Numerical Simulations of Potential Contribution of the Proposed Huangpu Gate to Flood Control in the Taihu Lake Basin of China

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Abstract. The Taihu Lake basin (36,895 km^2), one of the most developed regions in China located in the hinterland of the Yangtze River Delta, has experienced increasing flood risk. The largest flood in history occurred in 1999 with a return period estimate of 200 years, considerably larger than the current capacity of flood defense with the design return period of 50 years. Due to its flat saucer-like terrain, the capacity of the flood control system in this basin depends on flood control infrastructures and peripheral tidal conditions. The Huangpu River, an important river of the basin connecting the Taihu Lake upstream and Yangtze River estuaries downstream, drains two-fifth of the entire basin. Since the water level in Huangpu River is significantly affected by the high tide conditions in estuaries, constructing an estuary gate is considered as an effective solution for flood mitigation. The main objective of this paper is to assess the potential contributions of the proposed Huangpu gate to the flood control capacity of the basin. To achieve this goal, five different scenarios of flooding conditions and the associated gate operations are considered by using numerical model simulations. Results of quantitative analyses show that the Huangpu gate is effective to evacuate floodwaters. It can help to reduce both peak values and duration of high water levels in the Taihu Lake to benefit surrounding areas along the Taipu Canal and Huangpu River. The contribution of the gate to the flood control capacity is closely associated with its operation modes and duration. For the maximum potential contribution of the gate, the net outflow at the proposed site is increased by 52%. The daily peak level is decreased by a maximum of 0.12m in the Taihu Lake, by a maximum of 0.26-0.37m and 0.46-0.60m in the Taipu Canal and Huangpu River, respectively, and by 0.05-0.39m in the surrounding areas depending on local topography. It is concluded that the proposed Huangpu gate can reduce flood risk in the Taihu Lake basin, especially in those low-lying surrounding areas along the Taipu Canal and Huangpu River significantly, which is of great benefits to the flood management in the basin and the Yangtze River Delta.

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

1 Introduction

The Huangpu River, located in the downstream part of the Taihu Lake basin, is the main shipping and drainage route to the port city Shanghai in China. It flows through the urban core of Shanghai city, which is evaluated as one of the most vulnerable metropolises to extreme flood disasters in the world (Balica et al., 2012). Wang et al. (2012) predicted that half of Shanghai will be flooded and 46% of seawalls and levees will be overtopped in 2100, causing serious urban flooding. Typhoon is one of main natural factors to trigger flood disasters in this area. When typhoon comes, the concomitant storm surges will be driven into the Yangtze River estuaries to further increase storm tide levels due to the shallow waters and confined dimensions within the estuaries (Nai et al., 2004). When this coincides with the astronomical high tides, the storm tide traveling into the Huangpu River can rapidly raise water levels in river and possibly cause inundation of the urban areas of Shanghai. It has been reported that along with global climate change, the frequency and intensity of typhoons have increased substantially (Qin et al., 2005).

The Taihu Lake is located about 80 kilometers away west of the Shanghai city center (Fig. 1). The Huangpu River is the major river draining floodwaters of both Shanghai city and the Taihu Lake basin. After the completion of eleven key projects for the integrated water resources management in the basin, the discharge from the upper reach of Huangpu River is increased, resulting in a considerable water level rise in the Huangpu River (Zhou et al., 2016). The river embankments, a traditional flood defense infrastructure, were built along the Huangpu River in 1950s. Its flood control capacity, however, has been 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 raised periodically to withstand the increasing water levels.

The designed return period of the Huangpu River embankment approved in 1985 is 1000 years. The historical highest water level was recorded during the No.11 typhoon in 1997. At the Huangpu Park hydrologic station near the Shanghai city core, the water level reached the historical height of 5.72 m (0.5 m higher than the second largest historical record occurred in 1981) and only 0.14 m lower than the design water level at this location (Nai et al., 2004). Based on the revised hydrologic analyses which extended the water level time series from 1912-1983 to 1912-2002, the embankment height in its original design corresponds to less than 200-year return period due to the newly recorded high tide in 1997 (Shao, 1999; Yao, 2001; Lu, 2008). In 2004, the standard of 1000-year return period was found to be degraded to the 100-year level mainly due to sea-level rise and land subsidence (Tang et al., 2014), indicating that the flood protection capacity was reduced. To enhance the flood protection capacity of Shanghai city, the height of embankments has to be raised to meet the standard of 1000-year return period. However, the continuous increase in height will not only require huge economic cost but also affect urban landscape and water environment, with another potential risk being that the extreme dam-break floods will be more devastating. In addition, the reliability of the reinforced embankment structures is in question because of its aging foundation built around 1950s (Zhou et al., 2016).

A combination of flood defense walls and estuary barriers has been proposed as an alternative measure against the reduced capability of flood control in the low-lying areas in England, Netherland, Germany, among other countries (Xiao, 2017; Jin, 2016). The Thames barrier in UK, for instance, has been operated for more than 30 years with a significant flood control capacity for protecting large cities upstream. It can effectively mitigate flood risks caused by discharges from upstream areas and high tides caused by storm surges (EA, 2012). Xiao (2017) reported that an area of 125 km^2 in London can be protected against the high water level of the 1000-year return period due to the Thames barrier. After the completion of the Delta Storm Surge Barriers project in the Dutch delta, the protection standard is increased from return period of 1250 years to that of 4000 years, protecting one third of the areas of Netherlands as well as 4.5-million people. The Aames tidal gate in Germany has raised the level of protection against storm surges from the North Sea up to 3.7 meter above the mean sea level. Inspired by these international experiences of flood protection, the Municipal Government of Shanghai city has continued to investigate the feasibility to protect the study area with a storm surge barrier at the mouth of the Huangpu River since 1998.

As the Huangpu River runs through one of the most important metropolitan areas in China, numerous studies since 1990s have demonstrated the significance of constructing an estuary gate to enhance the safety of Shanghai city (Chen, 2001; Shao, 1999; Shao and Yao, 1999). Chen (2001) and Shao (1999) carried out comparative studies based on the well-known Thames Barrier in UK and the Delta Storm Surge Barriers in Netherlands. Jin (2016) conducted an in-depth analysis of typical large tidal gates built globally on various aspects of planning and design, investment and construction, and operation and maintenance. Chen (2002a) estimated the economic benefits in terms of the protected areas by the proposed tidal gate at the estuary of the Huangpu River.

Most afore-mentioned previous studies on the importance of constructing an estuary gate are based only on comparative and qualitative analyses. Although some previous research provided quantitative estimation of the potential benefits of gate construction (Chen, 2002b; Cui et al., 2012), the majority of them only considered the role of gate in blocking tide intrusion for the local estuary areas of the Huangpu River. Few studies have provided a holistic evaluation on the potential contributions of the proposed gate to flood control of the entire Taihu Lake basin, in particular the synergistic effects for the upstream areas of the basin due to gate construction. As the Huangpu River connects the Taihu Lake with the Yangtze River estuary to drain floodwaters from both local and lake upstream areas, the investigation of potential contributions of gate construction to the flood control capacity of the entire basin is of great engineering significance, which is the main goal of this study. To achieve, various scenarios of the monsoon-induced floods are analyzed and their potential impacts are quantified by using numerical simulations in this study.

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, and the East China Sea on the east (Fig. 1). This basin is not a sizable basin (36,895 km^2), only 0.4% of the total national areas (Hu and 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 the national total, and the regional per capita GDP is more than 2.5 times of the national average. This region is of great significance for the social and economic development of China. However, the extensive urban development has contributed to the risk of increasing magnitude and frequency of floods over this region.

