

Analysis of impacts of polders on flood processes in Qinhuai River Basin, China, using the HEC-RAS model

Yuqin Gao, Yu Yuan, Huaizhi Wang, Zhenxing Zhang and Liu Ye

ABSTRACT

Flood control with polders is prevalent in East China. Their impact on flood processes is critically important for flood control, but has not been well documented. The Qinhuai River Basin was selected as the study area. A Hydrologic Engineering Center – River Analysis System (HEC-RAS) hydraulic model was developed to simulate and predict storm flood processes and the associated impact of polders. The study shows that the HEC-RAS model is capable of simulating the impact of polders on flood processes in the Qinhuai River Basin. The polders increased the water level outside of the polders. The polders in upstream watersheds have a greater impact on the water level than polders close to basin outlets when individually distributed. The maximum water level at Dongshan section shows an increasing trend for different sized flood with the increasing number of polders in the basin, and a linear increasing trend associated with urbanization. The smaller the flood scale is, the greater the maximum water level changes.

Key words | flood level, flood simulation, HEC-RAS, urban agglomeration polder, urbanization

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INTRODUCTION

The hydrological effects of urbanization have been receiving increasing attention. The increasing impervious area due to the land use and land cover change caused by urbanization has been found to have a profound impact on urban hydrological process (Liu *et al.* 2011; Yerramilli 2012; Zhang & Song 2014). The impact of urbanization on the hydrological cycle in urban areas includes changes to rainfall, evaporation, and runoff (Song & Zhu 2008; Zhang 2012). Increasing impervious area due to urbanization leads to the corresponding increase of the runoff coefficient, resulting in magnified flood volumes and advanced peak flows in flood processes (He *et al.* 2003; O'Driscoll *et al.* 2010; Hamel *et al.* 2013; Schirmer *et al.* 2013). Hammer (1972) found that hydrological processes would be greatly affected when the impervious percentage of a drainage

reaches 10% or more (Hammer 1972). Klein (1979) studied 23 small watersheds in Maryland and concluded that baseflow was negatively correlated with watershed imperviousness (Klein 1979). Ng & Marsalek (1992) found that peak flows and flood volumes would increase by 20% when the impervious rate of a basin increases two times (Ng & Marsalek 1992). Jennings & Jarnagin (2002) found that urban expansion would increase river runoff (Jennings & Jarnagin 2002). Zhou *et al.* (2013) analyzed the influence of urbanization on the hydrological processes in the Yangtze River Delta region, and pointed out that the surface runoff and baseflow respond strongly to urbanization (Zhou *et al.* 2013).

Flood control is critical to a city's long-term sustainable development. Flood-related hydrological parameters of an area change during the urbanization process. Flood control policies must adapt to these changes (Stevens 2012).

Polders are the areas enclosed by embankments in coordination with advantageous terrain, natural rivers, or

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artificial rivers (Gao & Mao 1993). In flood control practices, flood protection zones, also known as urban polders, are built with existing dikes. Runoff in the polders has no direct contact with the external rivers. Polders are connected with rivers through gates and pumping stations. Flood control with urban agglomeration polders is particularly prevalent in East China, especially Suzhou, Wuxi, Changzhou and Jiaxing in Yangtze River Delta plain, and Nanjing in Qinhuai River Basin. Gao and Han qualitatively studied the influence of polders on flooding, based on an analysis of the change of water surface rate in Taihu Lake Basin (Gao & Han 1999). Yuan Yu *et al.* simulated the storm flood processes with urban agglomeration polders, using the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) with polders, and found that urban agglomeration polders have detrimental impacts on hydrological processes, including increased peak flows and flood volumes (Yuan *et al.* 2015). Gao *et al.* (2017) found that the geographic distribution of polders has no obvious impact on flood volumes, but does change peak flows. Flood volumes and peak flows gradually increase with increasing urbanization (Gao *et al.* 2017).

