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Inundation modelling for fluvial and pluvial flooding during typhoons – a case study in Shanghai city

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ABSTRACT: The co-occurrence of storm surge, high tides and heavy precipitation increases flood probability and potential consequences compared to each hazard separately in Delta cities. The Huangpu River (HP) is a tributary of the Yangtze River in China, which drains Tai Lake to the west of Shanghai city, and meanders through downtown Shanghai. During typhoon events, storm surge reverses the river flow and pushes the water level up as far as 100km upstream. If storm surge (1-2 m above msl) co-occurs with high tide (2-3 m above msl), it poses great threats to the HP floodwall (crest level from ~3-5.5m above msl). At the same time, typhoons cause heavy precipitation (up to 70-80mm/hour) in the city, which increases urban drainage discharge in the pipeline system. In order to prevent elevated water levels in the river, stormwater drainage is ceased to effectively work in this situation. Pluvial and fluvial flooding occur simultaneously. The objective of this paper is to develop a hydrodynamic model to simulate simultaneous pluvial and fluvial flooding and to produce inundation maps due to failure of floodwalls and the urban drainage system. We apply the Delft3D FM numerical model to compound flood events in Shanghai. Results raise risk awareness for decision-makers during compound flood events and demonstrate the importance of compound flood modelling at a city scale.

1 INTRODUCTION

Shanghai is affected by typhoons 2-3 times a year, bringing strong wind and intense rainfall. Wind induced storm surge is typically ~1m; combined with a high astronomic tide of 2-3m above m.s.l, flooding would occur regularly if no flood defenses(e.g. floodwall) were installed along the river. High tide and storm surge could reverse the flow direction of the Huangpu river during typhoons, and threaten failure of floodwalls along the rivers. In addition, river mouth gates can stop high tides and storm surge from flowing up into the river and causing overflowing/overtopping of floodwalls during the typhoon period. Only the Huangpu River (HP), which is a main drainage river of Tai Lake (which is to the west of Shanghai), is open to the Yangtze Estuary without any gate or barrier. Figure 1 shows a schematic diagram of HP river system in Shanghai. There are five hydrological stations distributed in HP and Taipu River, namely Wusongkou (WSK), Huangpu Park (HPP), Mishidu (MSD), Jinzhe (JZ) and Pingwang (PW), which have time series of observed water levels.

Typhoon-induced rainfall can produce high runoff and increase water level in the upstream reach of HP. The safety standard for floodwalls in the upstream reach is 1/50 per year, which is far more lower than the safety standards of 1/1000 per year in the middle and downstream reaches. Therefore, the upstream reach of floodwall can be easily overflowed or breached. The latest breach occurred during Typhoon Fitow in 2013 along the upstream reach of HP with a breach width of ~15m.

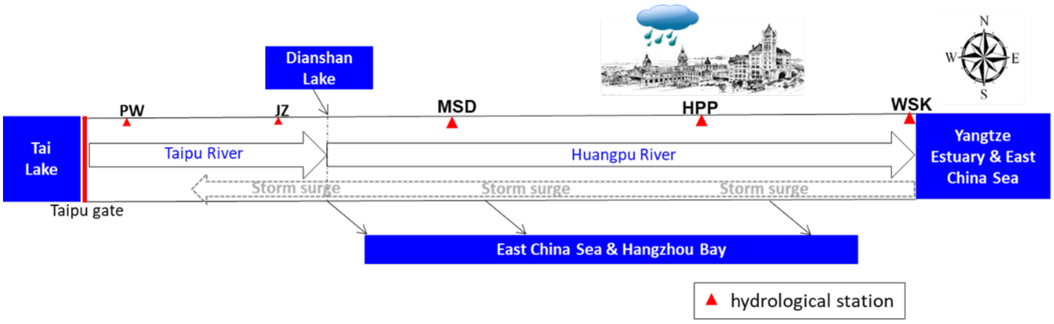


Figure 1. Schematic diagram of the river system in Shanghai (PW- Pingwang; JZ – Jinzhe; MSD – Mishidu; HPP – HuangpuPark; WSK-Wusongkou)

The pluvial flood hazard is caused by insufficient drainage capacity, or because the increased water level in the river hinders the drainage of rainwater into the river through pipeline systems driven by gravity or pumps. The latter mechanism could occur due to coincidence of fluvial and pluvial flooding during typhoon events. The objective of this paper is to develop a hydrodynamic model to simulate combined pluvial and fluvial flooding and to produce inundation maps due to failure of floodwalls and the urban drainage system. Results could raise risk awareness for decision-makers during compound flood events and demonstrate the importance of compound flood modelling at city scale.

