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Assessing the Effects of Urbanization on Flood Events with Urban Agglomeration Polders Type of Flood Control Pattern Using the HEC-HMS Model in the Qinhuai River Basin, China

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Received: 9 June 2018; Accepted: 27 July 2018; Published: 29 July 2018

Abstract: Urban agglomeration polders type of flood control pattern (UAPFCP) is an extensively used pattern for urban flood control in plain water system areas. Urbanization and polders are two main factors that affect the runoff process in these regions. The Qinhuai River basin, one of the representative watersheds of this flood control pattern in East China, was selected to perform the study. Five urbanization scenarios (the historical, current, and three assumed future urbanization scenarios) of the basin were defined in this paper. The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) was used to simulate basin runoff. The results indicate that the UAPFCP increased the flood volume (Q_v) and peak flow (Q_p) compared to the results under the condition without polders. With the constant improvement of the urbanization level of the basin, Q_v and Q_p under the with polder condition increased correspondingly, and the potential changes show a linear relationship. The urbanization and urban agglomeration polders have interactions with flood events. The effect of urbanization on the flood process is weakened because of the existence of urban agglomeration polders. With the constant improvement of the urbanization level, the effect on the flood process caused by urban agglomeration polders becomes gradually weaker.

Keywords: urbanization; urban agglomeration polders; HEC-HMS; flood simulation; hydrological response

1. Introduction

Urbanization typically replaces permeable vegetated land surface with imperious surface area and significantly changes the hydrologic fluxes of a drainage basin [1]. It decreases infiltration, baseflow, and lag times while increasing flood volume, peak flow, and water depth etc. [2,3]. Since urbanization develops so rapidly nowadays, flood problems in cities are becoming steadily worse [3]. In developed regions, the flood risk problem is much more serious due to the highly developed economy, dense population, and high degree of urbanization [4]. Many researches on simulating and assessing the hydrological response to urbanization on the watersheds scales have been carried out. Beighley et al. pointed out that urbanization would increase the runoff volume and peak flow while decreasing the streamflow variability in a Mediterranean climate watershed [5]. Zhou et al. found that the surface runoff and baseflow are more sensitive to urbanization in the Yangtze River Delta region, China [6]. Remondi et al. explored the hydrological impact of land use and land cover changes (LUCC) on a river catchment in Indonesia and pointed out that the uncontrolled urban expansion leads to a noticeable increase of flood events during the rainy season [7].

Urban flood control is facing enormous challenges, because of the accelerated process of urbanization. In order to deal with the problem, the urban flood control pattern has been evolved from single city flood control to urban agglomerations flood control [8]. The UAPFCP is an extensively used pattern at present for urban flood control in many countries [9], particularly prevalent in plain water system areas. The flood situations are affected by the UAPFCP. Since the polders' levees split the original river network system, the flood processes and flood formation mechanisms are significantly different from before. The hazard-formative environment also changes greatly [10]. Zhao et al. developed a raster-based distributed hydrological model for runoff simulation integrating flood polder regulation in the Xitiaoxi catchment of Taihu Lake basin and pointed out that the peak flow and flood volume were increased because of the existence of urban agglomeration polders [11].

Based on the above introduction, urbanization and urban agglomeration polders are the two main factors that affect the runoff process. With the accelerated urbanization process and increased popularization of the UAPFCP, research on the hydrological response to urbanization has become more urgent and important, and needs further discussion. Moreover, the interaction between urbanization and urban agglomeration polders on flood events has not yet been clearly illustrated.

Hydrological models are frequently used for flood processes simulation on the watershed scale [6,12]. The purpose of study and data accessibility determine the principle of model selection [13]. Many researches have confirmed that the HEC-HMS hydrological model is applicable in simulating runoff processes. HEC-HMS was developed by the Institute for Water Resources Hydrologic Engineering Center of US Army Corps of Engineers. Meenu et al. applied HEC-HMS in the Tunga-Bhadra river basin of India to assess the hydrological response to climate and land cover change [9]. Suriya and Mudgal considered the land use change in HEC-HMS to discuss the influences of urbanization on flooding for flood risk management in the Thirusoolam sub-watershed in India [14]. Du et al. applied HEC-HMS in the Qinhuai River basin of China to assess the effects of rapid urbanization on flood events and annual runoff [15].