Hydrologic Engineering Center – River Analysis System (HEC-RAS) is an extensively applied hydraulics software developed by the US Army Corps of Engineers Hydrology Engineering Center (USACE) for constant flow surface curve calculation, unsteady flow simulation, movable boundary sediment transport calculations and water quality analysis (Brunner 2010; Xue *et al.* 2014). Wang *et al.* (2011) simulated water level changes of the Three Gorges Reservoir during 2006 and 2007 with HEC-RAS, and analyzed the reduction of floods in four parts of the watershed, downstream of the reservoir (Wang *et al.* 2011). Deng & Li (2012) applied the HEC-RAS model to the flood control evaluation of the Meg River Bridge and demonstrated that the model is applicable to the analysis of backwater height changes (Deng & Li 2012). Yerramilli (2012) analyzed and evaluated the vulnerability of Jackson, Mississippi, USA to floods by the Pearl River, using geographic information system (GIS) and HEC-RAS model (Yerramilli 2012).

This study is mainly aimed to simulate flood processes, examine the impact of urban agglomeration polders, and explore the relationship between the flood control and flood level, using the HEC-RAS model.

MATERIALS AND METHODS

Study area and data

The Qinhuai River Basin, with an area of 2631 km², is located in the lower Yangtze River Basin (Figure 1). The center of the basin is a polder plain bounded by hilly areas. It encompasses Nanjing and Jurong cities of Jiangsu province, China. The population and GDP within the polder areas account for a large proportion of the entire basin and polders play key role to control flood in the basin. There are two headwaters in the north and south of the watershed. The southern Lishui River and the northern Jurong River converge to form the main reach of Qinhuai River in Xibeicun of Jiangning District, and then diverge into two rivers in Dongshan town of Jiangning District, finally flowing into the Yangtze River at the northwest corner of Wudingmen station and Qinhuaixinhe station, respectively.

Daily discharge data for the Wudingmen and Qinhuaixinhe stations for the 21-year period of 1986–2006 are available. Flood process observation data for the main reach of Qinhuai River are available from Dongshan station. There are 44 existing observation cross sections in the basin, 13 of which lie in the 11 km long reach from Qianhancun to Dongshan village, 15 in the 15 km long reach from Dongshan village to Qinhuaixinhe station, 8 in the 11 km long reach from Dongshan village to Wudingmen station and 8 in the 12.5 km long reach from Wudingmen station to Sancha estuary.

Model setup

HEC-RAS model in Qinhuai River Basin

The HEC-RAS model is commonly used to simulate one-dimensional steady flow and unsteady flow in order to develop water surface curve calculations under different scenarios. This research examined the influence of urban polders on the flood process in the Qinhuai River Basin by using HEC-RAS model. The upper boundary condition of the model is the discharge rate at the Qianhancun station. The influence of the Yangtze River tide is not taken into