2 DATA AND METHODOLOGY

We apply the Delft3D FM (DFM) numerical model (Deltares, 2018) to model the overland flooding due to overflowing of floodwall along the Huangpu River (caused by storm surge, high tide and high discharge from upstream watersheds) and rainfall-induced flooding events in Shanghai. Figure 2 shows the model set-up in DMF. The mesh consists of 78,963 triangular and curvilinear

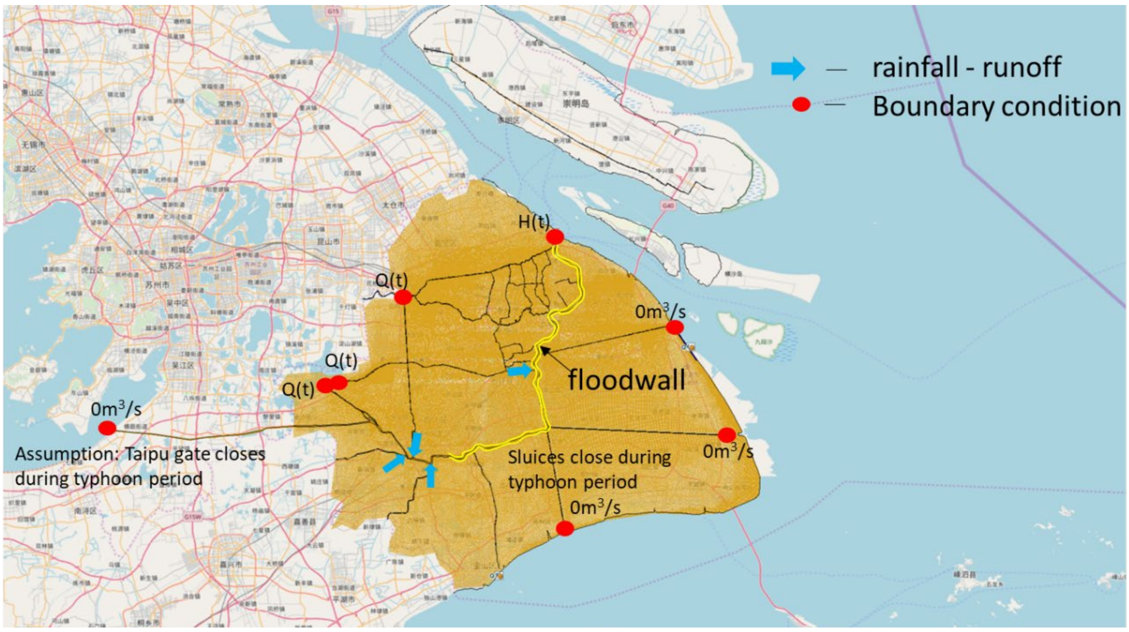


Figure 2. Model set-up in Delft3D FM for overland flooding in Shanghai city. Boundary conditions of 0 m^3/s represent lift gates that are closed during typhoons to prevent upstream propagation of storm surge.

cells, which ensures computation efficiency and accuracy (Bomers et al., 2019). The resolution of the grid cells is between ~200 and ~300m for the overland area and ~10m for the river system based on the available bathymetry data (i.e. measured bed level points). Digital Terrain Model (DTM) data (15m resolution) was then averaged onto the grid for the city. The river roughness was calibrated and validated by de Bie (2018) and van Achteren (2019). The overland roughness value (i.e. manning's roughness coefficient) was assigned based on nine land use types in Shanghai (1. Public buildings; 2. Industry and commercial buildings; 3. Residential buildings 4. Industrial facilities; 5. Green land; 6.Transportation; 7. Farmland; 8. Water bodies; 9. Unknown type.). Type 1-4 were assigned a value of $0.08 sm^{-1/3}$ and the other types were simply assigned a value of $0.025\ sm^{-1/3}$ (Kaiser et al., 2011; Ruji, 2007).