With the acceleration of urbanization since China's reform and opening-up in the 1980s, urban flood control has become an important factor restricting economic development, especially in some fast-developing regions, such as the Yangtze River Delta. In 2016, the documents "Yangtze River Economic Belt" and the "Development Planning of Urban Agglomeration in Yangtze River Delta" were approved by the State Council of China, these documents proposed that by 2030, the Yangtze River Delta urban agglomeration would be built into a world-class urban agglomeration with global influence. There are many river systems in this region, such as the main stream of the Yangtze River, Taihu Lake river system, the Lixia River system, the Qinhuai River system and the Yong, Cao, Pu districts river system etc. The flood issues caused by rapid urbanization and urban agglomeration have become increasingly prominent in these regions. In order to deal with this kind of flood problem, since 2000, the UAPFCP has been gradually developed in many large and medium-sized cities in the Yangtze River Delta region, such as Changzhou, Suzhou, Wuxi in the Taihu Lake basin, Fenghua, Yinzhou in the Yongjiang River basin and Jurong, Nanjing in the Qinhuai River basin. The Qinhuai River basin, one of the most developed regions in the Yangtze River Delta region, is a representative watershed of the flood control pattern, and has typical characteristics of "a small watershed but big flood control problem". Since 2009, the existing layout of UAPFCP in the Qinhuai River basin has basically taken shape.

This paper used the HEC-HMS model to explore the effects of urbanization on flood events of UAPFCP in the Qinhuai River basin. Based on the distribution of urban agglomeration polders and the historical and current land use situations in the study area, the main objective of this study was to develop the layout of UAPFCP, establish the HEC-HMS model, and assume different urbanization scenarios. Based on the layout, model and scenarios, the impact of UAPFCP on flood events and the hydrological response to urbanization of UAPFCP were analyzed, and the interaction between urbanization and polders on flood events was discussed.

2. Materials and Methods

2.1. Study Area

The Qinhuai River basin, located on the south bank of the Yangtze river between longitude 118°39′~119°19′E and latitude 31°34′~32°10′N, was selected to study in this paper (Figure 1). The area of the basin is 2631 km^2. It is one of the core areas of the Yangtze River Delta. There are two outlets of the study basin, and there are gauge stations for the two outlets, which are the Qinhuaixinhe station (QHXHS) and the Wudingmen station (WDMS). The total discharge of the watershed is the sum of the discharge of the two outlets.

