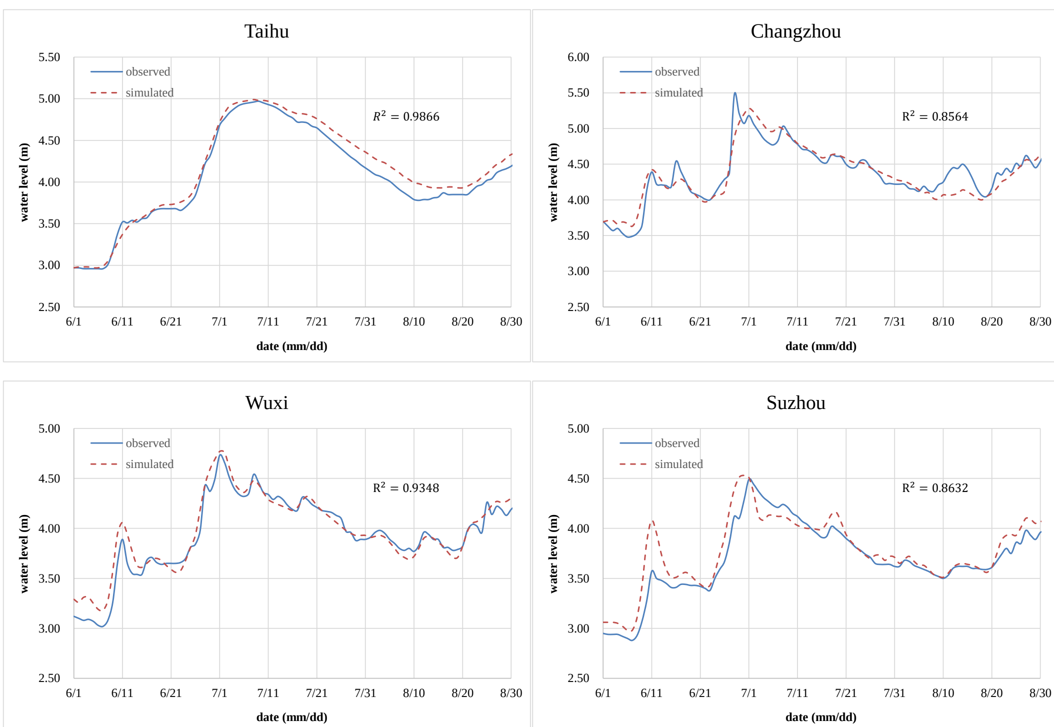


Figure 2: Schematization of the extended HOHY model (modified from Jin et al., 2008)



