

# Examining the effects of urban agglomeration polders on flood events in Qinhuai River basin, China with HEC-HMS model

Yuqin Gao, Yu Yuan, Huaizhi Wang, Arthur R. Schmidt, Kexuan Wang and Liu Ye

## ABSTRACT

The urban agglomeration polders type of flood control pattern is a general flood control pattern in the eastern plain area and some of the secondary river basins in China. A HEC-HMS model of Qinhuai River basin based on the flood control pattern was established for simulating basin runoff, examining the impact of urban agglomeration polders on flood events, and estimating the effects of urbanization on hydrological processes of the urban agglomeration polders in Qinhuai River basin. The results indicate that the urban agglomeration polders could increase the peak flow and flood volume. The smaller the scale of the flood, the more significant the influence of the polder was to the flood volume. The distribution of the city circle polder has no obvious impact on the flood volume, but has effect on the peak flow. The closer the polder is to basin output, the smaller the influence it has on peak flows. As the level of urbanization gradually improving of city circle polder, flood volumes and peak flows gradually increase compared to those with the current level of urbanization (the impervious rate was 20%). The potential change in flood volume and peak flow with increasing impervious rate shows a linear relationship.

**Key words** | flood simulation, flood volume, HEC-HMS model, peak flow, urban agglomeration polders, urbanization

**Yuqin Gao** (corresponding author)

**Yu Yuan**

**Huaizhi Wang**

**Liu Ye**

College of Water Conservancy and Hydropower Engineering,  
Hohai University,  
No. 1, Xi Kang Rd, Gu Lou District,  
Nanjing City 210098,  
Jiangsu Province,  
China  
E-mail: 178164576@qq.com

**Arthur R. Schmidt**

**Kexuan Wang**

Civil Engineering from University of Illinois Urbana-Champaign,  
UrbanaChampaign,  
USA

## INTRODUCTION

With the accelerated process of urbanization, urban flood control is developing from flood control of a single urban area to that of urban agglomerations. Among the flood controls of urban agglomerations, the single urban model plays its own role in constructing the urban flood control circle, which is known as polder type flood control pattern, and is an extensively used pattern at present. The urban agglomeration polders type of flood control pattern is particularly prevalent in plain river network regions and some of the moderate-sized basins in the eastern part of China, such as Suzhou, Wuxi, Changzhou and Jiaxing in the Yangtze River Delta plain and Nanjing, Jurong and Gaochun in the Qinhuai

River basin. The urban agglomeration polders type of flood control pattern makes new impacts on flood situations. Since the original river system is lacerated by dikes, the flood water level is higher than before. Flood formation mechanisms and flood processes are therefore different than before, with the hazard-formative environment changed greatly (Gao & Han 1999). Research on the polders type of flood control model under the background of urbanization is still in the qualitative analysis phase, which is not thorough and systemic enough.

With the gradual increase of the level of urbanization, urban agglomeration polders have significant impacts on hydrological processes in watersheds, such as increasing the peak flow, flood volume and runoff coefficient and decreasing time of concentration (Arensten *et al.* 2006; Ahn 2007). Zhou *et al.* studied the hydrological responses of land use and land cover changes in the Yangtze River Delta region, China, and pointed out that surface runoffs

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

doi: 10.2166/wst.2017.023

and baseflows were more sensitive to urbanization (Zhou *et al.* 2013). Hammer drew a conclusion through research that the watershed hydrological processes would be seriously affected when the impervious rate of the basin reached 10% (Hammer 1972). Ng and Marsalek found that the peak flow and flood volume would increase by a fifth when the impervious rate of the basin increased by 300% (Ng & Marsalek 1992). Hollis concluded that the basin was healthy while the impervious rate of urban watershed was about 10% to 20% (Hollis 1975). Rose and Peters compared the simulation results of the runoffs in the Atlanta area using different hydrological models, and discussed the influence of urbanization on watershed runoff (Rose & Peters 2001). Jennings and Jarnagin found that urban area increase had a positive role in increasing the river runoff (Jennings & Jarnagin 2002).

The HEC-HMS hydrological model is applied extensively in river basin flood processes simulation. Meenu *et al.* used the HEC-HMS model to evaluate the hydrological impacts of climate change in the Tunga-Bhadra River basin, India (Meenu *et al.* 2013). Yusop *et al.* used the HEC-HMS model to model storm flow hydrographs in an oil palm catchment in the upstream of the Skudai River in Johor (Yusop *et al.* 2011). Knebl *et al.* modeled a regional scale flood with HEC-HMS in the San Antonio River basin, USA (Knebl *et al.* 2005). Wang *et al.* confirmed that the HEC-HMS model is suitable for the areas along the Eastern Route of the South-to-North Water transfer Project. The results from the model could provide the inflow for the water resources configuration in large watersheds (Wang *et al.* 2007). Du *et al.* examined the effects of urbanization on annual runoff and flood events using the HEC-HMS model in the Qinhuai River basin, China (Du *et al.* 2012).