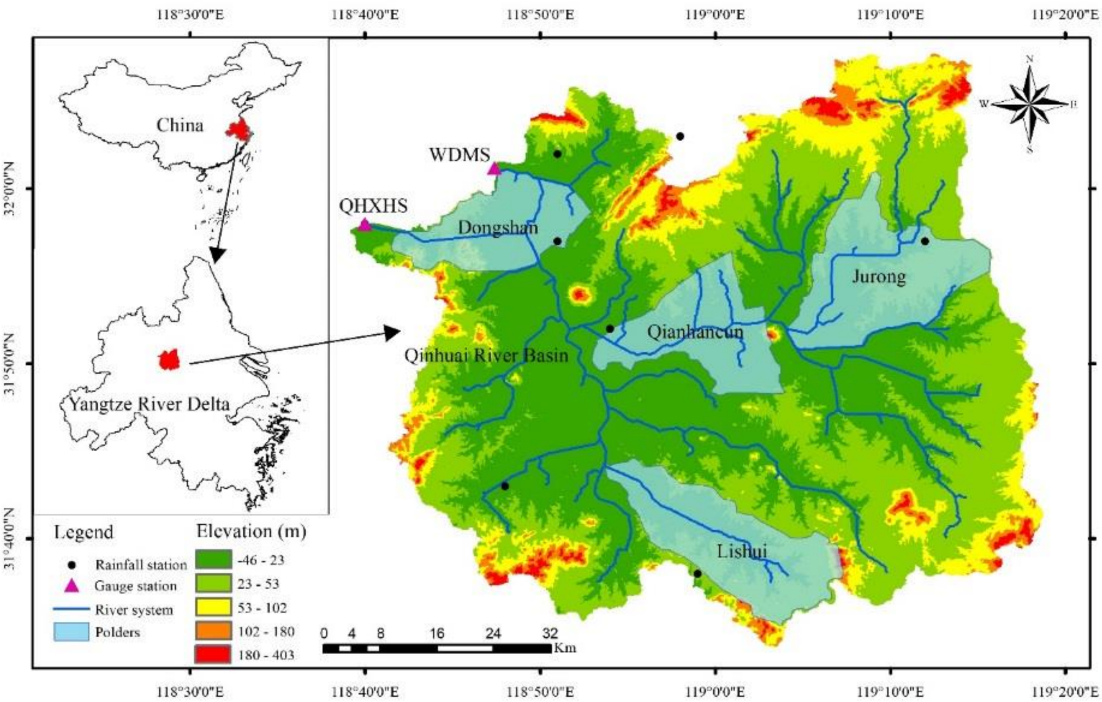

Figure 1. Location of the study area, distribution of urban agglomeration polders, and rainfall and gauge stations.

The research area is located in the semi-humid climate region. The average annual temperature is approximately 15.4 °C and precipitation is about 1047 mm. The main land use types include paddy field, urban land, and dry land. The dry land in the study area mainly includes dry farming land and bare land. According to the Harmonized World Soil Database, there are mainly six kinds of soil types in the Qinhuai River basin, Dystric Regosols (RGd), Eutric Fluvisols (FLe), Cumulic Anthrosols (ATc), Eutric Gleysols (GLe), Haplic Luvisols (LVh), and Eutric Planosols (PLe). Because of the weather characteristics and underlying surface characteristics, flood disasters occur frequently in the study area, mainly in the heavy rainy season (April to September).

The Qinhuai River basin is relatively flat with hilly areas surrounding it, and there are low-lying plains in the center. The basin is a typical place of plain water system area, with well-developed, crisscrossed and wide rivers as well as scattered lakes and reservoirs. Based on the above characteristics, the basin has a certain ability of peak regulation, peak flow is smaller and the flood processes are comparatively gentle and last longer.

The data used in this study is presented in Table 1.

Table 1. The data used in this study.

Data Types	Time	Sources
Daily rainfall	1986–2015	China Meteorological Data Sharing Service System
Daily discharge	1986–2015	China Meteorological Data Sharing Service System
Soil data	2009	Harmonized World Soil Database
Land use data	1988, 1994, 2002, 2016	European Space Agency GlobCover
Digital Elevation Model	2009	Shuttle Radar Topography Mission

2.2. Description of Urban Agglomeration Polders

Urbanization is the main cause of the existence of UAPFCP. Given the existence of city circle polders, the policy-making department tends to give priority to urbanized area planning inside polders, instead of the areas outside the polders. This leads to the increase of the urbanized areas ratio inside the polders. For instance, in 2007, the document "overall urban planning in Nanjing" proposed that the development of urbanized areas inside the Qianhancun and Dongshan polders needed to be expanded and accelerated. The agricultural land, such as paddy fields and garden plots, inside the polders needed to be transferred outside, and the areas of residential, commercial and first class industrial lands inside the polders needed to be increased. As for the regions surrounding the polders, the areas of the second and third class industrial lands were planned, and the population settlements were expanded and increased. Besides, road construction needed to be strengthened to intensify the connection between the regions inside and outside the polders.