The boundary condition at the mouth of Huangpu River is a time series of observed water level (H(t) in Figure *2*) at WSK during the period of typhoon event. The other discharge boundaries at tributaries of HP were set as uniform annual average values. It was assumed that Taipu gate closes and other gates close to sea were also closed (0 m^3/s) to prevent storm surge from propagating upstream during the typhoon period (see Figure *2*).

Additional discharges generated by typhoon-induced rainfall were calculated by the rational method and the estimated time of concentration and travel time from the upstream catchments to HP were calculated by the Passini model and Manning equations (see details in Goldaracena, 2019). Floodwall data with crest height was input to function as a flood defense in DFM. It should be noted that the availability of floodwall elevation data only covered the main reach of HP (see Figure *2*), meaning that the upstream reach of floodwall was excluded because of lack of data.

Typhoon Winnie (i.e. Typhoon 9711) brought historical records of storm tide of 5.99m (Wusong datum[1]) at WSK and 5.72m at HPP. This is equivalent to approximately a 200 year return period of water level (Ke et al., 2018). During Typhoon Fitow in 2013, a water level of 4.6m was recorded at MSD; this is the highest record at this location since 1949. In addition, Typhoon Fitow brought torrential rainfall of more than 300mm/day after typhoon landfall (Bao et al., 2015). The Shanghai climate center (SCC) provided spatially varying radar rainfall data of Typhoon Fitow. In this paper, the DFM model is validated against HP water levels during Typhon Fitow. Then to investigate combined flooding, a hypothetical typhoon event was created and implemented in DFM, which took the storm tide at WSK during Typhoon Winnie as a boundary condition, and torrential rainfall during Typhoon Fitow for the rainfall-runoff calculation and for the simulation of pluvial flooding.

Due to lack of drainage system data in the whole city of Shanghai, it is assumed that the drainage capacity equals a one year return period rainfall (36mm/h); this is currently the actual design drainage capacity for most areas of Shanghai (China Daily, 2012).

3 RESULTS AND DISCUSSION

3.1 *Water level validation*

Typhoon Fitow in the period of 03-09 October, 2013 was chosen for a validation of water level at MSD in HP. Figure *3* shows an example of a comparison of measured and simulated water levels with and without the consideration of rainfall-runoff. It implies that rainfall-runoff from the upstream catchment is crucial to the results of water level, especially to the peak water level (~4.6m on the date of October 8, 2013) at MSD (which represents the upstream reach of HP).

3.2 *Inundation map*

3.2.1 *River overflow*

Figure 4 shows an inundation map due to river overflow caused by high storm tide (a coincidence of high tide with storm surge) during typhoon Winnie in 1997. The 2D inundation model shows an inundation depth of 0.2m-0.8m along the River (See Figure 4 (b)). The floodwall data was

[1] Wusong datum (WD) is around 2m lower than mean sea level in Shanghai; WD is applied in the model.