Basin flood problems caused by the urban agglomeration polders type of flood control pattern are both important and urgent in the current process of urbanization. In this study, the HEC-HMS model is used to explore the effects of urban agglomeration polders on flood events in the Qinhuai River basin, which is a typical representative basin of the flood control model. The specific objectives of this paper are to: (1) simulate the flood events of the Qinhuai River basin and investigate the applicability of the HEC-HMS model; (2) analyze the impacts caused by the urban agglomeration polders type of flood control pattern compared with the scenario without polders; (3) examine the effects of the city circle polder with various distributions on flood events; (4) explore the potential hydrological response to the varying impervious rate of urban agglomeration polders on flood events.

## MATERIALS AND METHODS

### Study area and data

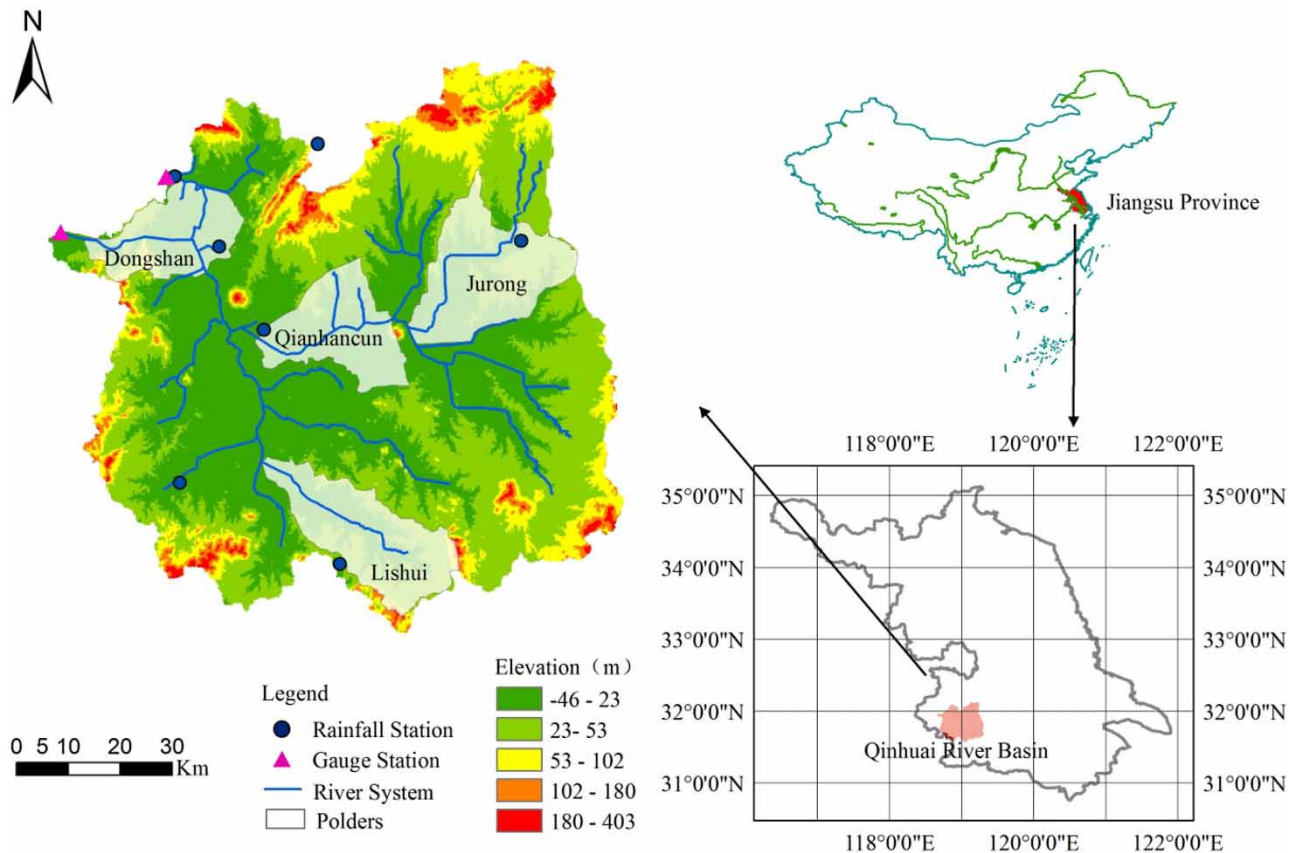
The Qinhuai River basin is located on the south bank of the reach of the Yangtze river in Nanjing between the latitudes of 31°34'–32°10'N and longitudes of 118°39'–119°19'E. The area of the basin is 2,631 km<sup>2</sup>, and the elevations range from 0 to 417 m. It encompasses Nanjing and Jurong cities of Jiangsu Province, China. The studied area lies in the semi-humid monsoon climate region, with an average annual precipitation of 1,047 mm and temperature of 15.4 C. The main land use types are paddy field, dry land, urban land and shrubwood, and the main soil types are yellow-brown soil, purple soil and limestone soil. The study used two streamflow gauging stations at the outlet of the watershed and seven rain gauge stations. The basin location, elevations, streams, and distribution of rain gauge stations and flow gauging stations can be seen in Figure 1.