A city circle polder is a closed unit. The urban area which needs protection in the polder is divided within the basin river system by dikes. There is no direct interaction between the runoff in the polders and the river system outside. The connection is through a pump station and sluice gate [11]. The main land use types in the city circle polder are urban land and dry land, with low storage [8]. However, the main land use types in the general polder in China are farmland, woodland, and water body. Water surface ratio in the general polder is higher than the ones outside, so that there are certain storage capacities in the general polder. The main function of the city circle polder is city flood control with certain safety standards. Drainage modulus represents the drainage capacity. Maximum allowable water depth represents the flood control safety standard. In order to ensure the safety of urban flood control, the polders need to drain away flood in a timely manner. Due to these reasons, the drainage modulus of the city circle polder should be larger than the general polder and the maximum allowable water depth of a city circle polder should be less than a general polder. The water in the polder will not be pumped out until it reaches the maximum allowable water depth. Urban agglomeration polders are composed of several city circle polders.

There are four groups of city circle polders (i.e., Jurong, Lishui, Qianhancun, and Dongshan) in the study area. The four groups of polders formed the urban agglomeration polders of the Qinhuai River basin. The areas of Jurong, Lishui, Qianhancun, and Dongshan polders are 318.1 km^2, 256.7 km^2, 216.8 km^2, and 238.1 km^2 respectively. The distribution of urban agglomeration polders can be seen in Figure 1.

2.3. Model Setup

This paper used HEC-HMS to simulate the process of rainfall-runoff. Each model run consists of the meteorological model, the basin model, the control specifications, and the data systems [16].

The spatio-temporal precipitation was determined by the Specified Hyetograph method. The hyetograph of each sub basin was specified on the basis of the Thiessen Polygons, which was constructed according to the seven rain gage stations in the studied basin [10]. According to the location of the center of the gravity of the sub basin, the corresponding rain gage station of each sub basin can be determined. Figure 2a shows the distribution of sub basins and Thiessen Polygons of the Qinhuai River basin.

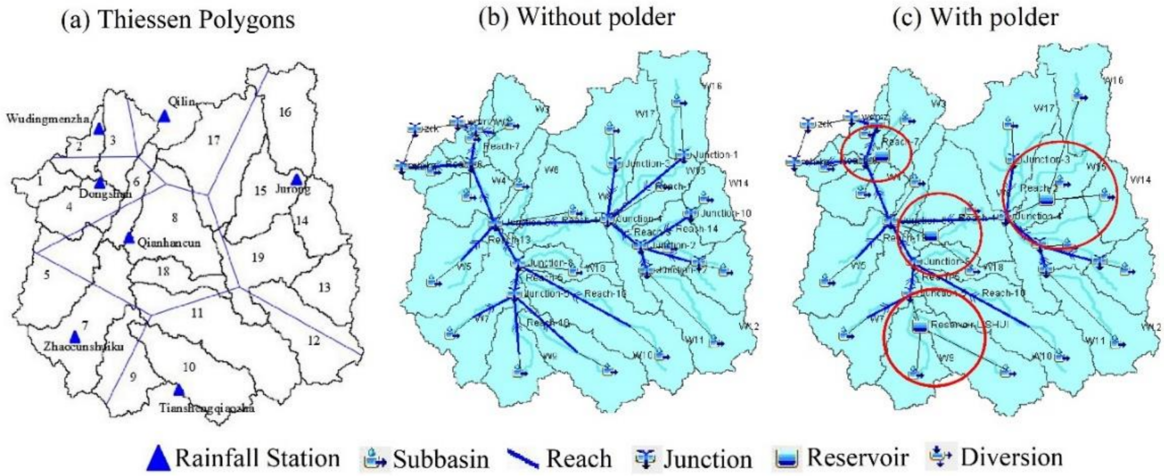

Figure 2. Thiessen polygons of the Qinhuai River basin and HEC-HMS models of the Qinhuai River basin under both with and without polder conditions, (**a**) Thiessen polygons of the Qinhuai River basin, (**b**) HEC-HMS model under without polder condition, (**c**) HEC-HMS model under with polder condition.