The Taihu Lake Basin is characteristic of a complex hydro-system that includes interlaced rivers, dense water nets, and dotted depression lakes of different sizes (Qin, 2008). The water network and drainage system in the basin possess the following unique properties: (1) it has a saucer-like landform with the elevation of more than half of floodplains lower than the water level of flood control; (2) it is a typical river plain area with a high river density of 3.2 km/km^2 and a total river length of 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 flooding seasons; (4) the daily drainage time of the peripheral outlets in the basin is about 13-14 hours due to the semi-diurnal tides. Overall, the capacity of flood control system in the basin is dependent to a large extent on the flood defense infrastructure and peripheral tidal conditions. Based on the characteristics of topography and water networks, the basin is divided into eight sub-areas, namely the Huxi, Zhexi, Taihu Lake, Wuchengxiyu, Yangchengdianmao, Hangjiahu, Puxi and Pudong (Fig. 1). The irrigation systems were built to control water exchange among these sub-areas. The unique saucer-like topography of the Taihu Lake basin dictates that the water storage is easy to accumulate but difficult to drain, hence renders the surroundings flood-prone areas (Gao et al., 2005).

The Taihu Lake basin lies in a subtropical climate zone characterized by mild temperatures, high humidity and abundant rainfall (long-term mean of 1177 mm/yr). The basin is prone to both monsoon-induced and typhoon-induced floods. The major flood disasters with the inundation areas greater 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, resulting in damages with direct economic loss of 16-billion USD (Wang et al., 2011). There are 239 typhoons hitting the basin during the 1949-2013 period, on average about 3 to 4 per year (Ye and Zhang, 2015). According to the recent assessment report (AR5) compiled by the Intergovernmental Panel on Climate Change (IPCC, 2013) in which the flood control of the coastal systems and low-lying areas was addressed, the Yangtze River Delta is identified as one of the highly vulnerable coastal delta regions in the world.

Generally, the basin is characterized by monsoonal climate with the flood period concentrated in summer (mainly June to July), lasting several weeks or even months. Consequently, the broad-scale rainfall events occur frequently with an excessive magnitude and long duration, contributing to the basin-wide flooding. The largest flood in history occurred in 1999 when the total rainfall during a 43-day monsoon period reached 670 mm, three times more than the long-term (1954-2010) average during the same period. The return period of the 1999 flood event is estimated as 200-year (Evans and Cheng, 2010), considerably larger than the current 50-year design return period of the flood control capacity of the basin. The mean 7-day, 15-day, 30-day, 45-day, 60-day and 90-day accumulated rainfall in the 1999 flood period all exceeded the historical records (Wu, 2000). During this flood, the high water level in the Taihu Lake set a new record of 5.08 m, exceeding the design water level of the 50-year return period by 0.43 m.

There are numerous tidal channels linking the Taihu Lake and the coast (bay, estuary) in the basin, and most outlets of them are controlled by the floodgates subject to tidal locking. The Huangpu River meandering through the downtown area of the Shanghai City connects the westward-located Taihu Lake with the Yangtze River estuary in the North East, as shown in Fig. 1. The Huangpu River is 113 km long, with a depth of 5-15 meters and a width of 300-500 m (800 m at the estuary), formed by the convergence of three rivers: (1) the Xietang River originated from the Taihu Lake and the Yangchengdianmao area, (2) the Yuanxiejing Creek, and (3) the Maogang Creek originated from the Hangjiahu area. The Huangpu River finally injects into the Yangtze River at the estuary mouth. The tidal effect complicates the flow patterns of Huangpu River, and helps to keep floodwaters in rivers. Generally, the river can naturally drain floodwaters for 13-14 hours per day. The Huangpu River experiences two high tides and two low tides each day (semi-diurnal tides), receiving 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 areas is about 10.02 billion m^3 per year. Its sediment concentration upstream is 0.049 kg/m^3, and it is 0.213 kg/m^3 downstream (Yan, 1992). The problem caused by sediment and siltation is not serious for this river because the inflow from upstream areas is far more than the tidal water from the estuary.

3 Methodology

3.1 Description of five scenarios

It is instructive to investigate the potential contribution of the proposed Huangpu gate to the flood control in the Taihu Lake basin, which is currently still in the preliminary demonstration-of-benefit stage. The main research strategy used in this study is the scenario analysis based on numerical model simulations.

In total there are five different scenarios considered in this study as summarized in Table 1. Among them, the first scenario considers the case without gate construction, while all the other four scenarios consider the case with gate construction but with different operation modes. The scenario Base A is used as the baseline case for comparison with other scenarios, which represents the case that the estuary gate is not constructed at the Huangpu River mouth. The scenarios A1 and A2 are two cases the proposed gate began to operate when the Taihu Lake is under severe flooding situation. The scenario A3 is designed to analyze its contribution to prevent tidal water intrusion exceeding a pre-defined threshold. The last scenario A4 is the case for analyzing its contribution to block all tidal water intrusion, which is the potential maximum contribution of gate construction to flood control of the Taihu Lake basin.

For the scenario Base A, the estuary gate is not constructed at the outlet of Huangpu River. Thus, the water in the Huangpu River and Yangtze River estuary can exchange naturally. For the scenario A1, the proposed gate would be operated in the rising stage of the lake levels according to weather forecast. In the model simulation of the 1999 flood, the gate began to operate seven days in advance before the lake level reached its peak value.

For the scenario A2, the proposed gate would be operated when a large basin-wide flood occurs with the lake level higher than 4.50 m, indicating a severe and urgent flooding situation in the Taihu Lake basin. All drainage rivers linking the lake and the coast (bay, estuary) require the acceleration of floodwater drainage including the Huangpu River.

For the scenario A3, a portion of tidal water intrusion would be blocked by the gate, and the gate will remain open until the tide rises to a threshold (defined here as 4.0 m). That is, the gate would not be closed for blocking tide intrusion for each day;

instead, it would be closed only under the situation when the high water exceeds the tide threshold (4.0 m) and is also forecasted to continue rise.

For the last scenario A4, the gate would prevent all tidal water intrusion during the entire flooding period. It represents a hypothetical extreme case since it is not practical in implementation owing to the difficulty in overly frequent operation of such a huge gate with a width of about 400–500 m. This scenario is just a hypothetical case for analyzing the potential maximum benefits to flood control of the basin. Indeed, it is not necessary to block all tidal water intrusion since under such operation it is also likely to produce negative impacts on both waterway transportation and water environment system.

Considering the time needed for policy-making and gate construction, it is highly likely that the Huangpu gate will not be completed and start operation until after 2025. For this reason, the proposed flood control projects in the plan designed by MWR (2008) will also be incorporated as the scenarios of flood defense in this study. Hu (2006) proposed the Anchorage Ground located at the mouth of Huangpu River as the best site for gate construction since the negative impacts to shipping and navigation are the least due to its location. Cui et al. (2012) and Lu (2008) proposed the same location for gate construction. Accordingly, in the following numerical model simulations the estuary gate will be located at the Anchorage Ground (shown in Fig. 1), which is about 5-6 km from the Huangpu River mouth.

The Huangpu River is the main shipping and drainage route in the Taihu Lake basin. In general, the embankment of the Huangpu River can protect against the occurrence of normal floods, while the proposed gate will be operated only under severe flooding situations. The following numerical model simulations for these five scenarios are all based on the condition during the 1999 flood event, which is the largest flood in history for the study area.

3.2 Model description

The HOHY model developed by the Hohai University in China will be used in this study. This model has been tested in numerous regional applications since 1970s, and was also applied at the Taihu Lake basin since 1997. It is one of the main products of a three-year water study at the Taihu Lake basin, supported by the World Bank and jointly undertaken by the Hohai University and the Delft Hydraulics in Netherlands. The HOHY model can simulate the cycle of floodwaters well. Meanwhile, the model can provide a broad-scale simulation of the flood control system in the Taihu Lake basin. It can simulate not only the complex hydro-systems with numerous interlaced rivers and lakes, complicated relationships between river nets, hilly topography and tidal boundaries, also the complex operational rules of control structures such as sluices, pumps and siphons. This model has been utilized in a variety of past studies, such as the preliminary demonstration-of-benefit stage of water works in the Taihu Lake basin. In particular, the model has been successfully applied in the flood control planning of the Taihu Lake basin as approved by WMR (MWR, 2008).