The data used in this study are: (a) SRTM 90 m Digital Elevation Data (DEM) of the Qinhuai River basin; (b) ESA Globe Cover 300 m land use data from Geospatial Data cloud of the Qinhuai River basin; (c) daily rainfall data of the seven rain gauge stations for a 21-year period (1986–2006) from the China Meteorological Data Sharing Service System; (d) daily discharge data of the Wudingmen station and Qinhuai station for the 21-year period (1986–2006) from the China Meteorological Data Sharing Service System.

### Description of polders

Polders in the catchment are located in the plains of the Qinhuai River basin with its tributaries enclosed by embankments. Runoff in the polders has no direct contact with the river system, while polders connect with outside streams through human-operated structures (Zhao *et al.* 2011). The gates and pumping stations regulate the water level. The water surface ratio in the polders is higher than those outside. 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 bottomed reservoirs. These reservoirs should have the same areas as 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 the maximum water depth. The drainage modulus expresses the drainage capacity of the pumping stations (Wang *et al.* 1997).

There are four city circle polder (Jurong, Lishui, Qianhancun, and Dongshan) in the Qinhuai River basin (Figure 1). The



**Figure 1** | Location map, observed sites and distribution of urban agglomeration polders of Qinhuai River basin studied in this paper.

areas of Jurong, Lishui, Qianhancun, and Dongshan polders are 348.1 km<sup>2</sup>, 286.7 km<sup>2</sup>, 246.8 km<sup>2</sup> and 348.1 km<sup>2</sup> respectively. The main land use types in the urban agglomeration polders are urban land and dry land, with low storage. The main function of urban agglomeration polders considered in this study is city flood control. In order to drain away the flood in a timely way, the drainage capability of urban agglomeration polders is larger than general polders. Combined with the actual situations of the polders in the Qinhuai River basin, this study set the maximum water depth as 0.1 m and the drainage modulus as 4 m<sup>3</sup>/(s·km<sup>2</sup>) in the model (Cui et al. 2008). This paper does not consider the impact of the design and operation scheme of polders on flood events, thus all the polders in this paper have the same devising and operation scheme.

## Model setup and calibration

### Model setup

The HEC-HMS hydrological model developed by the US Army Corps of Engineers Hydrologic Engineering Centre

was used in this study to simulate the precipitation-runoff processes of the studied basin. The HEC-HMS model setup consists of setting up a meteorologic model, a basin model, control specifications and data systems (Wang et al. 2004). The meteorologic model is mainly used for analysis of meteorological data and establishment of the relations of meteorological data with sub-basins. The basin model is used to convert atmospheric conditions into streamflow at specific locations in the basin, and contains the basin and routing parameters of the model. Control specifications include all the timing information for the model. Data systems contain all the data used in the model (Fleming & Doan 2009).

In this study, the Specified Hyetograph method was used to determine the spatio-temporal precipitation. Thiessen Polygons established by seven rain gauge stations were the basis of specifying the observed rainfall data to use for getting the hyetograph at sub-basins (Li 2012). The study area was divided into 18 sub-basins. The Soil Conservation Service (SCS) Curve Number method was used to compute the abstractions from the watershed, which uses cumulative

precipitation, soil type data, land use data and antecedent moisture to account for continuous changes in moisture content. The parameters for this method include curve number and impervious (Fu *et al.* 2012). The SCS Unit Hydrograph method was applied to estimate direct runoff. The parameter for this method is lag time. The Recession model adopted in the present study was used to calculate the base flow explaining the drainage from natural storage in a basin. The parameters for this model are initial discharge, a recession constant and the base flow threshold ratio to peak. The Muskingum method was adopted to calculate outflow from each reach, with two parameters of Muskingum weighting factor (X) and travel time (K) (Liang 2012).

Figure 2 shows the sketch maps in the models of the Qinhuai River basin without polders and with polders. And the red circles show the main different places between the model with polder and without polder.

### Model calibration and validation

In this study, four evaluation criteria, model efficiency (NSE) (Nash & Sutcliffe 1970), correlation coefficient (R), relative peak flow error (Rev) and relative flood volume error (Rep) were used to evaluate model performance (Yong *et al.* 2006). Based on the previous studies in the Yangtze River delta (Zhou *et al.* 2013) and Tunga-Bhadra River basin (Meenu *et al.* 2013), the acceptable values for

NSE and R are more than 0.8, and for Rev and Rep less than 20%. To calibrate and verify the HEC-HMS model, eight flood events during 1986–2006 were selected.

Lag time, recession constant, base flow threshold ratio to peak, Muskingum weighting factor (X) and travel time (K) were considered as HEC-HMS calibration parameters. The optimized parameter sets for each calibrated flood events were obtained by selecting peak-weighted root mean square error as the objective function and using the Nelder and Mead simplex search algorithm provided by HEC-HMS.

## RESULTS AND DISCUSSION

### Calibration and validation of HEC-HMS for flood events simulation

The calibration and validation results for flood events are shown in Table 1.