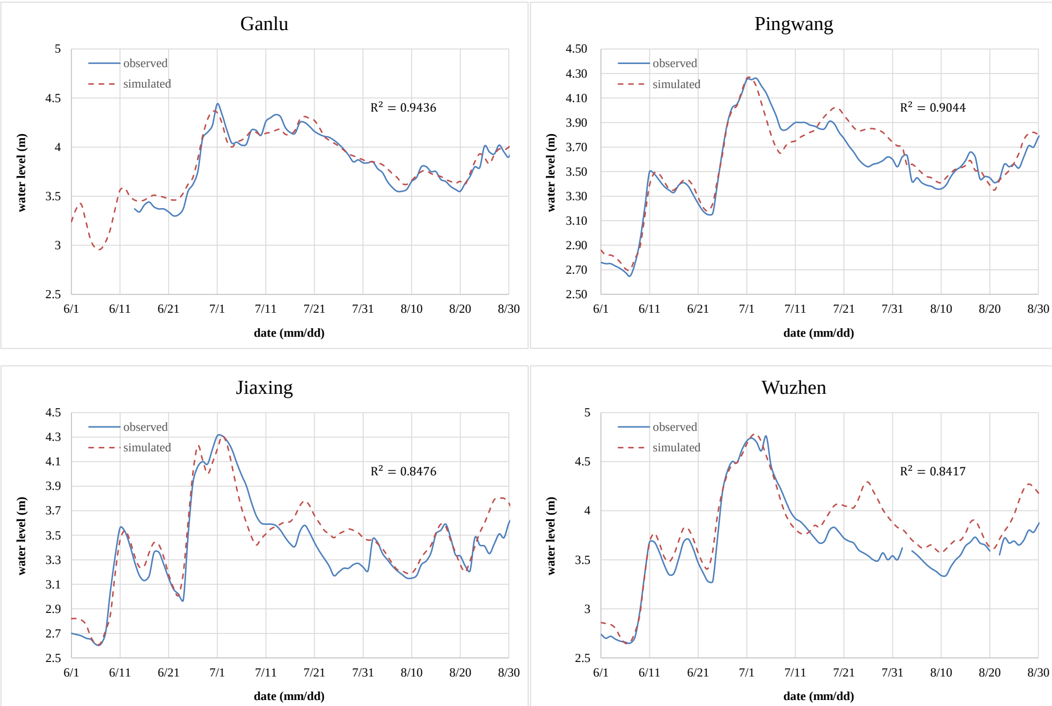


Figure 3: Comparison between observed (solid line) and simulated (dash line) water levels at eight representative stations (from Ou & Wu, 2001)

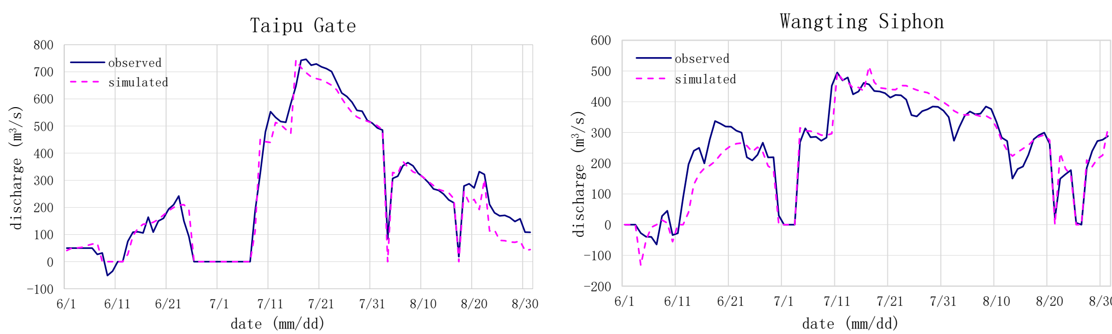


Figure 4: Comparison between observed (solid line) and simulated (dash line) daily discharges at the Taipu Gate and Wangting Siphon (from Ou & Wu, 2001)

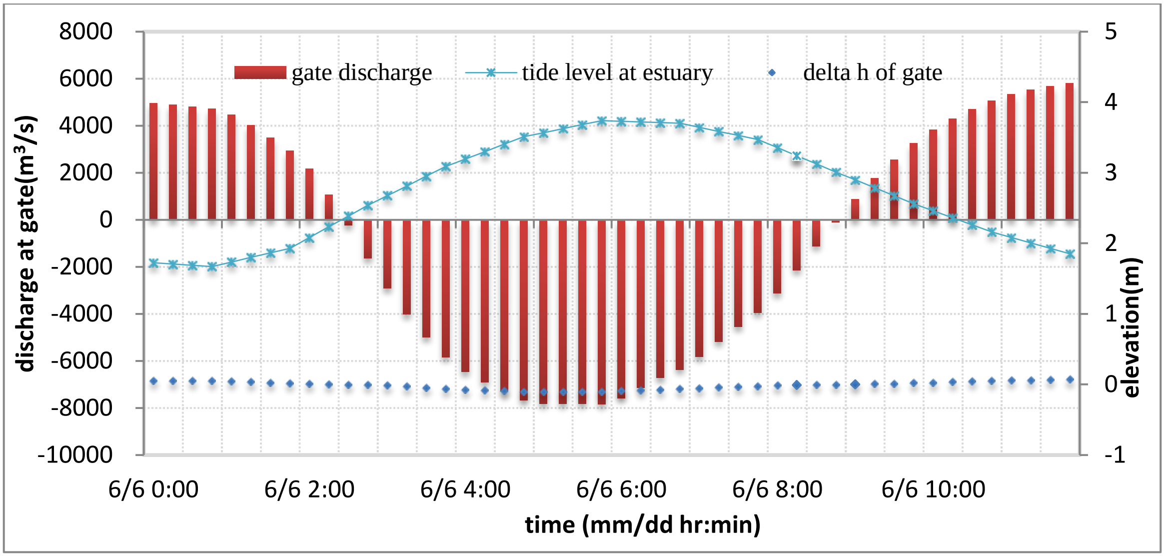


Figure5: A test example when the gate is keeping open due to the high water lower than tide threshold in this tidal period (t.l.: tide level; w.l. water level; a negative discharge indicates the tidal water intrusions)