The model is composed of two parts: a hydrologic part for simulating runoff generation and routing, and a hydraulic part for simulating channel flows. Each of them can run independently. The schematization of the model is shown in Fig. 2; more details of the model can be found in Cheng et al. (2006) and Jin (2009).

Runoff is generated when precipitation exceeds the total 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 parameterizations to calculate runoff generation, and then the total runoff is routed according to basin topography. In hilly areas, the instantaneous unit hydrograph method is used, considering the storage and drainage processes of reservoirs and large ponds. In plain areas, the method of runoff curve number is used for each computed area.

After the runoff from the hilly and the plain areas flows into river networks, the hydraulic method is applied for simulation of river flow. Only the lakes with a larger surface area are considered as possessing the function of storing floodwaters, while other smaller lakes are considered as intersections like the links among rivers. The operation of water-engineering works such as gates, pumping stations and siphons, is also simulated in the model. The Saint Venant Equations are used as the governing equations for the one-dimensional unsteady open channel flow, including the continuity equation (1) and the momentum equation (2) as follows

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_L \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(\alpha \frac{Q^2}{A}) + gA\frac{\partial Z}{\partial x} + gA\frac{n^2|Q|Q}{R^{1.333}} = q_L v_x \tag{2}$$

where x (m) is the distance along the channel; t (s) is the time; A (m^2) is the cross section area; Q (m^3/s) is the flow rate; Z (m) is the water level; α (-) is the momentum correction coefficient; R (m) is the hydraulic radius; q_L (m^2/s) is the lateral inflow per unit length of channel; Vx (m/s) is the velocity of the lateral inflow in the x-direction; and g (m/s^2) is the gravity acceleration.

The model parameters of the numerical simulations in this study are specified as the same as those used in the design plan by MWR (2008). The model calibration data are from two consecutive years 1984 to 1985, and the validation data are from 1995 and 1996. The model has also been validated by Ou and Wu (2001) using the observed water level and river flow data of the 1999 flood. Fig. 3 compares the difference in water level simulations with observations during the 1999 flood at eight representative stations of the basin (see Fig. 1 for their locations). Fig. 4 shows the differences in river discharges between observations and simulations at the Taipu Gate and Wangting Siphon (see the location shown in Fig. 1). These comparisons of simulated water levels and discharges with observations demonstrate that the simulations of HOHY model are of sufficient accuracy to be used in the following scenario analyses.

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

The model modification is based on the flowchart given in Fig. 2, focusing on the flood routing part related to the algorithms of unsteady open channel flow, and the control rules of gate related to the tidal condition. The main program was improved by adding a function to judge the stage of tide before running the gates (i.e. in the flood or the ebb tide), which makes the specification of the control rules of gates more flexible.

The modified HOHY model is tested by using a simple case in which the tide threshold is assumed to be 4.0 m. The simulation results are presented in Fig. 5 and Fig. 6. Fig. 5 describes the case when the gate remains open since the high water in the tidal period is always lower than 4.0 m. Fig. 6, as a comparison, is the case that the gate would be closed when the rising tide is higher than 4.0 m. The gate will re-open to drain floodwaters when the gate has the natural water-expelling ability to evacuate floodwaters in the ebb tide.

The model results, including the gate discharge, the tide water level at the estuary, and the difference in water levels between the upstream and downstream of the gate, show the reasonable relationships of the operational rules of the gate. Fig. 5 demonstrates that the discharge at the gate resembles a sinusoidal curve as affected by the tidal boundary. It is likely that the gate does not need to be closed since the high water during the tidal period is less than the tide threshold of 4.0 m. Fig. 6 is another case of the gate 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 exceeded the tide threshold 4.0 m, and the gate has to be closed. It was not re-opened in the ebb tide until 8:15 am, 15 August, 1999 when water level in upstream is higher than that in downstream near the gate location, meaning that the gate has the natural water-expelling ability to drain floodwaters at this moment (see the red bars in Fig. 6). Overall, the modified HOHY model has demonstrated its ability to simulate the complicated operational rules of the proposed Huangpu gate well.

4 Result and discussion

Based on the water systems and topography of the study region, the Huangpu River receives floodwaters from Taihu Lake and the surrounding areas draining into the Taipu Canal and Huangpu River, in particular those low-lying areas in the southern part of the Yangchengdianmao catchment, the northern part of the Hangjiahu catchment, and the western part of the Puxi catchment (see Fig. 7). Therefore, the potential contributions of the proposed Huangpu gate to flood control capacity will be analyzed in the following section with respect to three target regions: (1) the Taihu Lake, (2) the surrounding areas, and (3) the Taipu Canal and Huangpu River.

4.1 Potential contribution to flood control of the Taihu Lake

Table 2 summarizes the peak values of lake water level and the duration (the number of days) when various control levels were exceeded during the June-August period in 1999 for the five scenarios considered in this study. Fig. 8 plots the simulated water levels at the Taihu Lake corresponding to five scenarios during the 1999 flood event from June to August. As seen, the lake levels in the scenarios A1, A2, A3 and A4 were all lower than that in the scenario base A. Similarly, the duration when the water level is higher than a certain control level was also reduced. Compared with the maximum daily water level of 5.03 m (occurred in early July) in the scenario base A, the maximum water levels in other scenarios were decreased by 0.04, 0.01, 0.03 and 0.12 m, respectively, for the scenarios A1, A2, A3 and A4. Thus, these four scenarios contribute to the flood control capacity of the Taihu Lake and its adjoining low-lying areas to the west.

It should be noted that the differences in the design water levels corresponding to different return periods are not significant for such typical shallow lakes located in the low-lying plains. For instance, the design water level of 100-year return period is 4.80 m, 0.15 m higher than that corresponding to the 50-year return period. For this reason, the decrease in the peak lake level by 0.04 m in the scenario A1 as well as by 0.12 m in the scenario A4 is significant for flood control of the lake. Additionally, the western adjoining floodplains would also benefit from the gate construction. Due to the relatively lower flood control capacity of the western adjoining areas, those regions are likely to be inundated when the sluices cannot yet control the water intrusion from the lake to the adjoining areas once if the lake level is too high. The flooding condition in the western adjoining areas will be even worse once if the lake breaches the dike.

From the viewpoint of flood control of the lake, it can be concluded that the Huangpu River with an estuary gate is more effective than that without a gate. The gate operation would prevent or reduce the amount of tidal water from entering the Huangpu River that is already with high water levels caused by increased river flows from the lake and the surrounding areas. The extent of the gate contribution to flood control depends largely on its operation mode and duration. The longer the gate is operated, the less tidal water will intrude into the Huangpu River estuary, and the more floodwaters in the lake will be drained to the Yangtze River via the Taipu Canal and Huangpu River. Overall, the scenario A1 is a nice example to examine the potential contribution 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 with the case of operating the gate by a relatively short duration such as one week as assumed in the scenario A1, the contribution to reduce the peaks and the rising rate of lake levels is rather significant.

4.2 Potential contribution to flood control of the surrounding areas

The Huangpu River also receive the floodwaters drained from the following surrounding areas including the (1) Yangchengdianmao, (2) Hangjiahu, (3) Puxi and (4) Pudong catchment, as shown in Fig. 7. Therefore, the safety of these four catchments against flooding is also closely linked to the capacity of Huangpu River. Table 3 lists the peak water levels at the four representative stations (S1 to S4, shown as the orange circles in Fig. 1), each for one of the above four surrounding catchment. Fig. 9 plots the simulated daily water levels during the 1999 flood at these four stations, from which a similar trend in the water level as that in the Taihu Lake (Fig. 8) can be observed. The scenario A4 represents the potential maximum contribution of the gate, i.e., the maximum decrease in the daily peak level at the four stations in surrounding areas is 0.32, 0.19, 0.39 and 0.05 m, respectively. In contrast, the improvement in flood control capacity at station 4 located in the Pudong catchment is the smallest among four stations due to its unique terrain. The local floodwaters in the Pudong catchment have the priority of draining to the East China Sea over that draining to the Huangpu River due to its natural water-expelling ability. Generally, the flood capacity of station 4 does not depend much on the drainage capacity of the Huangpu River as the other three stations.