According to Table 1, over the calibration period, the Rev and Rep values are within 20%, and NSE and R values are greater than 0.8. Rev has an average value of 2.34%, Rep has an average value of 14.62%, NSE has an average value of 0.890, and R has an average value of 0.960. The Rep value of the 19890803 flood is slightly more than 20% but within 25%, while the other values are acceptable. Therefore, the

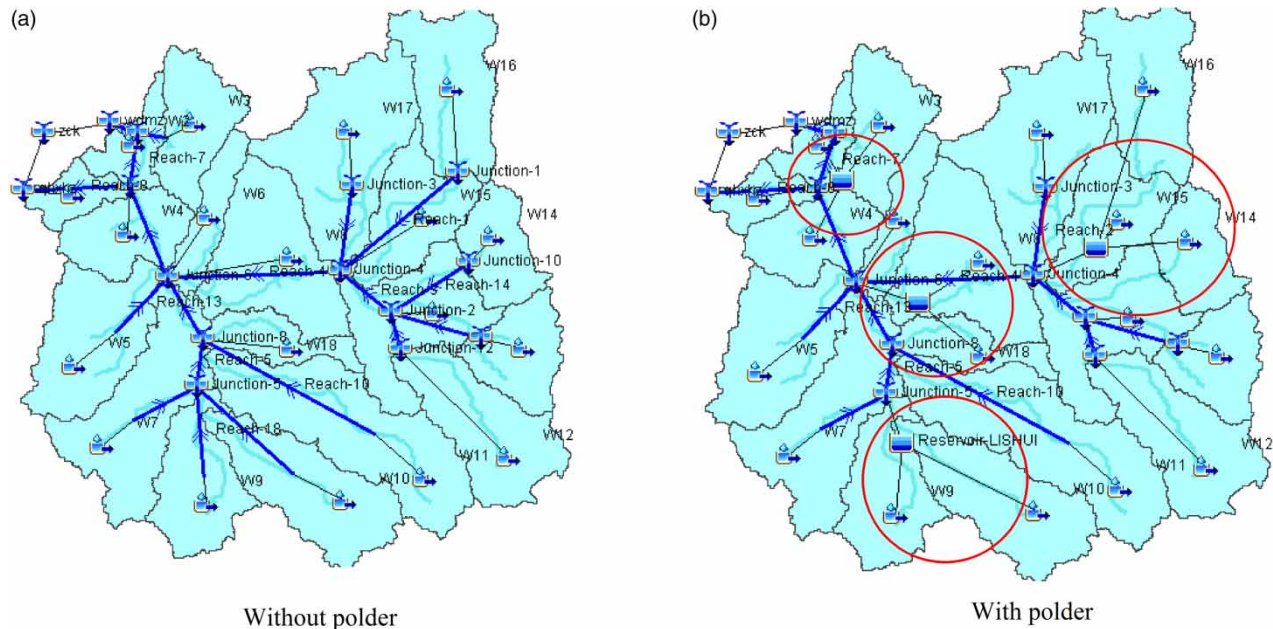


Figure 2 | Sketch maps of HEC-HMS model of Qinhuai River basin with and without the urban agglomeration polders.



**Table 1** | Summary of calibration and validation results for simulation at daily step

Period	Flood no.	Rep (%)	Rev (%)	NSE	R
Calibration	19870701	19.43	2.05	0.871	0.960
	19890803	22.94	7.03	0.900	0.970
	19990622	1.49	-2.05	0.908	0.950
Mean value		14.62	2.34	0.890	0.960
Validation	19870815	15.24	13.62	0.837	0.960
	19910630	-6.51	16.00	0.892	0.970
	19960626	14.26	-5.56	0.813	0.920
	20020619	-1.36	-6.99	0.959	0.980
	20030626	22.86	15.00	0.870	0.980
Mean value		8.90	6.42	0.870	0.960

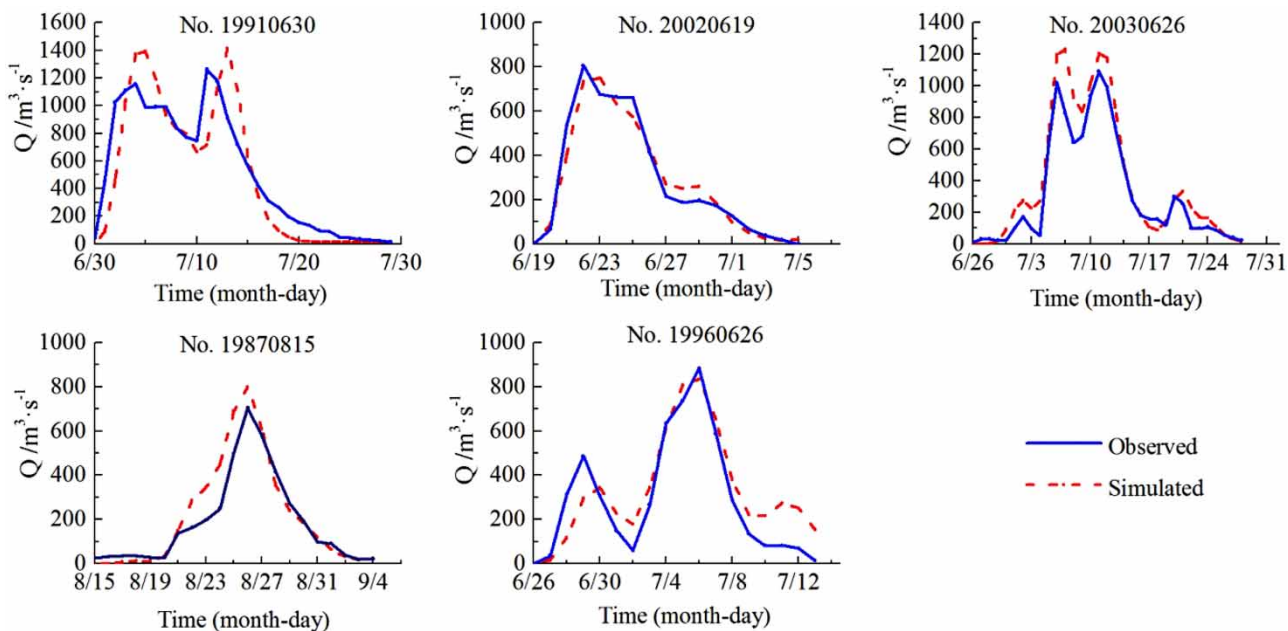
result meets the requirements. Over the validation period, Rev and Rep values are within 20%, and NSE and R values are greater than 0.8. Rev has an average value of 6.42%, Rep has an average value of 8.90%, NSE has an average value of 0.870, and R has an average value of 0.960. The Rep value of the 20030626 flood is slightly more than 20% but within 25%, and the other values are acceptable. Therefore the result meets the requirements. The comparison of simulated and observed discharges for flood events of the validation period is shown in Figure 3. It can be seen that the computed flood hydrographs agree well with the observed hydrographs. These results indicate that the HEC-HMS model was suitable for flood simulation in Qinhuai River basin.