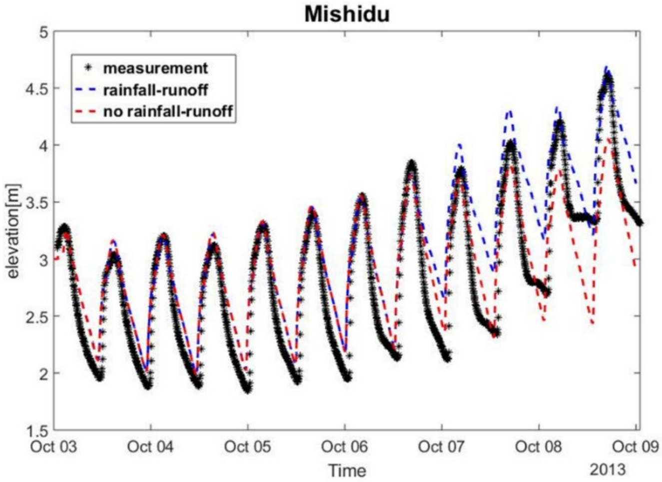
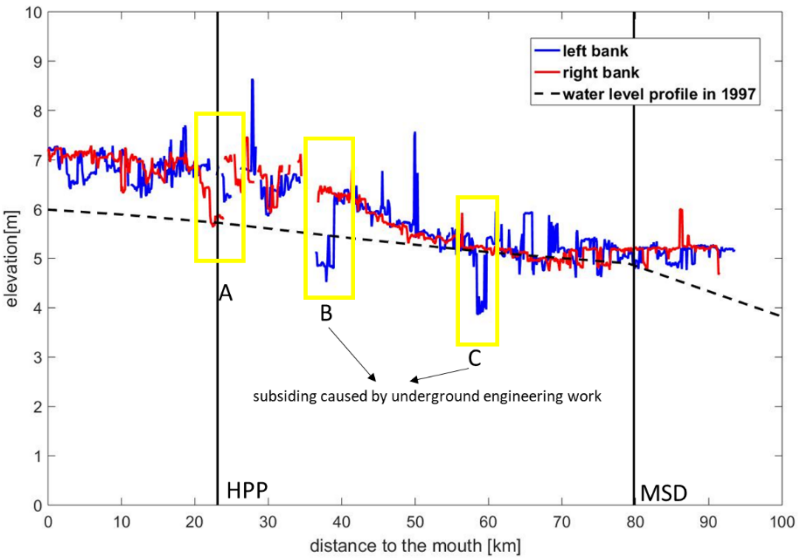
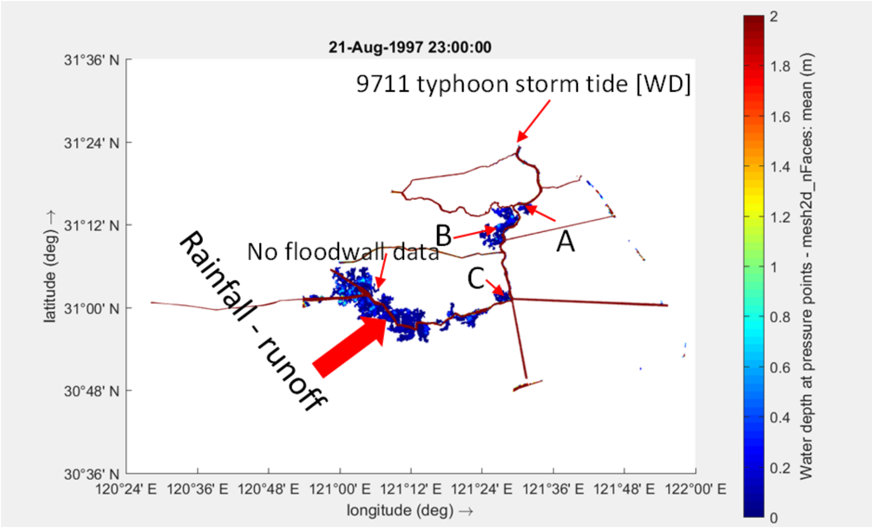


Figure 3. Comparison of measured and simulated water levels with and without the consideration of rainfall-runoff at Mishidu station in HP river during Typhoon Fitow (elevations are based on local datum)

collected in 2010's (representing current floodwall system); it had been significantly reinforced and raised after 1997 by the Shanghai Water Authority. The inundation result cannot be validated due to the updated floodwall system (which could not properly reflect the real situation at the time of 1997) and the lack of inundation data in 1997. Figure 4 shows the simulated inundation extent and depth under a scenario of high storm tide of Typhoon Winnie and high runoff from the HP upstream reach during Typhoon Fitow. It provides an indication of the performance of the present floodwall system along the Huangpu River if Typhoon Winnie storm tide and Typhoon Fitow rainfall simultaneously occur. In Figure 4(a), section A, B and C indicate vulnerable sections which require further maintenance and reinforcement. The extreme low crest height of sections B and C are caused by nearby underground engineering works and the subsequent subsidence. The inundated areas adjacent to points A and B are in downtown Shanghai, which could potentially lead to huge direct and indirect economic damage. The floodwall section between MSD and Point C also deserves a further check since (potential) inundation was observed.