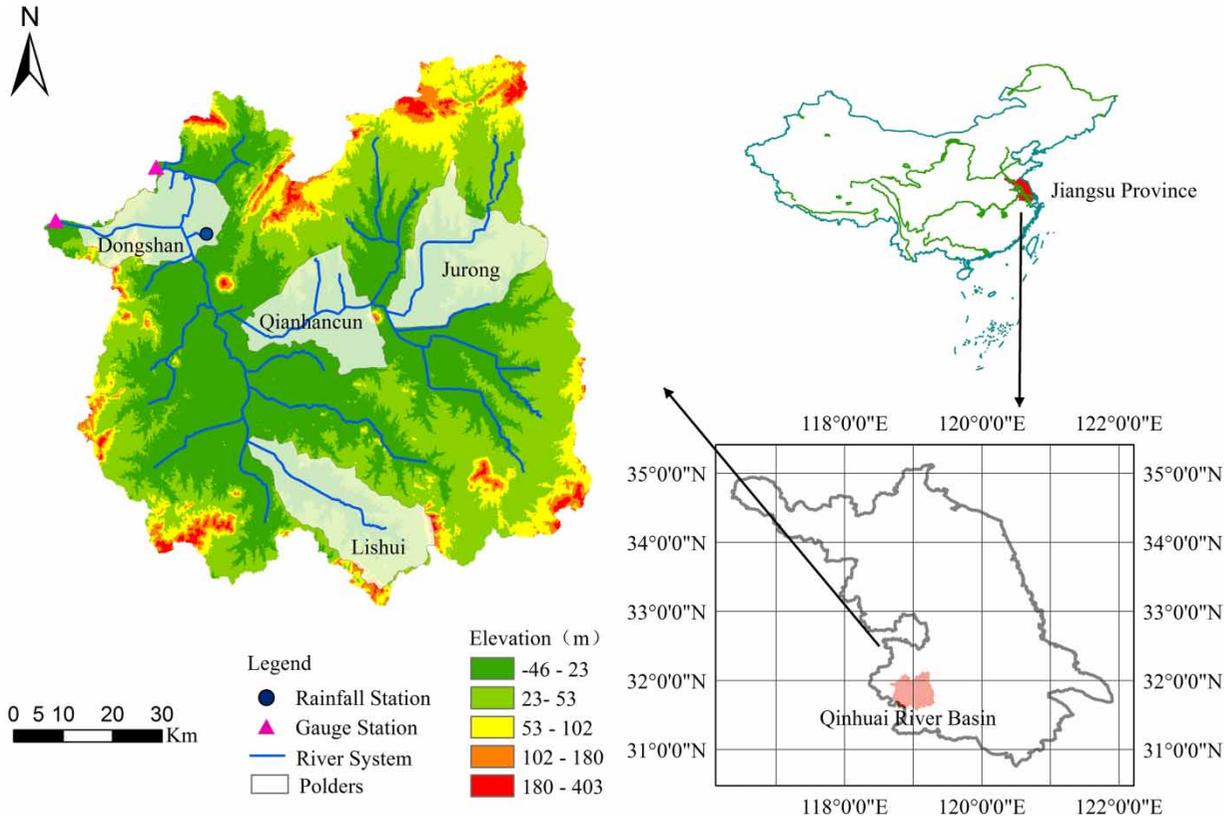


Figure 1 | The Qinhuai River Basin and its four polders.

account and the water level is subject only to flood processes in the river. The basin outlet is set to be free outflow and the lower boundary conditions are set to be normal water depth (outlet river slope) to analyze the influence of polders on mainstream river water levels.

The upper boundary discharge is based on the HEC-HMS model, which was first developed without considering polders, and then with polders added. Since the proportion of urban land in the polder is bigger than that without polder, within the hydrological model considering polders, the percentage of impervious cover and the change of CN value has increased, while the remaining model parameters such as lag time, Muskingum weighting factor X, and travel time K, stay unchanged. The model parameters of sub-basins outside the polders are the same for models with or without polders.

(a) Steady flow calculation

The simulation of steady flow in HEC-RAS software is mainly based on one-dimensional energy equation.

The direct progressive method is used to calculate the water surface curve section by section. The formula is:

$$Z_2 = Z_1 + h_f + h_j + \frac{\alpha_1 v_1^2}{2g} - \frac{\alpha_2 v_2^2}{2g} \tag{1}$$

where:

- Z_1, Z_2 are the water levels of the lower and upper sections, respectively, m;
- h_f is the frictional head loss between the upper and the lower section, m;
- h_j is the local head loss between the upper and the lower section, m;
- α_1, α_2 are the velocity coefficients of the lower section and the upper sections;
- v_1, v_2 are the velocities at the lower and upper section, m/s;
- g is the acceleration of gravity, m/s².

(b) Unsteady flow calculation

The simulation of unsteady flow in HEC-RAS software is mainly based on the continuous equation and momentum equation. The continuous equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (2)$$

where:

ρ is the density of water, kg/m³;

u is the velocity, m/s;

t is time, s;

and x is distance, m.

The momentum equation is as:

$$\frac{\partial \mu_i}{\partial t} + u_j \frac{\partial \mu_i}{\partial x_j} = f_i - \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad (3)$$

where:

f is the mass force, kg-m/s²;

p is pressure, kg-m/s²;

ν is the kinematic viscosity coefficient of water, m²/s.