Surface runoff was predicted from daily rainfall by the Natural Resource Conservation Service (NRCS) Curve Number method based on land use data, soil type data, cumulative precipitation data, and antecedent soil water content [17], with two parameters of impervious rate and curve number (CN) value [18]. The CN value is an important parameter of the NRCS method, which is determined by land use, the initial soil moisture condition, and the hydrological unit of the soil type. The NRCS Curve Number method determined three initial soil moisture conditions, which are the dry condition (wilting point), semi moist condition, and moist condition (field capacity). According to the research results of Xu et al. [19], the initial soil moisture condition in the Qinhuai River basin is generally the semi moist condition. The hydrological unit of a kind of soil type is determined by the final constant infiltration rate (Y), which reflects the hydrological properties of the soil type. The integrated CN value of each sub basin can be determined according to the land use and soil condition of the sub basin [20]. The empirical formula for calculating the final constant infiltration rate is as follows [21]:

$$Y = (20M)^{18} \tag{1}$$

where M is the average particle diameter of soil.

The SCS Unit Hydrograph method was used in the present study to estimate direct runoff with the parameter of lag time (t_{lag}), which is defined as the time difference between the center of mass of rainfall excess and the peak of the unit hydrograph [22]. t_{lag} can be calculated with the following equation:

$$t_{lag} = CC_t(LL_c)^{0.3} \tag{2}$$

where C is the conversion coefficient, C_t is the basin coefficient, L is the distance from the riverhead to the outlet section of the main channel, L_c is the distance from the outlet section of the main channel to the center of the basin.

The Recession model was adopted to calculate the base flow and explain the drainage from natural storage in a watershed, with three parameters of base flow threshold ratio to peak, recession constant, and initial value [23]. It defines the relationship of the base flow Q_t at any time t to an initial value Q_0 as:

$$Q_t = Q_0E^t \tag{3}$$

where E is an exponential decay constant. A threshold flow, after the peak of the direct runoff, should be specified either as a flow rate or as a ratio to the computed peak flow when applying the recession model.

The Muskingum method was adopted for channel flow routing, with two parameters of travel time through the reach (K) and Muskingum weighting factor (X, $0 \leq X \leq 0.5$). The method uses the following equation:

$$\begin{gathered} Q_2 = (c_1 - c_2)I_1 + (1 - c_1)Q_1 + c_2 I_2 \\ c_1 = \frac{2\times\Delta t}{2\times K\times(1-X)+\Delta t} \\ c_2 = \frac{\Delta t-2\times K\times X}{2\times K\times(1-X)+\Delta t} \end{gathered} \tag{4}$$

where I_1, I_2 are the inflows to the routing reach at the beginning and end of the computation step respectively, Q_1 and Q_2 are the outflows from the routing reach at the beginning and end of the computation step respectively, and Δt is the calculation step.

The urban agglomeration polders were gradually constructed, and would not change the drainage area and the general rainfall-runoff characteristics of the study area. Thus, the HEC-HMS model of the studied basin with urban agglomeration polders was constructed based on the model without polder. Under the same urbanization scenario, in order to reflect the characteristics of urbanization of the city circle polder, according to the planning and construction condition of city circle polders in the study area, this paper increased the urbanized area ratio of the sub basins inside the polder by 20%, which resulted in an increase of impervious ratio and a change of the CN value. However, the other parameters, such as lag time, K, and X etc., were not changed. As for the sub basins outside the polder, all the parameters were kept unchanged compared with the model without polder.

According to the characteristics of the city circle polders in the Qinhuai River basin, this research assumed the polders to be flat bottom reservoirs in the model. In the model setting, the runoff inside the polder directly flows into the reservoir. When the water volume reaches the maximum allowable volume (corresponding to the maximum allowable water depth), the reservoir starts to drain out the water with its drainage capacity defined by the drainage modulus, and the drainage is then stopped immediately after the water is emptied. The polder will start draining again until the next time the water volume reaches its threshold. Based on the actual data, the drainage modulus in the model is set to 4 $m^3/(s\cdot km^2)$ and the maximum allowable water depth is set to 0.1 m.

Figure 2b,c shows the HEC-HMS models of the Qinhuai River basin under both without and with polder conditions. The main differences between the models are circled in red.