In contrast, for the scenario A1 in which the gate is operated in advance, the gate can play a notable role in reducing the peak water levels by the amount between 0.15m and 0.35m except for the station 4. For the scenario A2, the gate can decrease the peak water levels only by 0.07-0.15 m. However, the scenario A2 has more advantages in speeding up the drainage rate of floodwaters at the recession stage and shortening the time of waterlogging.

4.3 Potential contribution to flood control of the Taipu Canal and Huangpu River

Fig.10 plots the simulated daily water levels in the Taipu Canal and Huangpu River at the seven cross-sections (as marked by the purple rectangular in Fig. 1). The daily water levels at the Taipu Canal and Huangpu River decrease to various extents when the gate is in operation. The scenario A4 represents the potential maximum contribution of the proposed gate due to complete prevention of tidal water intrusion. In this scenario, the maximum reduction in the peak water level is 0.26-0.37 m for the Taipu Canal and 0.46-0.60m for the Huangpu River.

The Huangpu River benefits more from gate construction than the Taipu Canal because the latter is located relatively farther away from the gate. The potential contribution of the gate can be attributed to the reduction of tidal water intrusion during the flood period. 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 Huangpu River when the gate is closed, and then the discharge rate will increase when the gate re-opens again due to the relatively large difference in water levels between the upstream and downstream side near the gate. Therefore, the gate can decrease the water levels of Huangpu River more markedly than that of the Taipu Canal.

In the scenario A1, the gate is operated in advance during the rising stage of the lake level, and the peak flood level in the Taipu Canal and Huangpu River can be decreased considerably due to the enlargement of drainage capacity of the Huangpu River. In the 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 the scenario A1, while the draining rate in the recession stage is faster. If the gate is operated by blocking the high tide during the flood period (Scenario A3), the peak water levels at 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 contribution of the proposed gate to the flood control of the lake and the surrounding areas.

4.4 Analyses of the inflow and outflows in the Huangpu River

Table 4 describes the inflow volumes from the upstream tributaries to the Huangpu River during the flood period. In addition to the Taipu Canal, there are many upstream tributaries originating from the northwest and southwest upstream areas of the Huangpu River (Fig. 7). In the 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 the scenario base A (1.50 billion m^3). The inflow from the northwest upstream areas in the scenario A4 is about 1.05 billion m^3, increases by 78% in comparison to that in the scenario base A (0.59 billion m^3). The inflow volume from the Taipu Canal is about 5.0 billion m^3, only increased by 27.2% compared to that in the scenario base A (3.93 billion m^3). In terms of the major inflows into the Huangpu River, the inflow volumes 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 upstream subareas.

Table 5 describes the tide intrusion and outflow volume at the site of the proposed gate during the flood period. The proposed gate helps to improve the drainage efficiency of the Huangpu River by preventing the river from tidal water intrusion. Compared to the scenario base A, the net outflow volume at the gate site during the entire flood period under the other four scenarios is increased by 4% (A1), 8% (A2), 22% (A3) and 52% (A4), respectively. Fig. 11 shows the comparison of simulated river discharge at the site of the proposed gate between the scenarios base A and A1 from June 27 to July 3 in 1999. The difference in river discharge between these two scenarios clearly reflects the difference in the drainage efficiency of the Huangpu River. Although the river discharge in the scenario A1 is only increased by 4% for the entire flood period (increased 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 (from Jun. 27^{th} to Jul. 3^{rd}) is more significant. The net outflow volume is nearly doubled by changing the bi-directional flow to the unidirectional flow (as shown in Fig. 11).

5 Summary and conclusions

Compared to a natural river channel, an estuary gate can prevent tidal water from intrusion into the upstream estuaries. This study shows that the construction of an estuary gate at the Huangpu River is an effective measure for evacuating floodwaters and reducing peak water levels along the Taihu Lake – the Taipu Canal – the Huangpu River – the Yangtze River Estuary. The potential contribution of the proposed gate is closely associated with its operation modes and duration. Regarding the potential maximum contribution, the net outflow at the site of the proposed gate is increased by 52% for the entire flood period in 1999 based on our model simulation results, and hence the efficiency of the drainage capacity from the Taihu Lake to the Yangtze River estuary is significantly improved.

Constructing the proposed gate will benefit the Taihu Lake and its adjoining upstream areas, and the surrounding areas along the Taipu Canal and Huangpu River. The inflow volume from the upstream tributaries into the Huangpu River is increased by 27% in the Taipu Canal, 78% in the north part of Hangjiahu catchment, and 117% in the south part of the Yangchengdianmao catchment. Meanwhile, the daily peak level is decreased by a maximum of 0.12 m in the Taihu Lake, by 0.05-0.39m in the surrounding upstream areas depending on local topography, and by 0.26-0.37m and 0.46-0.60m in the Taipu Canal and Huangpu River, respectively.

Difference scenarios of gate operation are considered in this modelling study. Different operation modes result in different drainage impacts although they are all helpful to drain floodwaters from the lake to the Yangtze River. For the scenario A1 (the gate began to operate one week in advance according to weather forecast), it has more advantages in decreasing the peak flood levels and slowing down the water level rise during the rising stage. For the scenario A2 (the gate began to operate when the large basin-wide floods occur), it is more helpful to speed up the drainage rate during the recession stage, to reduce the duration of high water level, and to decrease the flood risk of the lake and its adjoining upstream areas. For the scenario A3 (the gate began to prevent tidal water intrusion until the tide rises to a pre-defined threshold), it appears that the improvement of flood control capacity is more effective during the spring tides; namely, the contribution of the gate is more notable in August than in other months.

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

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Figure 1. Location map of the Taihu Lake basin in the Eastern China.

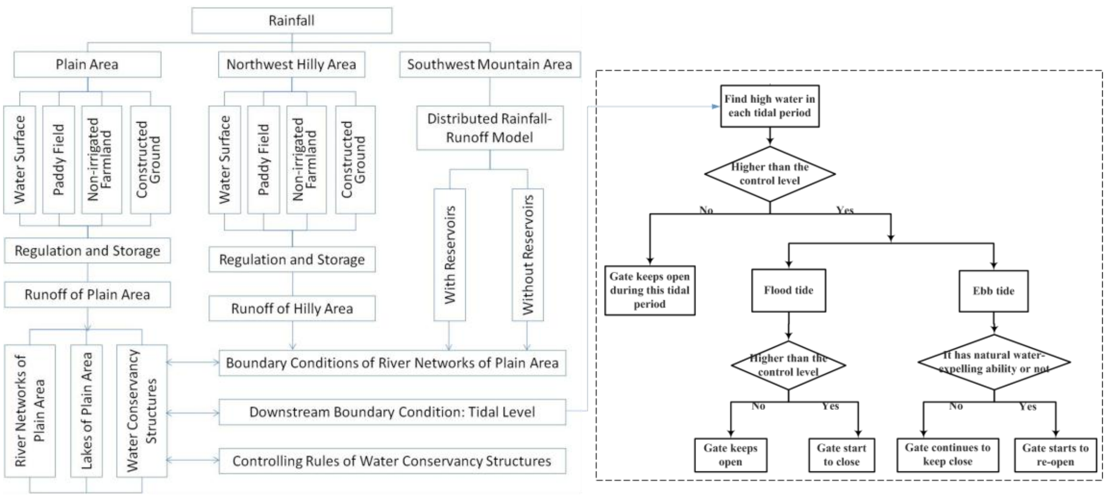


Figure 2. Schematization of the extended HOHY model (Modified from Jin et al., 2008).