Generalization of polders

Polders are located in the plains of Qinhuai River Basin with its tributaries enclosed by embankments. The gates and pumping stations regulate the water level. Rivers and ponds in the polders have certain storage capacities. Owing to the characteristics of the polders, the polders in the model are assumed to be flat bottom reservoirs. These reservoirs should have the same areas with the polders and have a certain height. According to the local investigation, the water in the polders will flow out without being pumped until it reaches maximum water depth. Drainage modulus expresses the drainage capacity of pumping stations (Wang *et al.* 1997).

There are four polders (Jurong, Lishui, Qianhancun, and Dongshan) in Qinhuai River Basin. The areas of Jurong, Lishui, Qianhancun, and Dongshan polders are 348.1 km², 286.7 km², 246.8 km² and 296.7 km², respectively. The primary land use type in the polders is urban land. In order

to drain away the flood timely for flood control, the drainage capability of urban agglomeration polders is larger than general polders. Combined with the actual situations of the polders in Qinhuai River Basin, this study set the maximum water depth as 0.1 m and drainage modulus as 4 m³/(s·km²) in the model (Cui *et al.* 2008). The location of the polders has a significant impact on water storage capacity in the basin. In order to better analyze the influence of different geographic distributions of polders on floods in the basin, the water storage area of the four polders is set to the same value and four scenarios are established:

Scenario a: Jurong polder only

Scenario b: Jurong and Qianhancun polders

Scenario c: Jurong, Lishui, and Qianhancun polders

Scenario d: Jurong, Lishui, Qianhancun, and Dongshan polders.

RESULTS AND DISCUSSION

Calibration and validation of HEC-RAS

The HEC-RAS model developed for this study is based on the cross sections and embankment data in the middle and lower reaches of Qinhuai River. The hydraulic calculation sketch and the HEC-RAS model scheme are shown in Figure 2 (the second figure was derived from the HEC-RAS model, it amplified the important region of Dongshan station). The main model parameter to be calibrated is the Manning coefficient n . The year 1987 was selected to calibrate the HEC-RAS model and the years 1991 and 2003 were selected to verify the model. The simulation results were compared with the observed water levels at Dongshan station.

The calibrated model parameters are shown in Table 1, and the results of the calibration and validation periods are shown in Figures 3 and 4, respectively. The correlations between the simulation results and the observations are shown in Figures 5 and 6, respectively. The absolute error of water level is 0.07 m on average, and the correlation coefficient is 0.981 for the calibration period. For the validation period, the average absolute errors of water level in 1991 and 2003 were 0.09 m and 0.07 m, respectively. The correlation coefficients were 0.979 and 0.977, respectively. Both

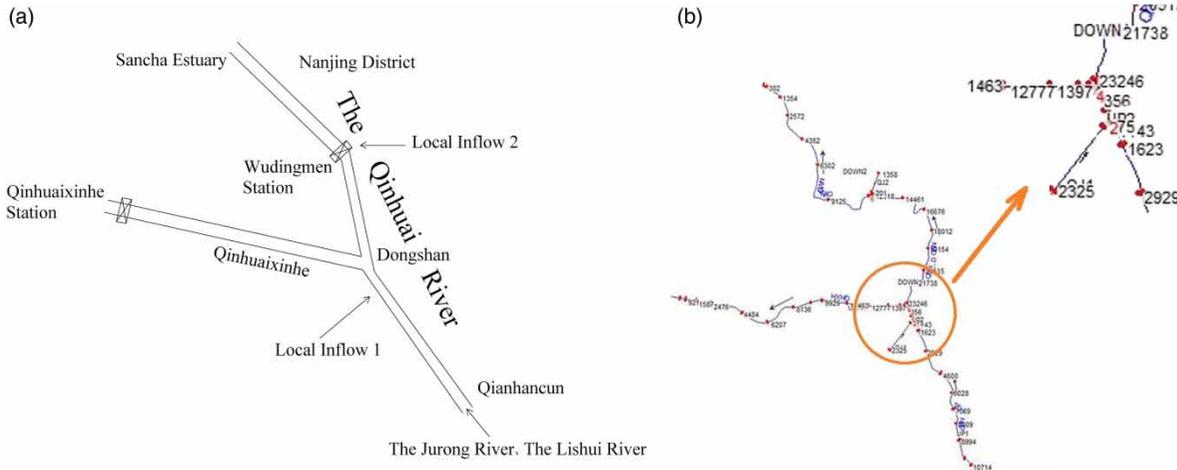


Figure 2 | Hydraulic calculation sketch and HEC-RAS model scheme of Qinhuai River Basin.

calibration and validation results demonstrated that the HEC-RAS model performed well at simulating flood processes in the middle and lower reaches of the Qinhuai River Basin.