2.4. Calibration of HEC-HMS

This paper used four evaluation criteria (i.e., Correlation coefficient (R), Nash–Sutcliffe efficiency (NSE), Relative flood volume error (Dv), and relative peak flow error (Dp)), to evaluate model performance. R was used to test the correlation of the change trend between the simulated results and observed data. NSE [24] was used to measure how well the plot of observed against the simulated flows fits the 1:1 line [9]. The equations for R, NSE, Dv, and Dp are as follows:

$$R = \frac{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q_o}\right)\times\left(Q_{si} - \overline{Q_s}\right)}{\sqrt{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q_o}\right)^2\times\left(Q_{si} - \overline{Q_s}\right)^2}} \tag{5}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{oi} - Q_{si}\right)^2}{\sum_{i=1}^{n}\left(Q_{oi} - \overline{Q_o}\right)^2} \tag{6}$$

$$Dv = \left(\sum_{i=1}^{n} Q_{si} - \sum_{i=1}^{n} Q_{oi} \right) / \sum_{i=1}^{n} Q_{oi} \tag{7}$$

$$Dp = (Q_{sp} - Q_{op}) / Q_{op} \tag{8}$$

where Q_{si} and Q_{oi} are the ith simulated and observed stream flows at time i, $\overline{Q_s}$ and $\overline{Q_o}$ are the average simulated and observed stream flows, Q_{sp} and Q_{op} are the peak flows of simulated and observed hydrographs of the simulated flood events.

The acceptable values for R and NSE are greater than 0.8, and for Dv and Dp less than 20% [17]. Five parameters (i.e., t_{lag}, base flow threshold ratio to peak, recession constant, K, and X) need to be calibrated in HEC-HMS. A series of model parameter sets was estimated using the automated optimization tool provided by HEC-HMS by selecting several objective functions, and for the whole calibration period, NSE was computed for each set of parameters to examine the calibration results. The peak-weighted root mean square error was used as the objective function to evaluate the calibrated model parameters. Validation was then performed; the parameters used during the calibration were not changed during the validation period.

3. Results and Discussion

3.1. Determination of CN Value

Table 2 shows the soil types and the corresponding hydrological unit, and Table 3 shows the CN values of the combination of different hydrological units and land use types in the study area. According to the proportion of soil types and land uses in the sub basins of the Qinhuai River basin in different periods, the corresponding CN values could be calculated.

Table 2. Soil types and the corresponding hydrological unit in the study area.

Soil Type	RGd	FLe	ATc	GLe	LVh	PLe
Hydrological unit	A	C	A	A	A	C

Table 3. Curve Number (CN) values of combination of different hydrological units and land use types in the study area.

Land Use Types	Hydrological Units	
	A	C
Urban land	69	86
Dry land	65	81
Paddy field	62	78
Wood land	25	70
Water	92	92

3.2. Calibration and Validation of HEC-HMS

The results of the above four evaluation criteria of the HEC-HMS model without polder for eight historical flood events in the calibration and validation period are listed in Table 4. The event's code shows the event's date of occurrence. Land use data for 1988 were used for flood No. 19870701, 19870815, 19890803, 19910630 simulation, land use data for 1994 were used for flood No. 19960626 simulation, and land use data for 2001 were used for flood No. 19990622, 20020619, 20030626 simulation. Because the existing layout of UAPFCP in the Qinhuai River basin was formed in 2009, the above flood events can be used to calibrate and validate the model without polder. The comparison of simulated and observed hydrographs for the selected eight historical floods is shown in Figure 3. The simulated and observed results are the sum of the two outlets (i.e., WDMS and QHXHS).

Table 4. The results of the four evaluation criteria of HEC-HMS model without polder for the selected eight flood events at the daily step in the calibration and validation period.