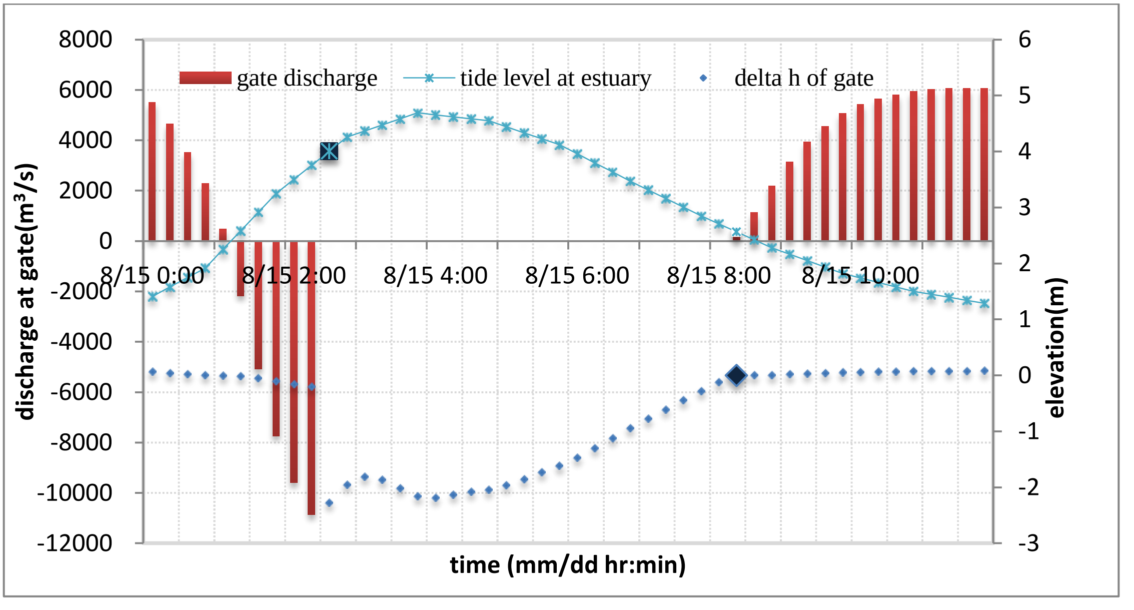


Figure6: A test example when the gate has to be closed due to the high water higher than tide threshold in this tidal period (t.l.: tide level; w.l. water level; a negative discharge indicates the tidal water intrusions)