## Impact of urban agglomeration polders type of flood control pattern on flood events

This section mainly studied the effects of the urban agglomeration polders type of flood control pattern on flood events at the current level of urbanization (impervious rate: 20%).

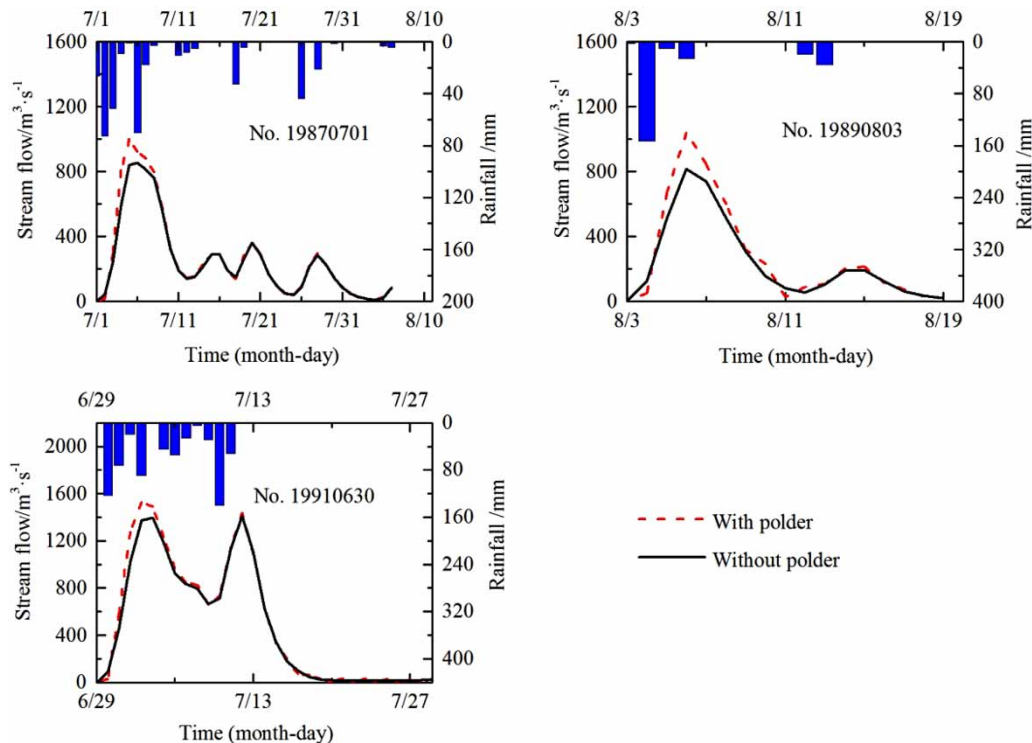
Table 2 shows the changes in flood volume and the peak flow of the flood control pattern with polders and without polders for flood events. The comparison of discharge processes for two kinds of flood control model of each flood event is shown in Figure 4. According to the results, for different-sized floods, the urban agglomeration polders type of flood control pattern increased the flood volume and peak flow discharge compared to that of the pattern without polders, with 10% average increase in flood volume and 17% average increase in peak flow.