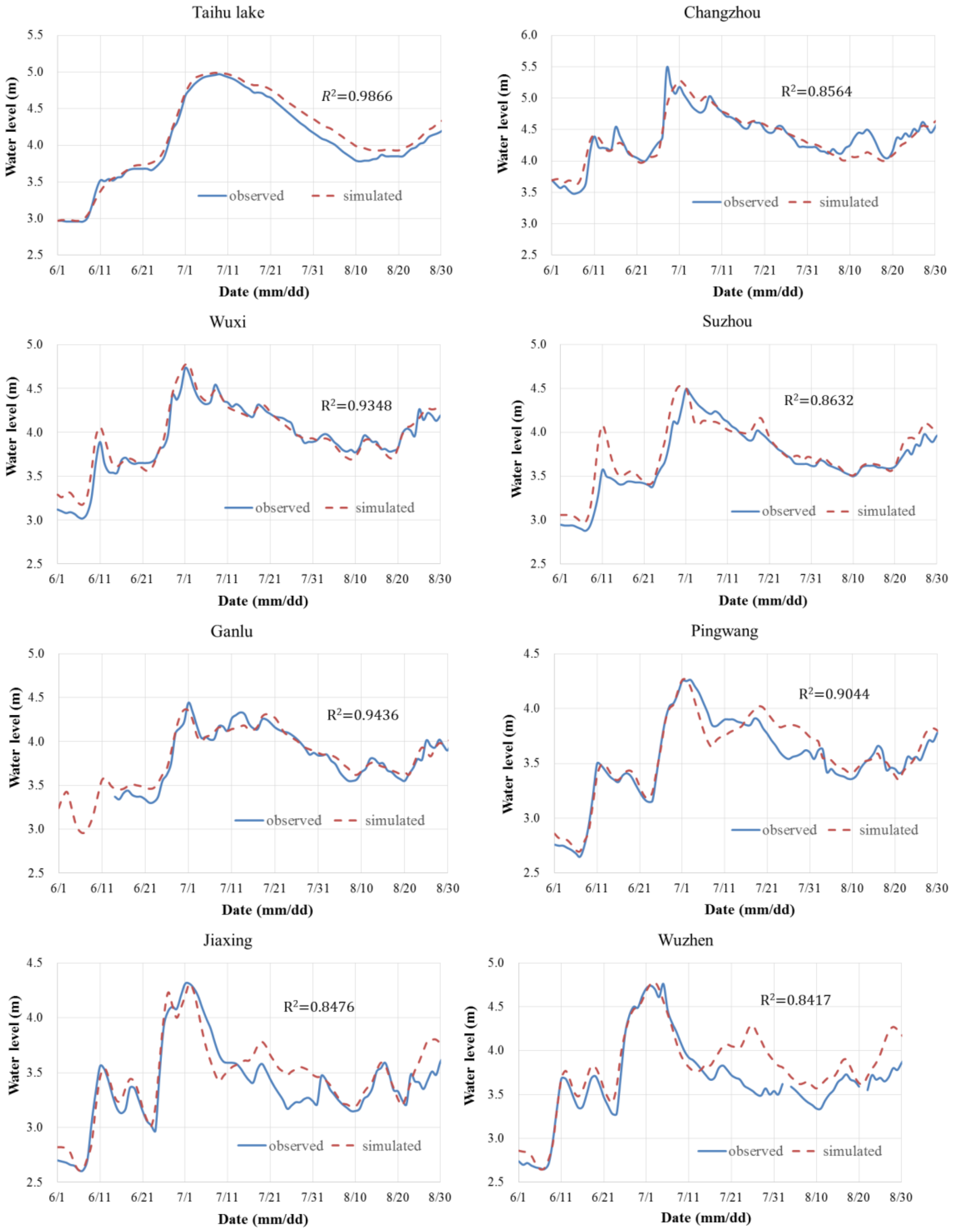


Figure 3. Comparison between the observed and simulated water levels from June to August in the 1999 flood event at eight stations as shown in Figure 1 (adapted from Ou and Wu, 2001).

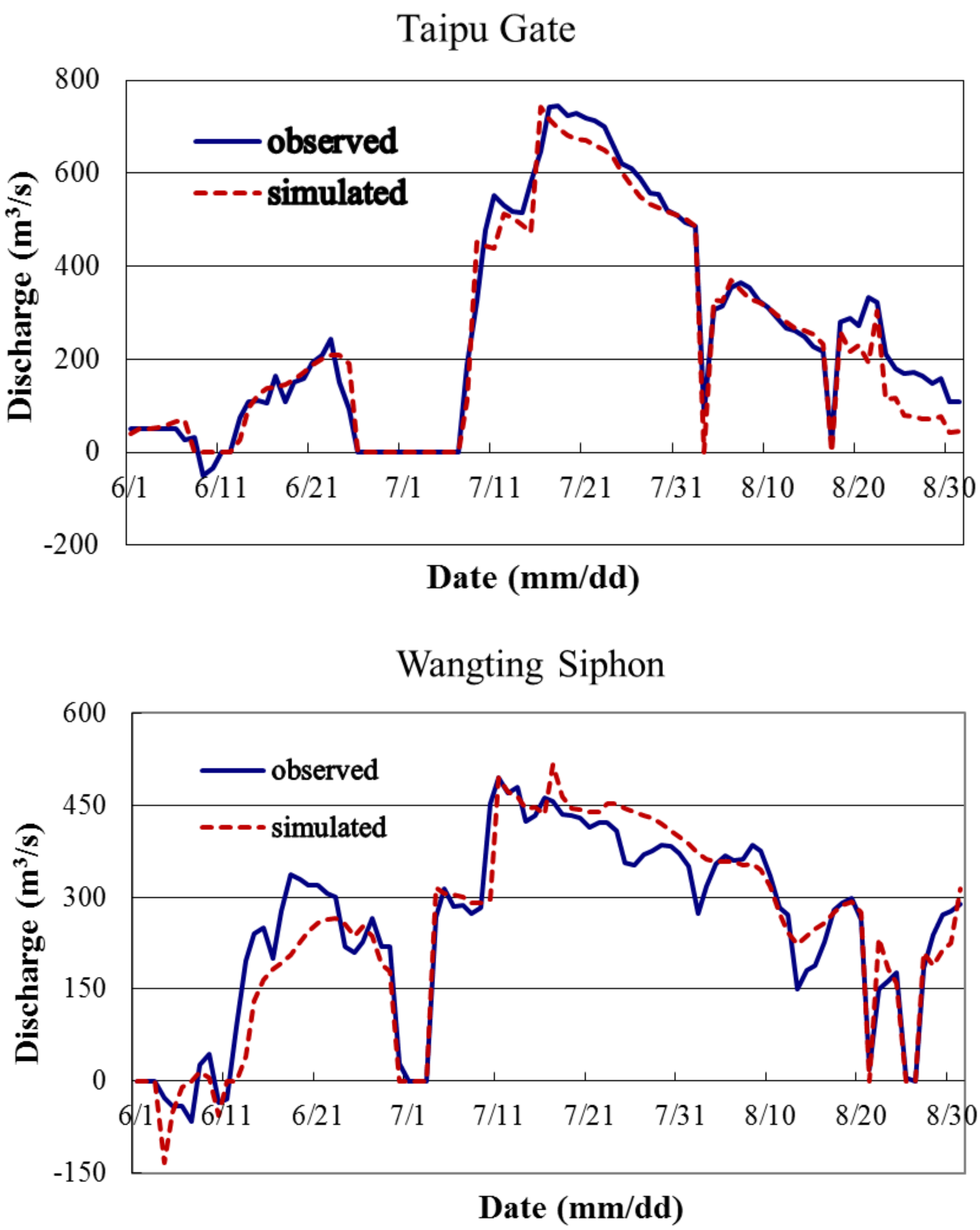


Figure 4. Comparison between the observed and simulated daily discharges from June to August in the 1999 flood event at the Taipu Gate station and Wangting Siphon station (adapted from Ou and Wu, 2001).