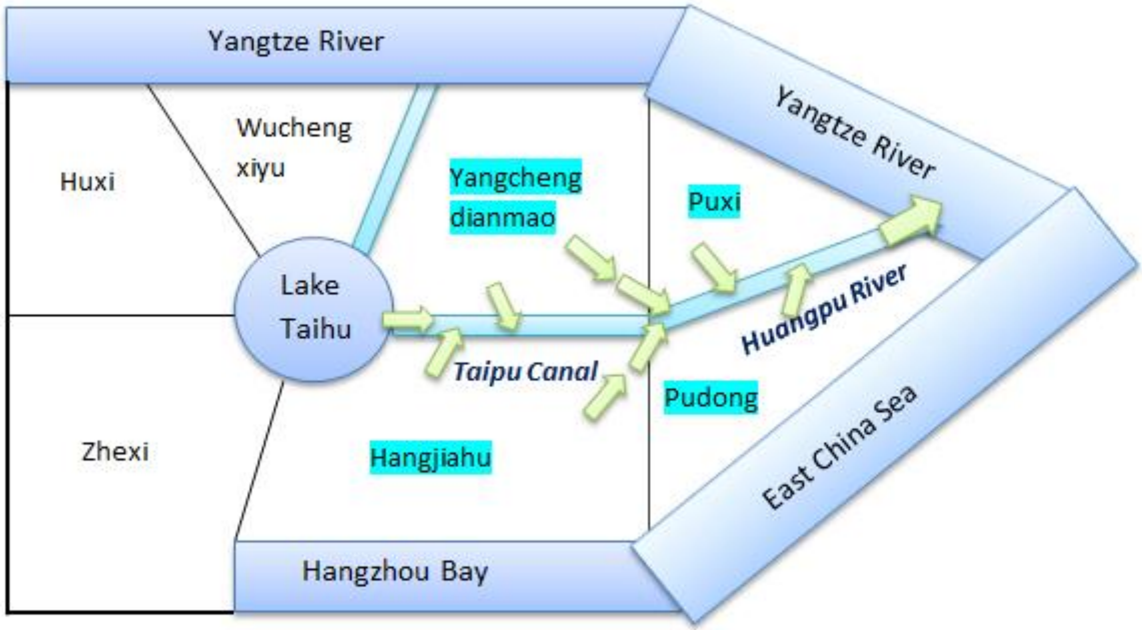


Figure 7: Conceptual drainage system along Lake Taihu – the Taipu Canal – the Huangpu River – the Yangtze River Estuary