(a)

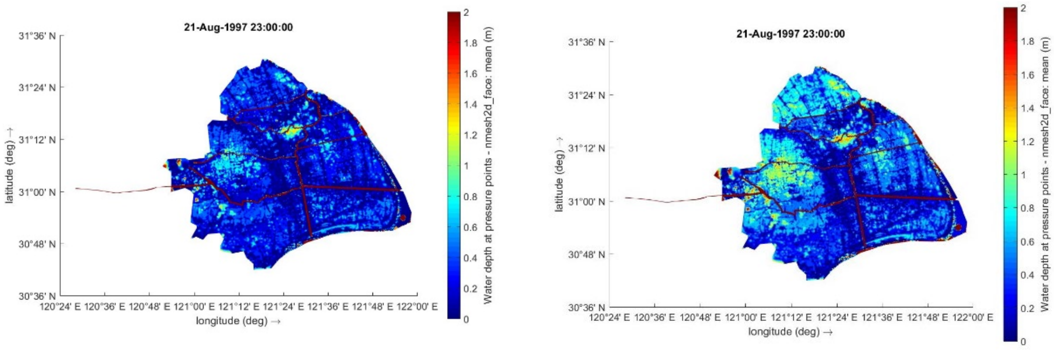


(b)

Figure 4. A comparison of floodwall crest height and water level profile under a hypothetical Typhoon case in DFM (a) and maximum inundation map due to river overflow along the HP (b)

3.2.2 *River overflow and pluvial flooding*

During a typhoon, it is very common that the water level in the river is too high, and thus the excess rainwater from the city cannot be drained by gravity or pumps. In order to ensure the stability of the floodwall system along HP, the Water Authority allows rainwater overflow into the streets. Therefore, pluvial flooding commonly occurs during typhoon events in Shanghai with tolerable water depth on the street (under 0.5-0.8m). Pluvial flooding usually causes social inconvenience (e.g. public transportation delay or flooding of the ground floors of houses) but with rarely fatal consequences. However, the failure of critical infrastructure caused by flooding, such as the blackout during Hurricane Sandy in New York, deserves further research in Shanghai. Therefore, it is worthwhile to show the expected inundation maps of the combined fluvial and pluvial flooding under scenarios with and without the drainage system.



(a) (b)

Figure 5. Maximum inundation map of Shanghai city under a hypothetical typhoon event (a combination of storm tide during Typhoon Winnie and torrential rainfall during Typhoon Fitow) under two scenarios of with drainage system (uniformly applied 36mm/hour) (a) and without drainage system (b)

Figure 5 indicates 0.7m and 0.9m average inundation depth for the scenarios of with and without the drainage system, respectively. In addition, it is shown that the west area of Shanghai suffers serious inundation in terms of extent and depth compared to other areas. This is due to the flat and relatively low topography in the west (2.5-3m WD) compared to east coastal area (4-4.5m WD) and downtown area (3-4m WD). It should be noted that the interaction of river level and the drainage system is not accounted for in the current model. This leads to an over-estimate of the inundation in Figure 5(b) since the drainage system would not really cease to function until a threshold water level (i.e. warning water level) in the rivers. In further study, real-time interaction of drainage with the river model should be implemented, where drainage only ceases after the threshold water level is reached.

4 CONCLUSION

This paper aims to develop a hydrodynamic model to simulate combined pluvial and fluvial flooding and to produce the associated inundation maps. It presents the inundation maps due to river overflow of the floodwall along HP and pluvial flooding resulting from the limited drainage capacity, under the combined scenario of two extreme events in Shanghai, namely Typhoon Winnie (with high storm tide) and Typhoon Fitow (with intense rainfall). It concludes that the current floodwall system along the Huangpu River deserves attention. The crest height is uneven due to land subsidence along several sections in the downtown area, and combined pluvial and fluvial flooding expected to be excessive in Shanghai if the drainage system can't evacuate water due to high water levels in the rivers. Storage area for excess rainwater should be planned and implemented for alleviating pluvial flooding in the future, especially under the context of climate change and rapid urbanization.

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