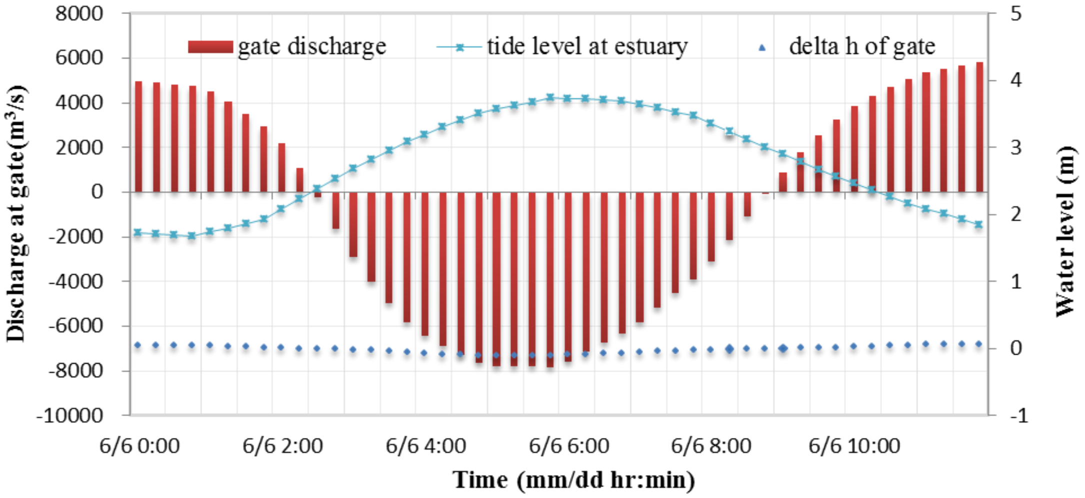


Figure 5. A test example when the gate keeps open due to the high water lower than tide threshold in this tidal period (t.l.: tide level; w.l. water level; a negative discharge indicates the tidal water intrusions).

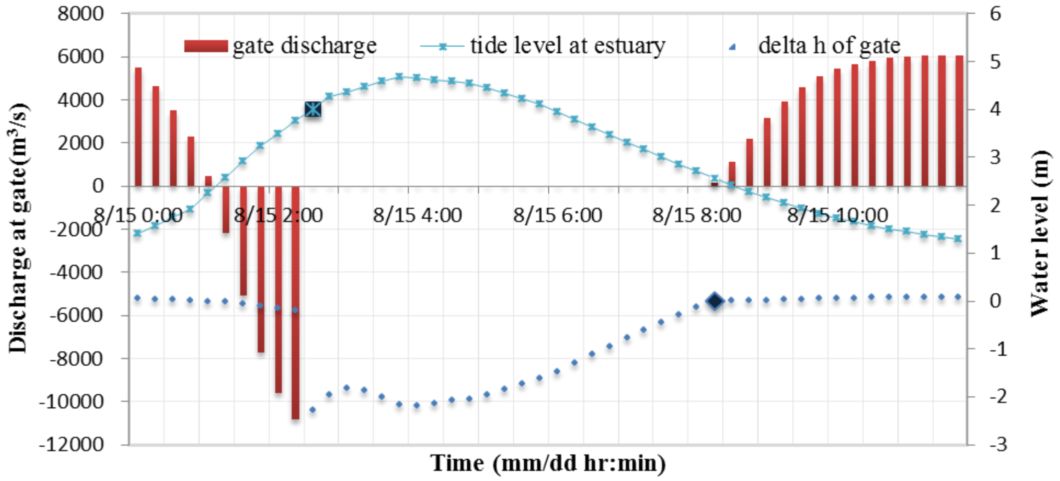


Figure 6. A test example when the gate needs to be closed due to the high water higher than tide threshold in this tidal period (t.l.: tide level; w.l. water level; a negative discharge indicates the tidal water intrusions).

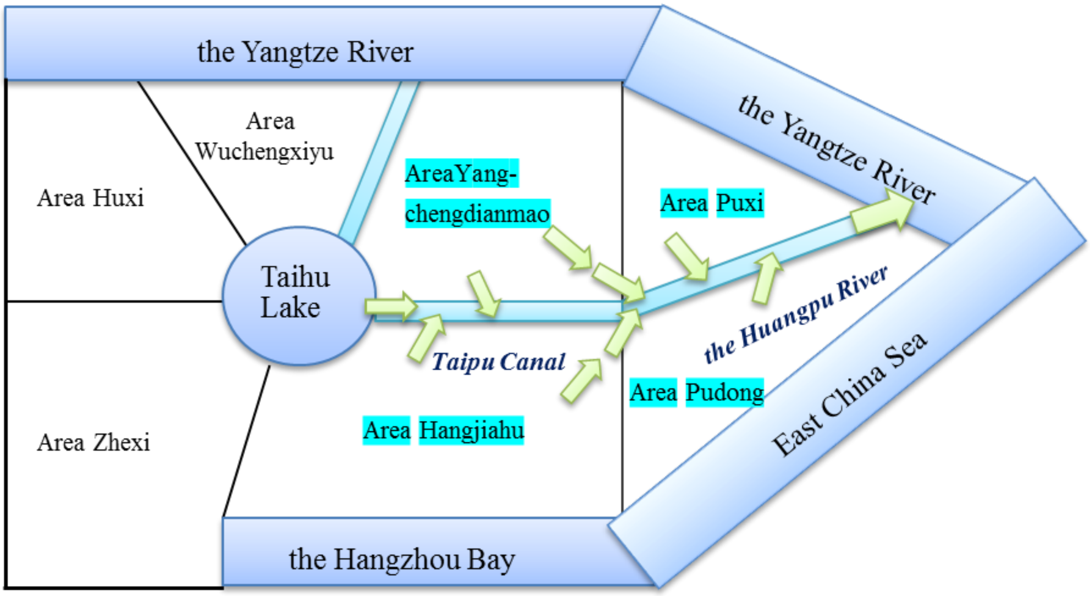


Figure 7. Conceptual drainage system along the Taihu Lake – the Taipu Canal – the Huangpu River – the Yangtze River Estuary.

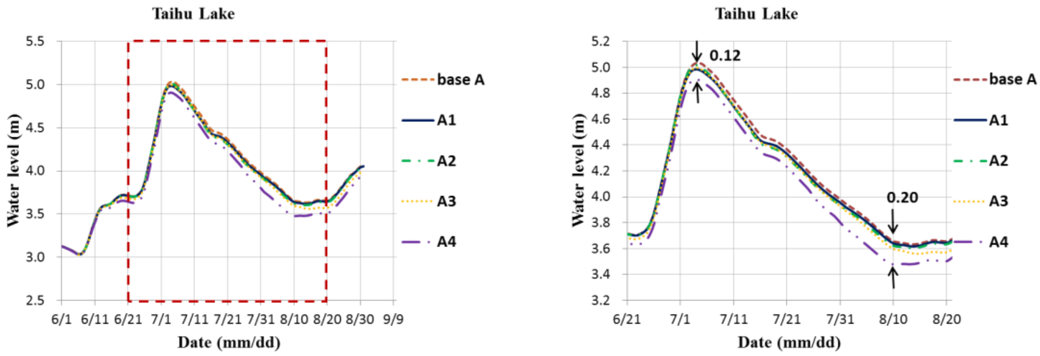


Figure 8. A comparison of the simulated daily lake levels during the period from June to August in 1999 in the Taihu Lake under the five scenarios considered in this study (The figure on the right-hand-side is the zoom-in plots of the figure on the left-hand-side).