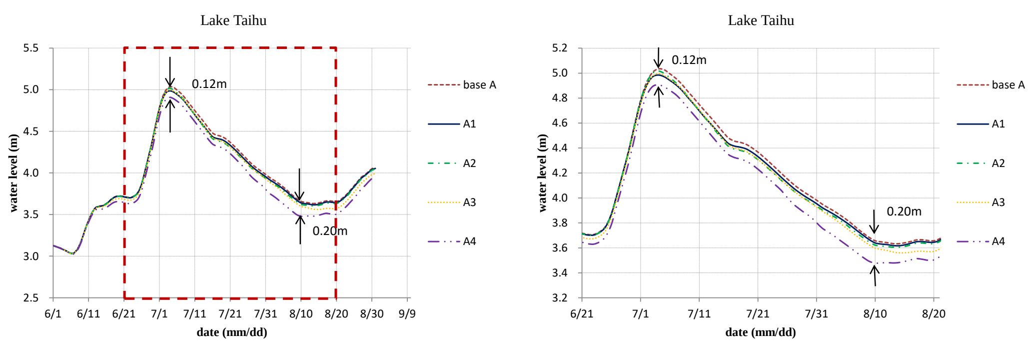


Figure 8: Comparison of the simulated daily lake levels among various scenarios

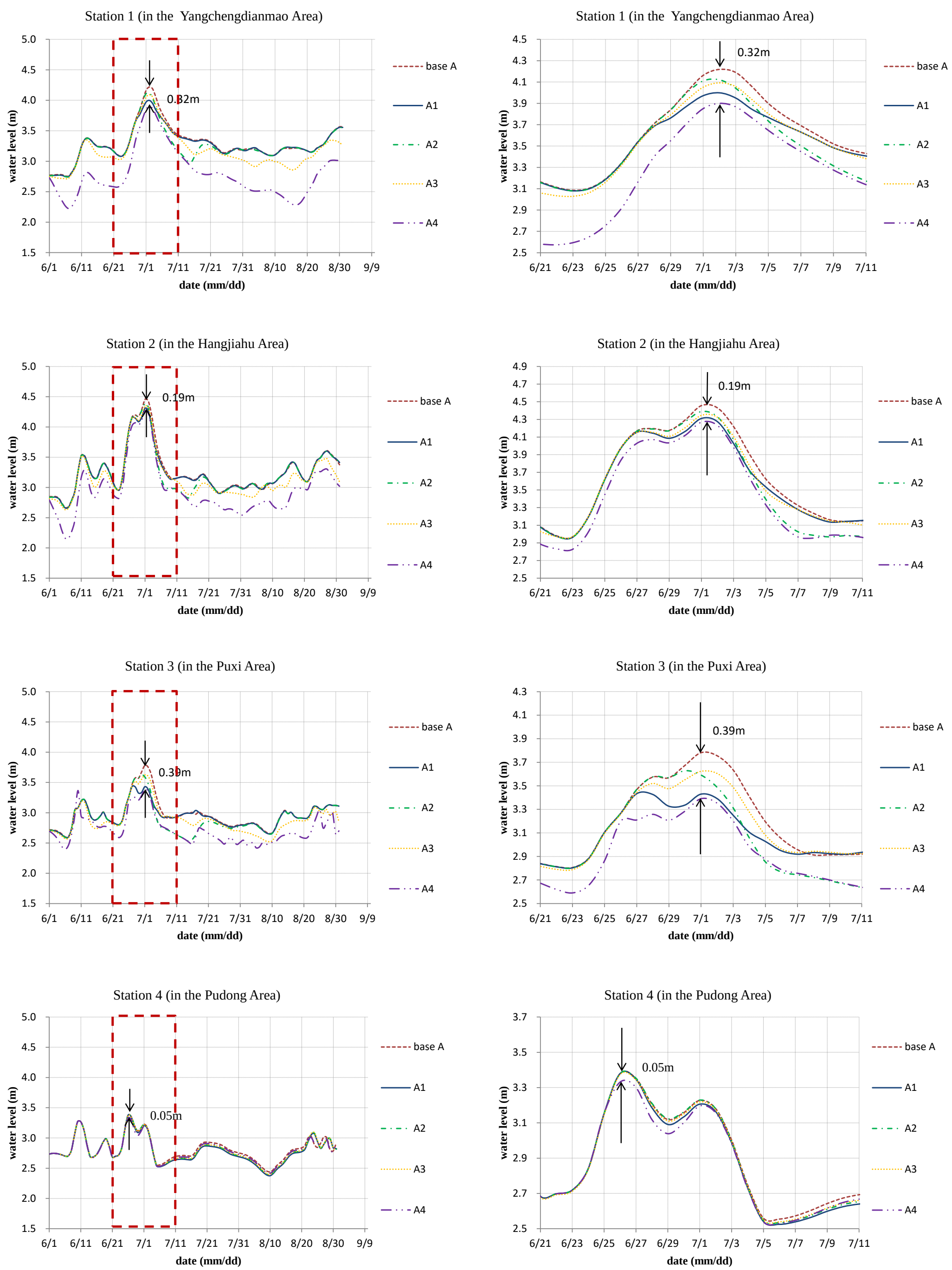
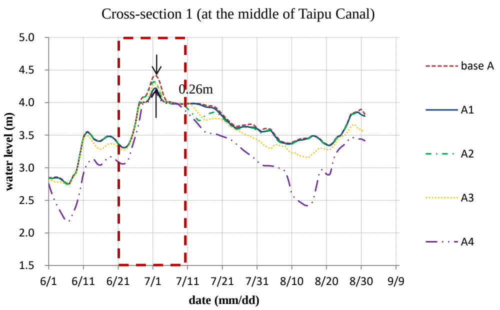
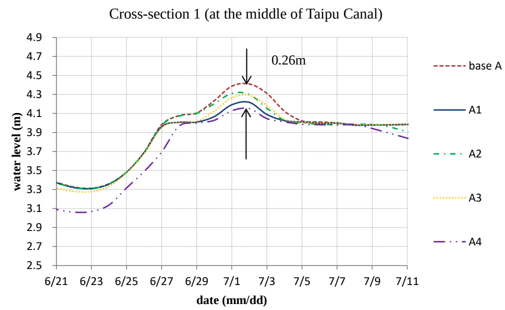
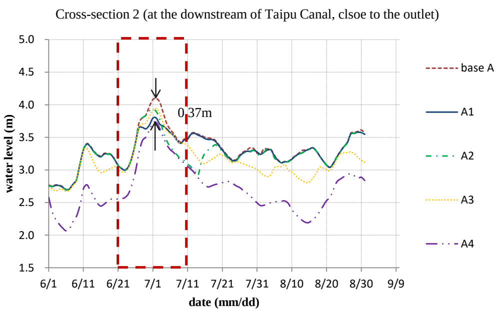
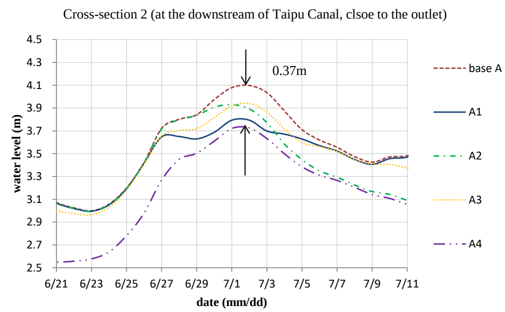