There are reasons: the underlying surface conditions change in the city circle polder compared to the land without a polder, and the increased proportion of land under urban construction results in impervious rate increases. Under similar rainstorms, runoff increases inside the city circle polder, and the drainage volume from the polder increases, so that the flood volume will increase. With the polder's water volume increased, the polder should drain the water in a short time, considering the flood control security of the city inside the polder. Drainage time for the water from the polder overlaps with the time of the peak

**Figure 3** | Comparison of simulated and observed stream flows for flood events of the validation period.

**Table 2** | Simulated results of flood control pattern with urban agglomeration polders and without polders for flood events

Flood no.	Flood volume (mm)		Relative flood volume error (%)	Peak flow (m <sup>3</sup> /s)		Relative peak flow error (%)
	With polder	Without polder		With polder	Without polder	
19890803	161	137	17.22	1,040	818	27.24
19870701	340	313	8.51	1,000	855	16.93
19910630	532	503	5.70	1,524	1,393	9.47
Mean value			10.48			17.88

**Figure 4** | Comparison of stream flows of flood control pattern with the urban agglomeration polders and without polders for flood events.

flow of the reach outside the polder, different polders' drainage time overlaps, so that the peak flow would increase.

Figure 5 shows the trend of relative change in flood volume of flood control pattern with polders and without polders for different-sized flood events. With the increase in flood volume of different-sized floods, the relative change decreased from 17.22% to 5.70%. The degrees of influence the polders have on the flood volume of different-sized floods were varied. The effects on flood volume caused by polders became obvious at small flood volumes.

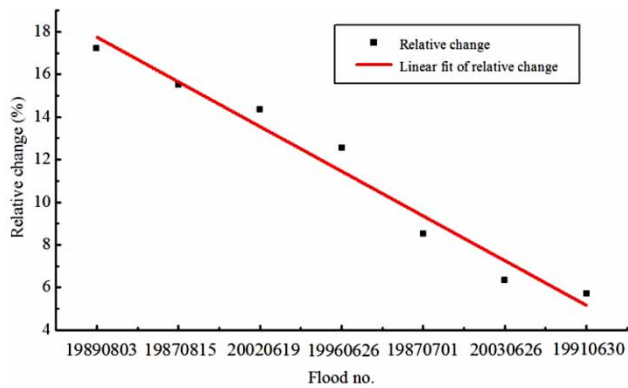
This is because runoff increment is similar under different-sized floods in the polder, the flood volume increases with the increase in the scale of the flood, so that the relative

change in the flood volume between the urban agglomeration polders type of flood control pattern and the pattern without polders decreases linearly.

### Impact of distributions of city circle polder on flood events

This section mainly studied the effects of distributions of city circle polder on flood events under the current level of urbanization (impervious rate: 20%).

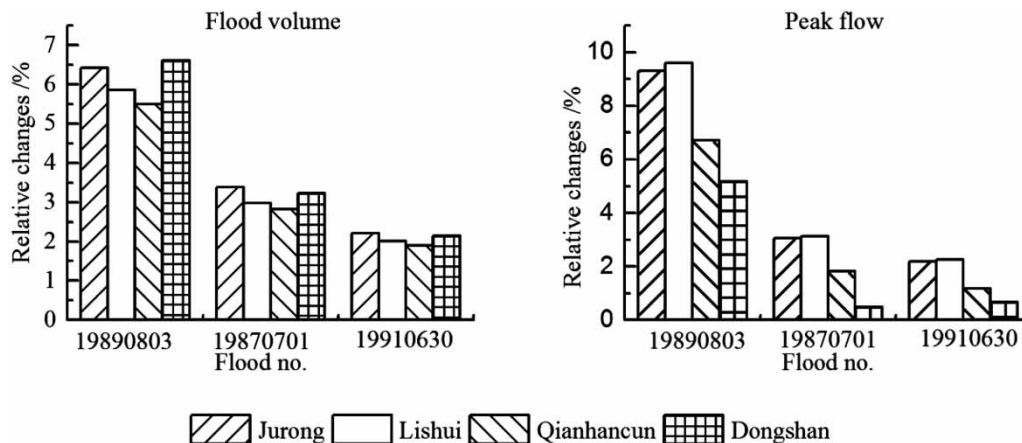
The relative changes of flood volumes and peak flows with four kinds of distributions of city circle polder compared to the results without polders can be seen in



**Figure 5** | The trend of relative change in flood volume of flood control pattern with polders and without polders for different-sized flood events.

**Figure 6.** It was found that the distribution of the city circle polder has no obvious effect on flood volume for different-sized floods. Taking flood No. 19910630 as an example, the relative changes of flood volume for four kinds of distributions of city circle polder (Jurong, Lishui, Qianhancun and Dongshan) compared with the results without polders are 2.21%, 2.00%, 1.90% and 2.16% respectively. Such phenomena could be explained by the fact that the storage area, maximum water depth and drainage modulus of the four polders are almost the same, so the increase in flood volume caused by the polders is about the same.

The results in **Figure 6** also show that the distribution of the city circle polder has an obvious effect on peak flow for different-sized floods: the closer the polder is to the basin outlet, the lower the influence it has on peak flows. The degree of influence is basically identical among Jurong and Lishui (distributed in the upper catchment), Qianhancun (distributed in the middle catchment) and Dongshan (distributed in the lower catchment) are gradually diminishing.