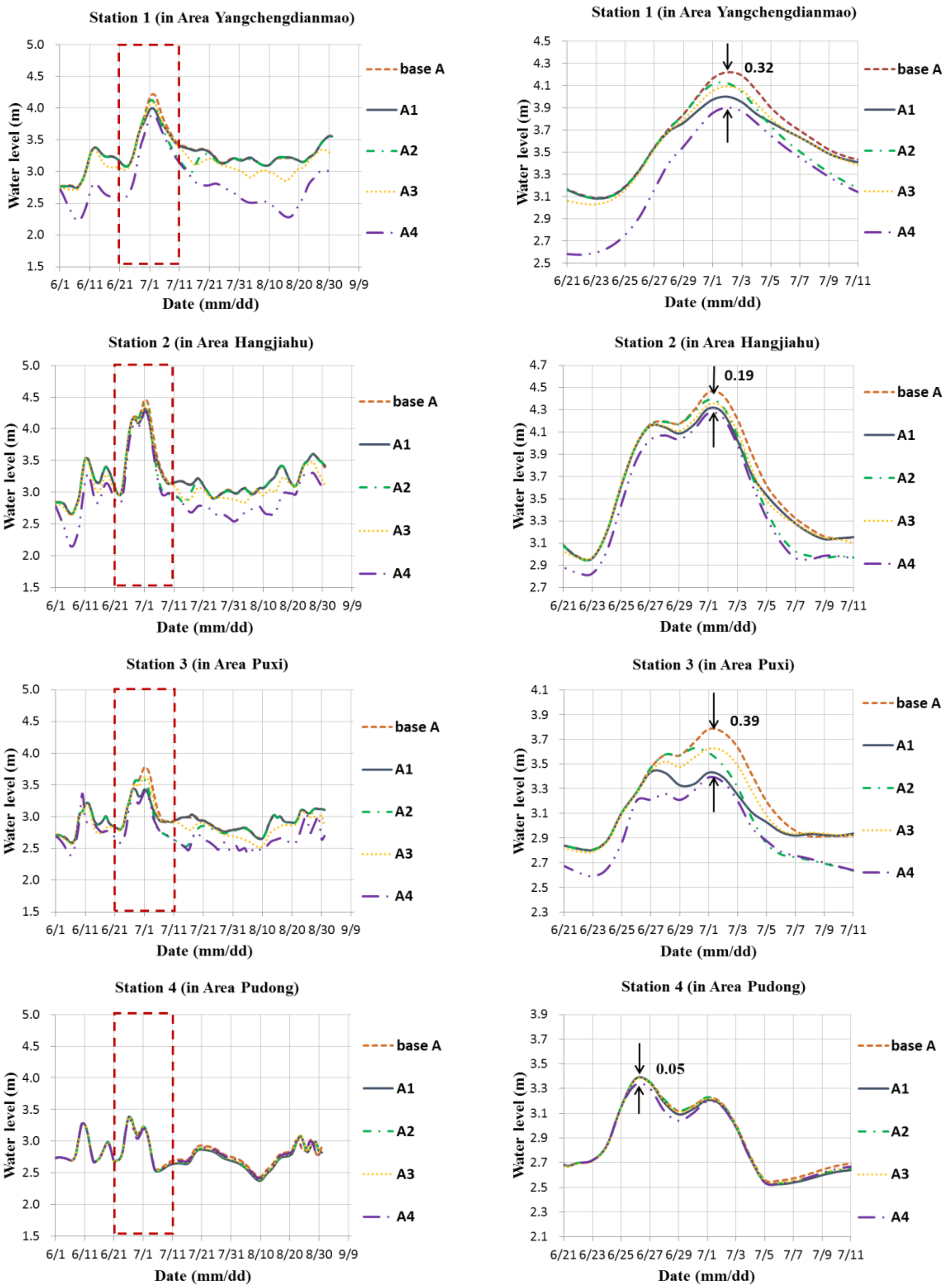
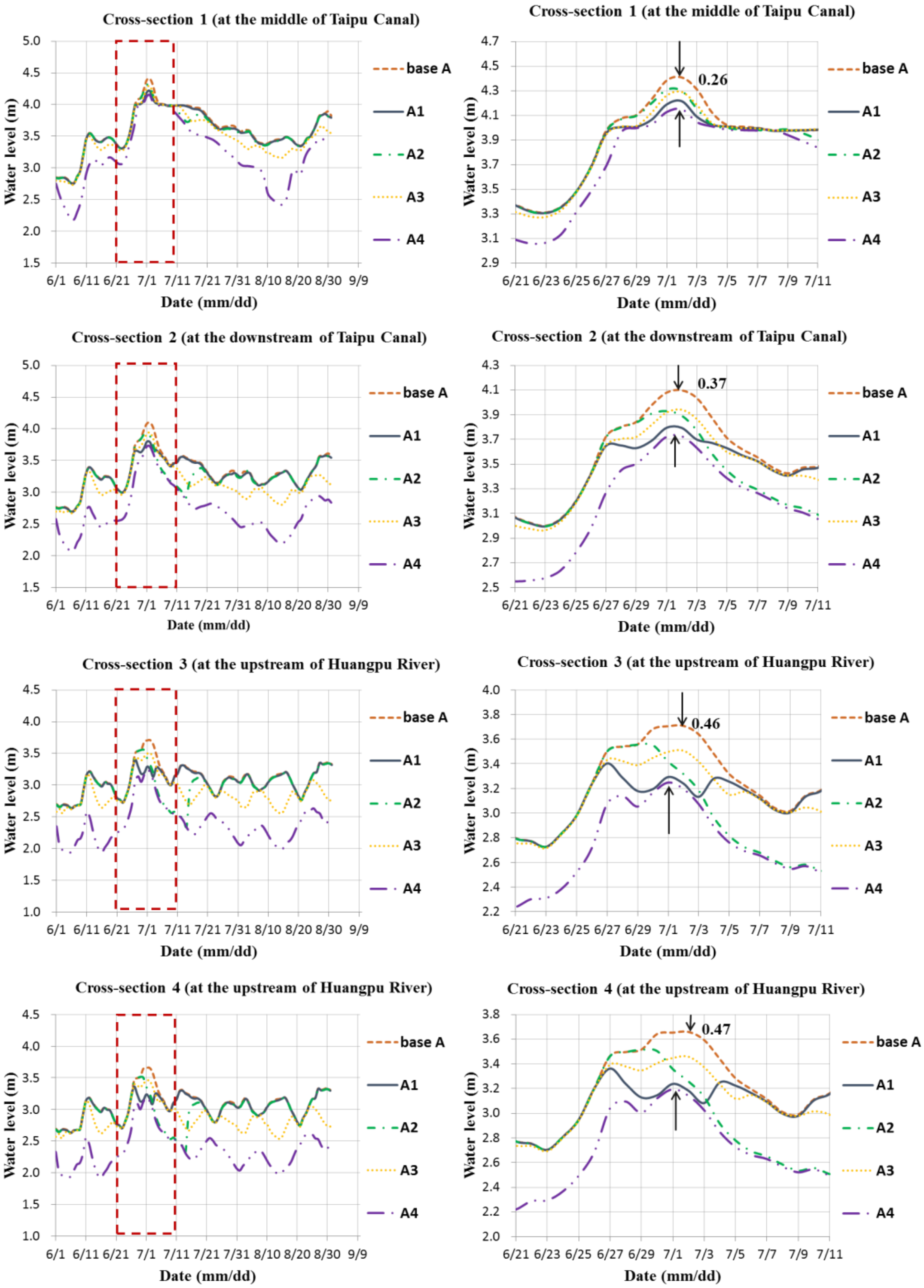


Figure 9. Comparison of the simulated daily water levels during the period from June to August in 1999 at four stations (as shown in Figure 1) under the five scenarios considered in this study (The figures on the right-hand-side are the zoom-in plots of the figures on the left-hand-side).