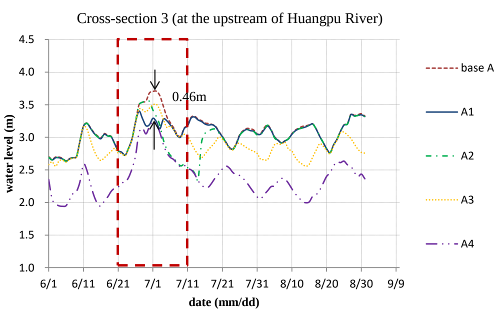
Figure 9: Comparison of the simulated daily water levels in the related surrounding areas among various scenarios

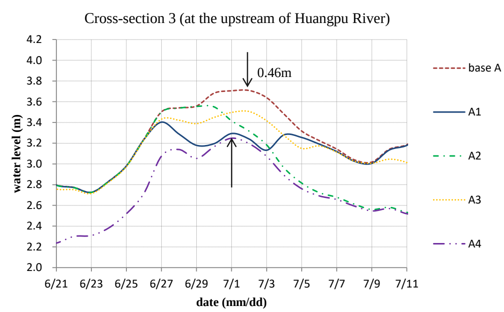

Cross-section 1 (at the middle of Taipu Canal)
water level (m)
date (mm/dd)
0.26m
base A
A1
A2
A3
A4

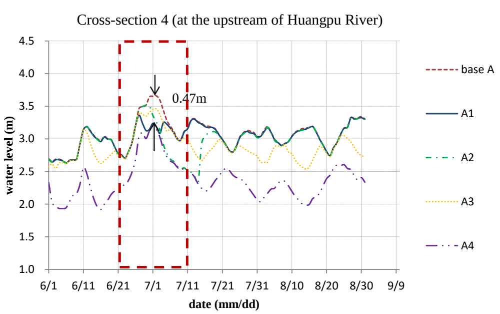

Cross-section 1 (at the middle of Taipu Canal)
water level (m)
date (mm/dd)
0.26m
base A
A1
A2
A3
A4

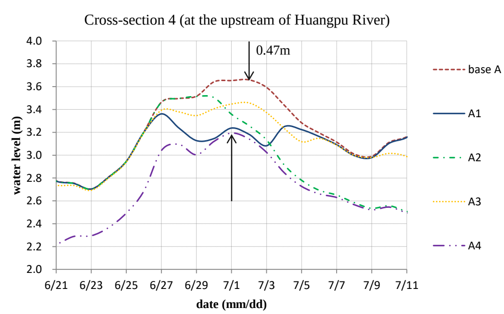

Cross-section 2 (at the downstream of Taipu Canal, clsoe to the outlet)
water level (m)
date (mm/dd)
0.37m
base A
A1
A2
A3
A4


Cross-section 2 (at the downstream of Taipu Canal, clsoe to the outlet)
water level (m)
date (mm/dd)
0.37m
base A
A1
A2
A3
A4


Cross-section 3 (at the upstream of Huangpu River)
water level (m)
date (mm/dd)
0.46m
base A
A1
A2
A3
A4


Cross-section 3 (at the upstream of Huangpu River)
water level (m)
date (mm/dd)
0.46m
base A
A1
A2
A3
A4


Cross-section 4 (at the upstream of Huangpu River)
water level (m)
date (mm/dd)
0.47m
base A
A1
A2
A3
A4


Cross-section 4 (at the upstream of Huangpu River)
water level (m)
date (mm/dd)
0.47m
base A
A1
A2
A3
A4