Impact of polders on flood processes

Based on historic flood observations (1986–2006) of the Qinhuai River Basin, the typical floods in the Qinhuai River Basin are divided into three groups: minor flood (200 mm or less), medium flood (200–350 mm), and major flood (350 mm or more). Three representative storm events, namely 19890803 (minor flood), 19870701 (medium flood), 19910630 (major flood), were selected for simulation and analysis of flood processes of varying scales. From Table 2, the water levels with polders are all higher than those without polders for all three floods, with an average increase of 5.83%. The polders appear to be detrimental with respect to floodwater levels, due to the

increased water levels on the mainstem of the river, outside the polders. This result was expected as excess flood drainage due to the operation of artificial water level controls generally increases water levels in rivers adjacent to and downstream of polders. Due to flood control concerns for the cities in the polders, a large amount of water would be drained in a short time by gates and pumping stations, resulting in increased flood volumes and peak flows in the downstream mainstem river. It is also noticeable that the polders include some flood plains, which would otherwise absorb some of the floodwater. Meanwhile, for some much smaller flood, it was not necessary to drain the water

Table 1 | Calibration results of hydraulics model parameter

Reaches on the Qinhuai River		Number of sections	Manning's coefficient n
From	To		
Qianhancun	Dongshan	13	0.023
Dongshan	Qinhuaixinhe	15	0.035
Dongshan	Wudingmen	8	0.023
Wudingmen	Sancha estuary	8	0.023

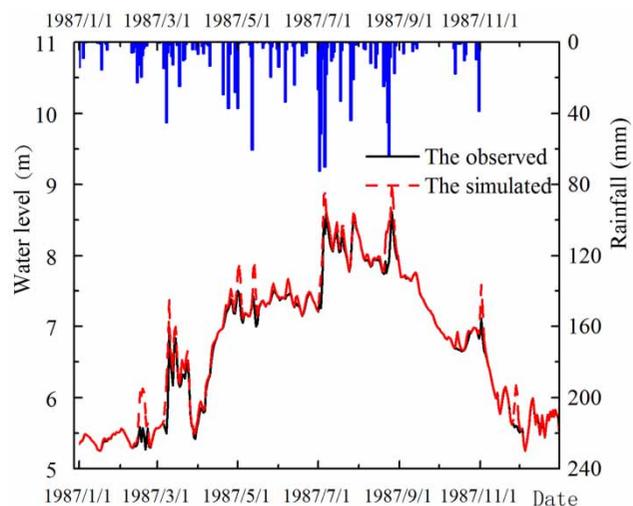


Figure 3 | Comparison of simulated and observed water levels at Dongshan gauging station for the calibration period (1987).