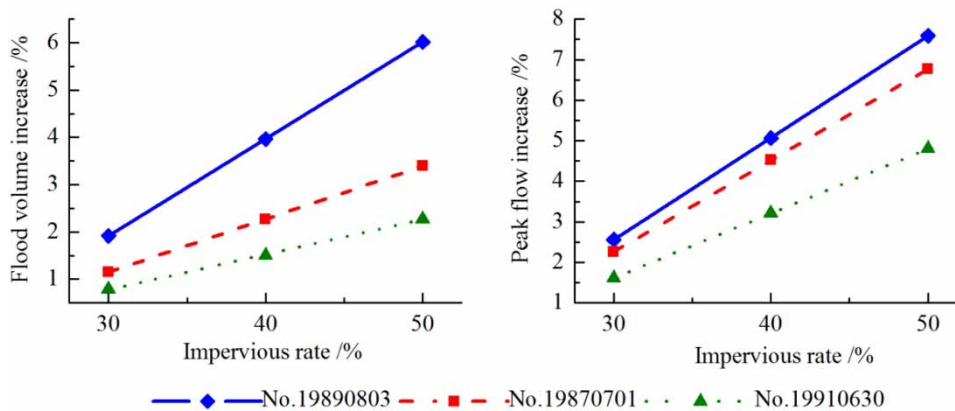
**Figure 6** | Percentage increase in flood volumes and peak flows of four kinds of distributions of city circle polder relative to the results without polders.

Taking flood No. 19890803 as an example, the relative changes of peak flow for four kinds of distributions of city circle polder (Jurong, Lishui, Qianhancun and Dongshan) compared with the results without polders are 9.31%, 9.61%, 6.70% and 5.17% respectively. This is because the closer the polder is to the upstream end of the river, the longer the distance and time of the flood pumped out from the polder routes in the river channel, and the flood will be superimposed onto most of the outflow of other sub-basins and the degree of change is much more prominent.

### Impact of urbanization of urban agglomeration polders type of flood control pattern on flood events

The runoff process is usually affected by climatic conditions and land use situations. In order to examine the effects of urbanization on hydrological processes of the urban agglomeration polders type of flood control pattern, this section predictively analyzes four urbanization scenarios on the premise of meteorological data being unchanged for flood events. Three flood events of different sizes were selected to assess the potential change in response to urbanization. Four urbanization scenarios, the current level of urbanization (impervious rate: 20%) and three assumed future urbanization scenarios (impervious rate: 30%, 40% and 50% respectively), were studied in this section. The imperious rate considered in this paper is the average level of the Qinhuai River basin.

The sensitivities of the flood volume and peak flow to urbanization (impervious rate) were examined, and the simulated flood volume and peak flow with increasing impervious rate for various flood events are shown in **Figure 7**. As the level of urbanization of the Qinhuai River basin urban agglomeration polders type of flood control pattern gradually



**Figure 7** | The potential changes in flood volume and peak flow with increasing impervious rate for different-sized floods.

improved, flood volumes and peak flows gradually increased for all the flood events. And it was found that all the curves are close to linear. Taking flood No. 19890803 as an example, the impervious rate increased from 30% to 50%, and the increases in flood volumes and peak flows compared with the current level of urbanization were from 1.92% to 6.2% and from 2.56% to 7.59%, respectively.

## SUMMARY AND CONCLUSION

This paper conducted a case study in the Qinhuai River basin using the HEC-HMS hydrological model to examine the effects of urban agglomeration polders on flood events. The following conclusions are drawn from the study.

Firstly, the HEC-HMS distributed hydrological model was found to be a good approach for simulating flood runoff in Qinhuai River basin.

Secondly, the impervious rate in the city circle polder is bigger than in the land without polder, and under similar rainstorms, runoff increases inside the city circle polder, and drainage volume from the polder increases. With the polder's water volume increased, the polder should drain out the water in a short time, considering the flood control security of the city inside the polder. The drainage time overlaps with the time of peak flow of the reach outside the polder, and different polders' drainage times overlap. Thus the urban agglomeration polders type of flood control pattern brought adverse impacts for the basin flood control, in that the flood volume and peak flow were increased compared with the pattern without polders. The runoff increment is similar under different-sized floods in the polder. The flood volume increases with the increase in the scale of the flood. Therefore the degree of influence of the polders on the flood volume of different-sized flood

was varied. The effects on flood volume caused by polders became obvious at small flood volumes.

Thirdly, since the storage area, maximum water depth and drainage modulus of the four polders are almost the same, the distribution of the city circle polder had no obvious effect on the flood volume for different-sized floods. The closer the polder is to the upstream end, the longer the distance and time for the flood to pump out from the polder routes into the river channel. And the flood will be superimposed onto most of the outflow of the other sub-basins. Correspondingly, the distribution of the city circle polder had an effect on peak flow, and the closer the polder was to the basin outlet, the lower the influence it had on peak flow.

Fourthly, as the level of urbanization gradually increases in the city circle polder, the increased proportion of urban construction results in increases in the impervious rate. Consequently, the flood volume and peak flow gradually increased compared with the current level of urbanization (the impervious rate was 20%), the potential change in flood volume and peak flow with increasing impervious rate showed a linear relationship. In simple terms, the relations between urbanization and flood volume and peak flow displayed positive correlation.