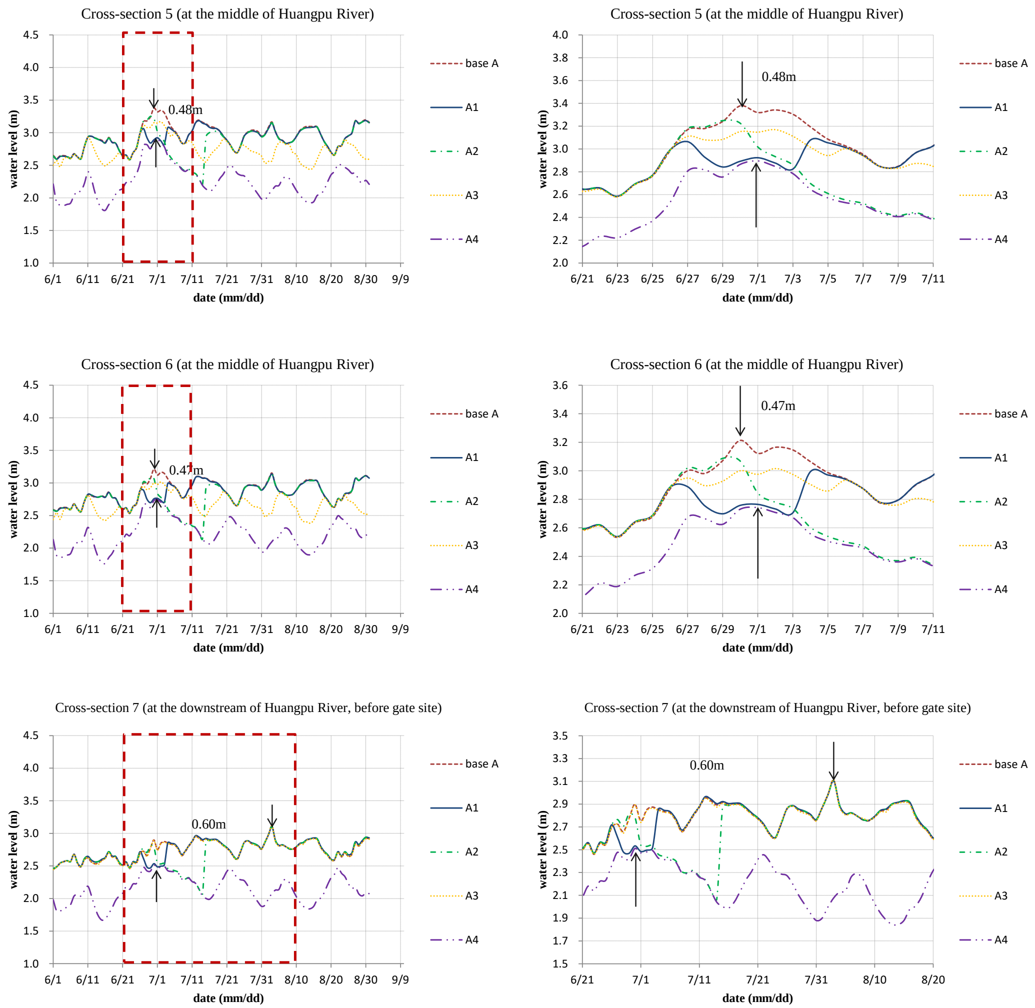


Figure 10: Comparison of the simulated water levels in the Taipu canal and Huangpu River from June to August, 1999

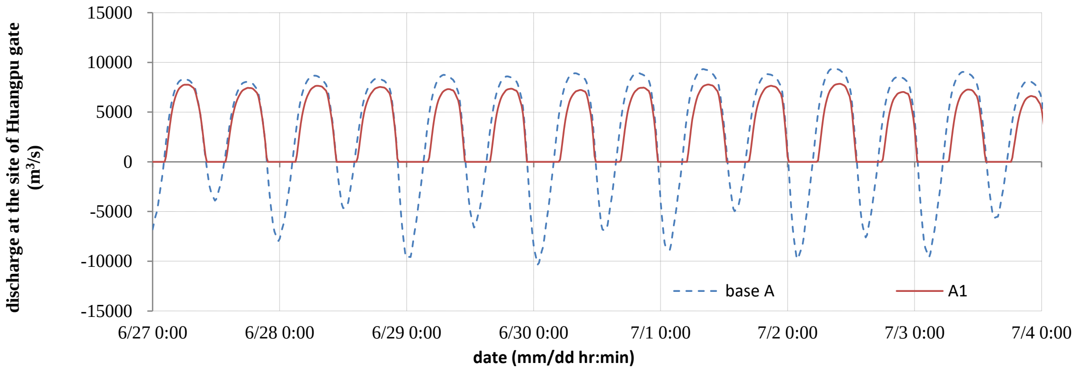


Figure 11: Comparison of discharges at the site of the proposed gate between the scenarios base A and A1 from June 27th to July 3rd (negative discharges means the tidal water intrusion)

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 meanthat 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 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