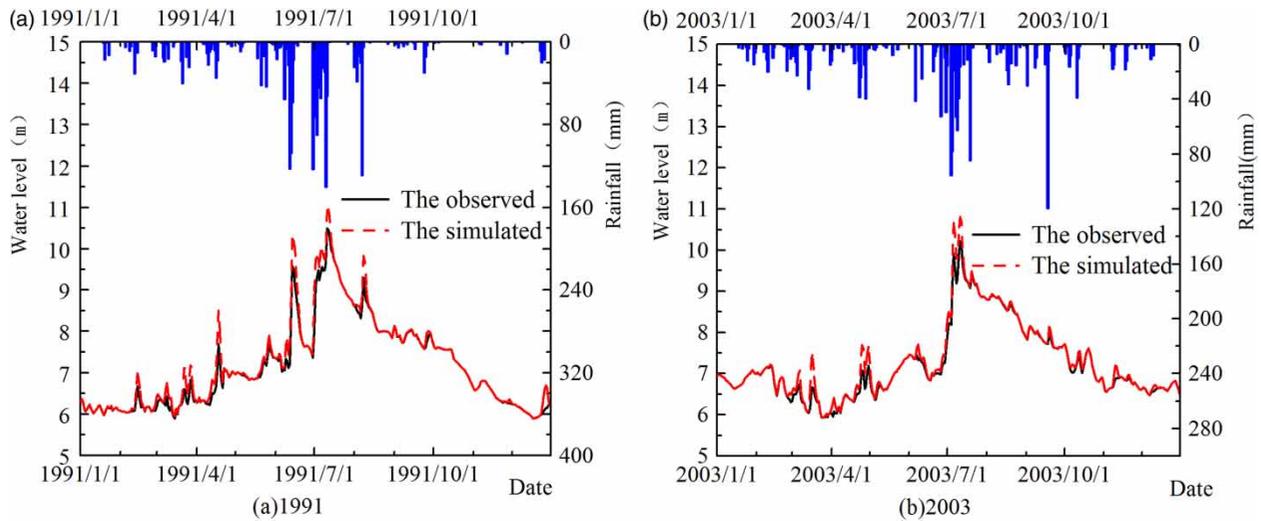


Figure 4 | Comparison of simulated and observed water levels at the Dongshan gauging station for the validation periods (1991, 2003).

inside polder, combined with the polder construction makes the area of runoff generation and confluence reduce, led to the decrease of flood volume and peak.

Impact of geographic distribution of polders

The simulated water levels at Dongshan section are shown in Figure 7. This polder, when positioned at different locations in the basin, produces different impacts to the water levels for different floods. The impacts of Jurong

and Lishui polders are similar, while the impacts from the Jurong, Qianhancun to Dongshan polders, show a gradually diminishing impact. Taking flood No. 19910630 as an example, the maximum water levels of Dongshan section for scenarios a–d are 9.66 m, 9.65 m, 9.60 m and 9.56 m, respectively. The closer the polder is to the outlet, the less impact it has on the water levels. In other words, the closer the polder is to the outlet, the greater the impact to the flows. The drainage volume from the upstream polders adds to the flood volume of the reach outside the polder, which increases the flow at the outlet and causes a corresponding increase in floodwater levels.

The simulation results for the maximum water levels at the Dongshan section for the three storm flood events under the four scenarios are shown in Table 3. It can be seen that more polders have a higher impact on the maximum water level at the Dongshan section. Taking flood No. 19870701 as an example, the relative change of the water level for scenarios a, b, c and d is 1.80%, 2.83%, 4.06% and 5.04%, respectively, showing an ascending trend. Polders cause the redistribution of water in the basin. Water is drained to maintain the low water level inside the polder for controlling floods. On the other hand, the drained water and intervening drainage are superimposed, thus causing flood process superposition outside the polder. As a result, the flood volume and peak flow are increased, increasing water levels in the rivers outside polders.

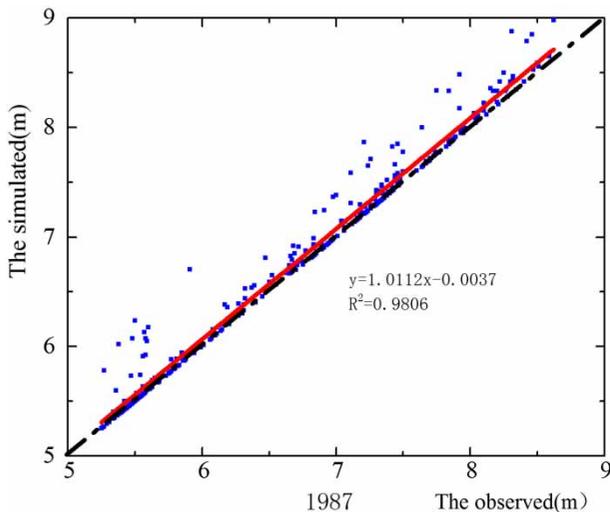


Figure 5 | Correlation of simulated and observed water levels at the Dongshan gauging station for the calibration period (1987).