The study method will provide helpful reference and consulting for related similar researches conducted in other regions. The conclusions of this paper will be useful for flood control and drainage and water resources planning and management in the Qinhuai River basin.

## ACKNOWLEDGEMENTS

The study is supported by the National Natural Science Foundation of China (No. 51309076), the Fundamental Research



Funds for the Central Universities (No. 2014B05814). Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

## REFERENCES

- Ahn, G.-C. 2007 *The Effect of Urbanization on the Hydrologic Regime of the Big Darby Creek Watershed, Ohio*. The Ohio State University, Ohio, USA.
- Arensten, P. R., Mesner, N. & Gillies, R. 2006 *The Effects of Urbanization on Watershed Functions: The Relationship between Impervious Surface Area and Water Quality in Cache County, Utah*. Utah State University, Utah, USA.
- Cui, H., Liu, J. & Gao, C. 2008 Study on drainage modulus calculation method of diked area. *Journal of Catastrophology* **3** (02), 15–18.
- Du, J., Li, Q., Rui, H., Zuo, T., Zheng, D., Xu, Y. & Xu, C. Y. 2012 Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China. *Journal of Hydrology* **464–465** (5), 127–39.
- Fleming, M. J. & Doan, J. H. 2009 *HEC-GeoHMS Geospatial Hydrologic Modelling Extension: User's Manual Version 4.2*. US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Centre, Davis, CA.
- Fu, S., Wang, X., Wang, H., Wei, X. & Yuan, A. 2012 Method of determining CN value in the SCS-CN method. *Arid Land Geography* **35** (03), 415–421.
- Gao, J. & Han, C. 1999 Polders in Taihu Lake region and its effects on floods. *Journal of Lake Science* **11** (02), 105–109.
- Hammer, T. R. 1972 *Stream channel enlargement due to urbanization*. *Water Resources Research* **8** (6), 1530–1540.
- Hollis, G. E. 1975 *The effect of urbanization on floods of different recurrence interval*. *Water Resources Research* **11** (3), 431–435.
- Jennings, D. B. & Jarnagin, S. T. 2002 *Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-Atlantic subwatershed*. *Landscape Ecology* **17** (5), 471–489.
- Knebl, M. R., Yang, Z. L., Hutchison, K. & Maidment, D. R. 2005 *Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event*. *Journal of Environmental Management* **75** (4), 325–336.
- Li, Q. 2012 *Changing of Spatial Pattern and the Hydrological Response of Urbanization in Qinhuai River Basin*. Nanjing University, Nanjing, China.
- Liang, R. 2012 *Application of HEC-HMS in the Beizhangdian Watershed*. Tai Yuan University of Technology, Taiyuan, China.
- Meenu, R., Rehana, S. & Mujumdar, P. P. 2013 *Assessment of hydrologic impacts of climate change in Tunga-Bhadra basin, India with HEC-HMS and SDSM*. *Hydrological Processes* **27** (11), 1572–1589.
- Nash, J. E. & Sutcliffe, J. V. 1970 *River flow forecasting through conceptual models part I – a discussion of principles*. *Journal of Hydrology* **10** (3), 282–290.
- Ng, H. Y. F. & Marsalek, J. 1992 *Sensitivity of streamflow simulation to changes in climatic inputs*. *Nordic Hydrology* **23** (4), 257–272.
- Rose, S. & Peters, N. E. 2001 *Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach*. *Hydrological Processes* **15** (8), 1441–1457.
- Wang, L., Peng, P., Zhou, Y. & Du, J. 1997 *Study on mechanism of runoff-yield in plain polders*. *Journal of Nanjing University (Natural Science)* **33** (01), 160–164.
- Wang, J., Zhang, X. & Lu, Z. 2004 *Digital hydrological model of Qinhuai River basin and its application*. *Journal of Hydraulic Engineering* **35** (04), 42–47.
- Wang, L., Zhao, H. & Jiang, Y. 2007 *Application of HEC-HMS program to water resources allocation for east route of South-to-North diversion project*. *South-to-North Water Transfers and Water Science & Technology* **5** (06), 58–61.
- Yong, B., Zhang, W., Zhao, D. & Zhu, Q. 2006 *Application of hydrological modeling system HEC-HMS to Baohe catchment of Hanjiang Basin*. *Bulletin of Soil and Water Conservation* **26** (3), 86–90.
- Yusop, Z., Chan, C. H. & Katimon, A. 2011 *Runoff characteristics and application of HEC-HMS for modelling stormflow hydrograph in an oil palm catchment*. *Water Science & Technology* **56** (8), 41–48.
- Zhao, G., Hörmann, G., Fohrer, N., Gao, J., Li, H. & Tian, P. 2011 *Application of a simple raster-based hydrological model for streamflow prediction in a humid catchment with polder systems*. *Water Resources Management* **25** (2), 661–676.
- Zhou, F., Xu, Y., Chen, Y., Xu, C. Y., Gao, Y. & Du, J. 2013 *Hydrological response to urbanization at different spatio-temporal scales simulated by coupling of CLUE-S and the SWAT model in the Yangtze River Delta region*. *Journal of Hydrology* **485**, 113–125.

First received 25 July 2016; accepted in revised form 3 January 2017. Available online 20 February 2017