Cross-section 1 (at the middle of Taipu Canal)
Cross-section 1 (at the middle of Taipu Canal)
0.26
Cross-section 2 (at the downstream of Taipu Canal)
Cross-section 2 (at the downstream of Taipu Canal)
0.37
Cross-section 3 (at the upstream of Huangpu River)
Cross-section 3 (at the upstream of Huangpu River)
0.46
Cross-section 4 (at the upstream of Huangpu River)
Cross-section 4 (at the upstream of Huangpu River)
0.47
Water level (m)
Date (mm/dd)
base A
A1
A2
A3
A4

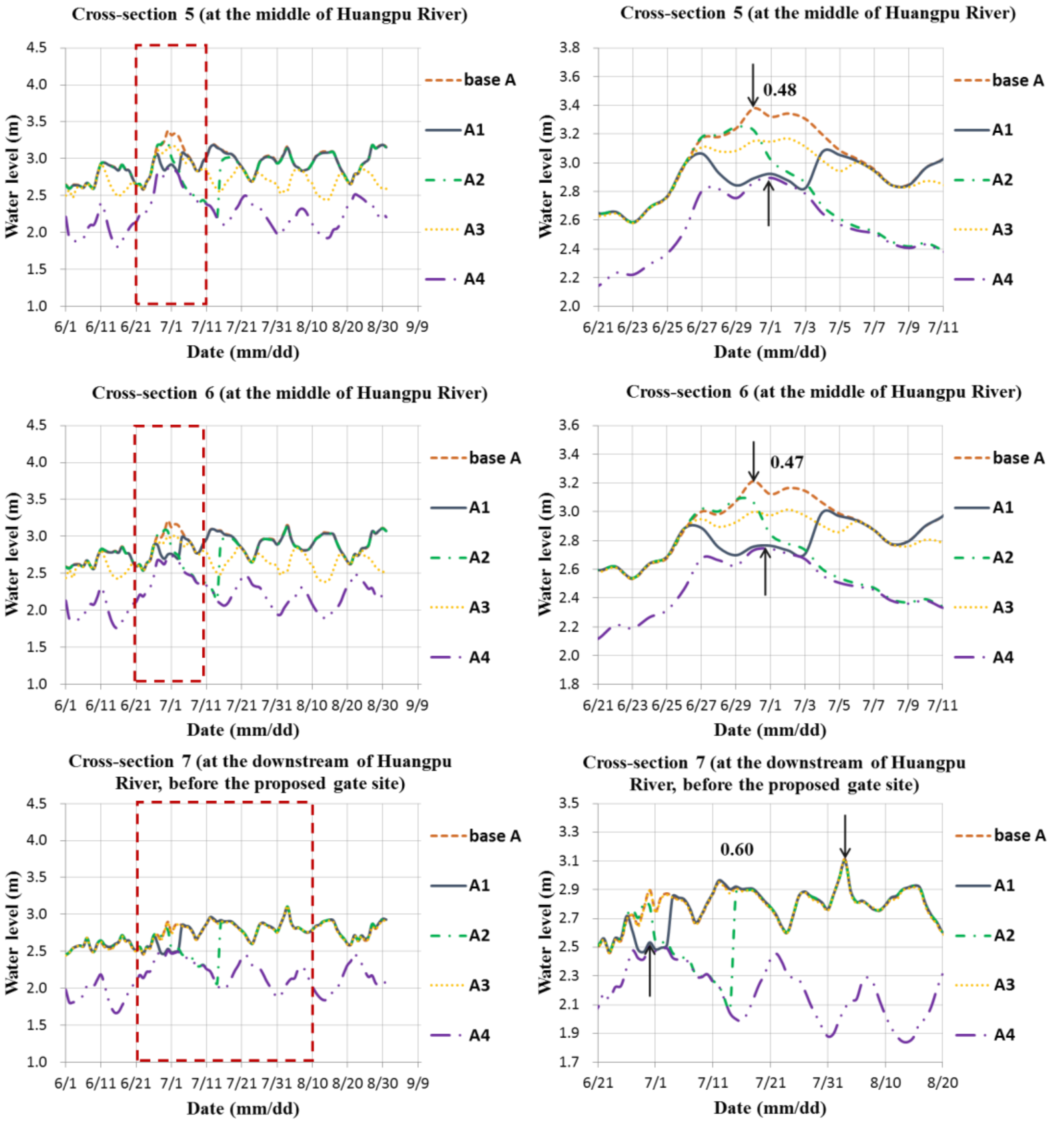


Figure 10. Comparison of the simulated water levels during the period from June to August in 1999 at the seven cross-section points (as shown in Figure 1) along the Taipu Canal and Huangpu River under five scenarios considered in this study (The figures on the right-hand-side are the zoom-in plots of the figures on the left-hand-side).

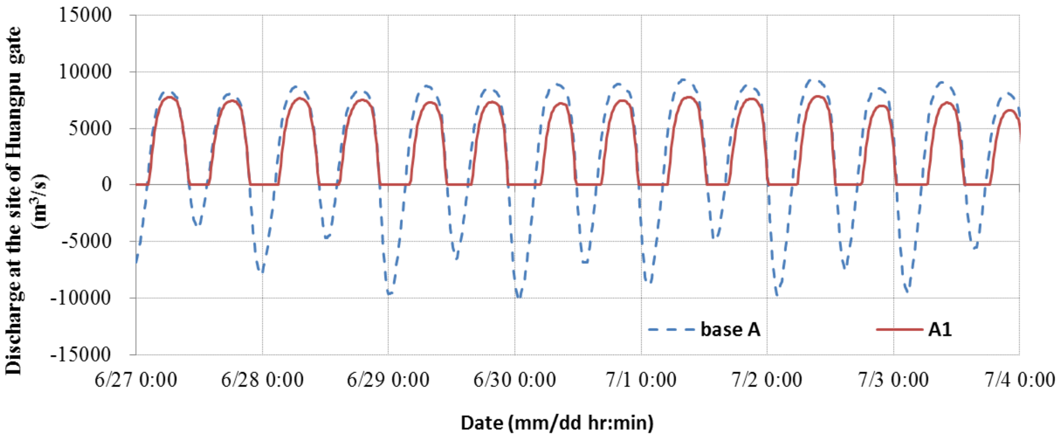


Figure 11. Comparison of discharges at the site of the proposed gate between the scenarios base A and A1 from June 27 to July 3 in 1999 (The negative discharges mean the tidal water intrusion).

Table 1. The definitions of five different scenarios considered in this study.

Scenario	Definitions
base A	without the construction of the proposed gate at the estuary of Huangpu River
A1	with the gate, and operated to prevent tidal intrusion 7 days in advance before the lake level reaches the peak
A2	with the gate, and operated to prevent water intrusion when the large basin-wide floods occur (defined as the lake level higher than 4.50m)
A3	with the gate, and it will not be closed to prevent tidal water intrusion until the tide rises to a pre-defined threshold (defined as 4.0m in this study)
A4	with the gate, and it will always be closed whenever the tidal water intrudes

Table 2. Peak lake water levels and the duration (the number of days) from June to August of 1999 when lake water levels are higher than a certain control level under five scenarios considered in this study.

Scenario	Peak value (m)	Flood control level (3.5m) (days)	High water level (4.0m) (days)	Design water level 4.65m (1/50) (days)	Design water level 4.8m (1/100) (days)
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 water levels at the four representative stations under five scenarios considered in this study (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 of the Huangpu River from June to August in 1999 under five scenarios considered in this study (unit: billion m^3).

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 under five scenarios considered in this study (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