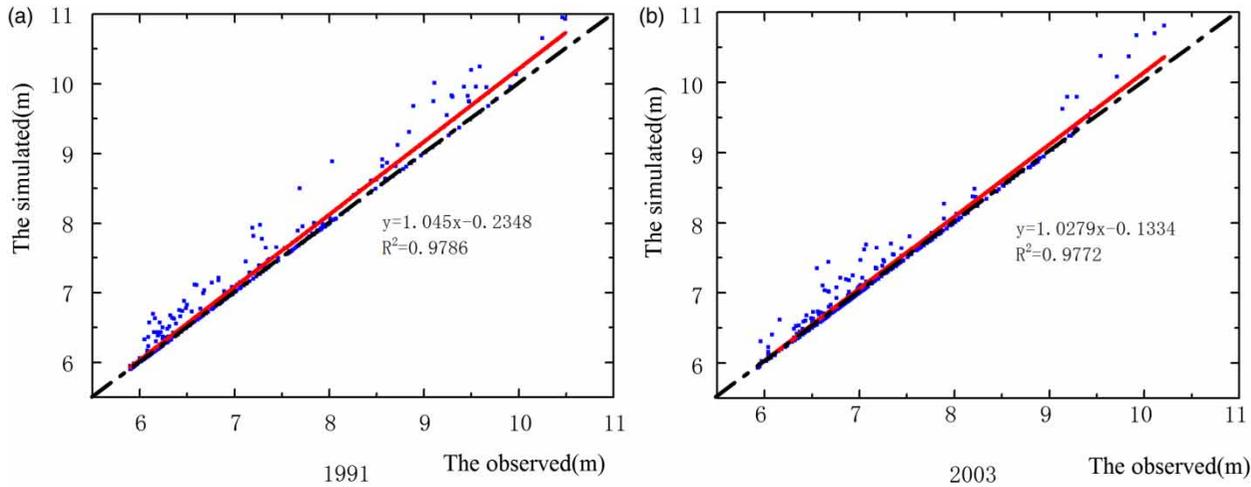


Figure 6 | Correlation of simulated and observed water levels at the Dongshan gauging station for the validation periods (1991, 2003).

Impact of polders under urbanization

In this study, four urbanization scenarios were studied: the current level of urbanization (urban land percentage of 20%) and three hypothetical urbanization scenarios (urban land percentages of 30%, 40% and 50% respectively). The hydraulic model parameter varied in the four urbanization scenarios is the imperviousness inside of the polders, while the parameters outside of the polders were unchanged.

The simulated relative change in water levels for different floods is shown in Figure 8. Compared with the current urbanization level, the maximum water level at the Dongshan section gradually increases as urban expansion increases. The water levels are positively correlated with the urbanization level. For example, the corresponding percentage of water level increase with the urban percentage of 30%, 40% and 50% are 0.23%, 0.94% and 2.00%,

Table 2 | Comparison of simulated and observed water levels at Dongshan, with and without urban agglomeration polders

Flood event	Water level (m)		Relative change (%)
	Without polders	With polders	
19890803	7.95	8.52	7.12
19870701	8.13	8.57	5.33
19910630	9.49	9.97	5.05
Mean value			5.83

respectively. Impermeable areas grow with the increase in the proportion of urban land, resulting in an increase in the runoff coefficient and the increase of surface runoff (Shao & Pan 2012). The relative trends in water level for different urbanization scenarios show a diminishing trend for minor, medium and major flood events, and that flood events of smaller scale are more sensitive to urbanization. Compared with the other two flood events, flood No. 19890803 is smaller and has a shorter duration so that the soil is not completely saturated, and the groundwater level remains low. This results in a greater impact of urbanization on the floodwater levels.

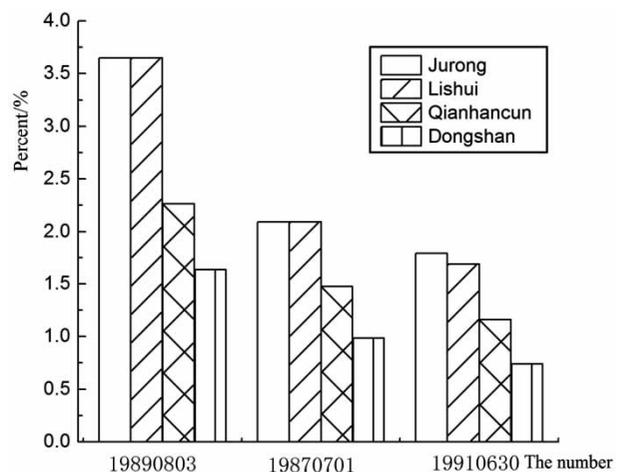
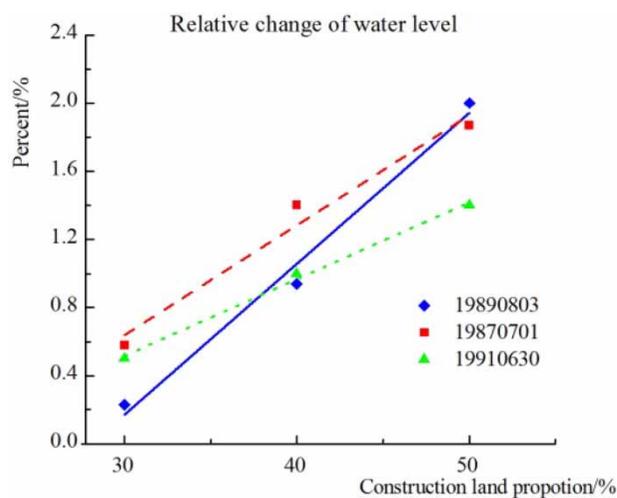


Figure 7 | The percentage of water level increase at Dongshan.

Table 3 | The simulation results of maximum water levels of four polder location scenarios for different-sized floods at the Dongshan section

Flood no.	Water level (m)				
	Without polder	a (Jurong polder only)	b (Jurong and Qianhancun polders)	c (Jurong, Lishui, and Qianhancun polders)	d (Jurong, Lishui, Qianhancun, and Dongshan polders)
19890803	7.95	8.24	8.30	8.41	8.52
19870701	8.13	8.30	8.37	8.44	8.57
19910630	9.49	9.66	9.76	9.88	9.97

**Figure 8** | The Dongshan section relative water level changes for different urbanization scenarios and different-sized floods under the flood control with urban agglomeration polders.

SUMMARY AND CONCLUSIONS

In this paper, a HEC-RAS model was developed to simulate flood processes in the Qinhuai River Basin for minor, medium, and major floods. The impact of polders and their geographic distribution on flood processes was investigated. In addition, the impact of urbanization on polders and associated hydrological processes were analyzed and predicted. The following conclusions were reached:

First, the HEC-RAS model developed for this study is suitable for the simulation flooding in the Qinhuai River Basin, a very unique hydrologic setting with polders.

Second, the polders have detrimental impacts on watershed flood control as they cause floodwater level increases outside the polders.

Third, a polder has greater impact on water level if it is located closer to the outlet of the watershed. The results also

show that increasing the number of polders increases flood-water levels.

Fourth, urbanization appears to have a linear impact on water level. Minor floods tend to be more sensitive to urbanization than major floods.

The research results reveal the flood variation and its mechanism, watershed disaster environment changes caused by the urbanization process' polders construction, which has important scientific significance to exploring proper development mode of city flood control of China's eastern region and middle basin city, and flood control construction planning and guidance as well. On the basis of this study, polder scale and distribution should be optimized, and the polder scheduling should be strengthened, reasonable allocation of polder drainage time and drainage volume cannot only protect flood control levee safety, but also reduce the influence of polder on flood process, improving the flood control capacity of river basin. The impact of polders on floodwater levels using the HEC-RAS hydraulics model in Qinhuai River Basin was explored, but there are still issues to be further examined to more fully understand the impact of polders on flood processes. For example, the discharge from the polder pumping stations may partially block the main river flood discharge. Besides, the parameter of polders in the model should be further researched to enrich the study of polders impact on the flood process.

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