Period	Flood No.	*Dv* (%)	*Dp* (%)	*NSE*	*R*
Calibration	19870701	19.43	2.05	0.871	0.960
	19890803	18.94	7.03	0.900	0.970
	19990622	1.49	−2.05	0.908	0.950
Mean value	-	13.29	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	19.86	15.00	0.870	0.980
Mean value	-	8.30	6.42	0.870	0.960

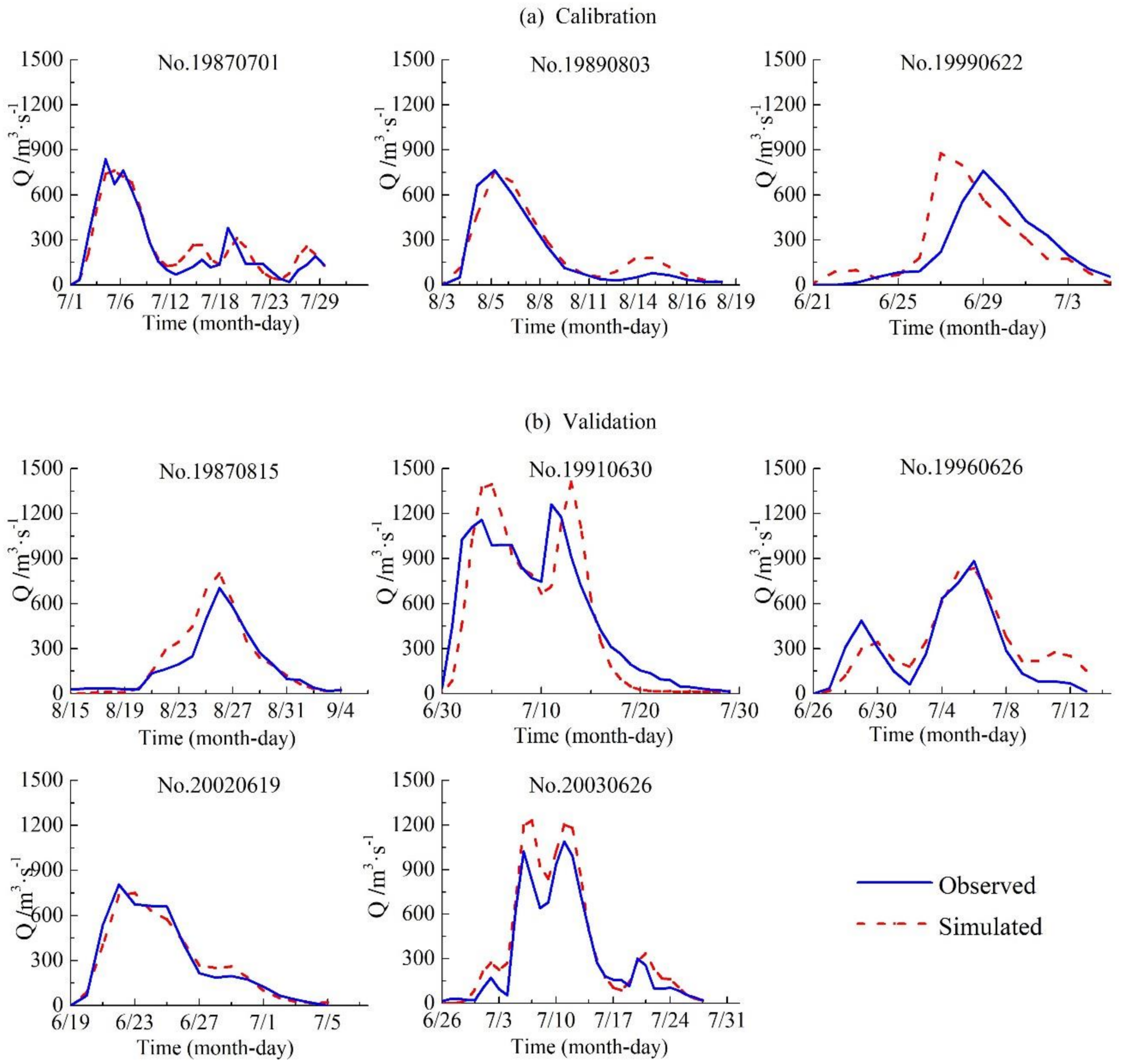

Figure 3. Comparison of simulated and observed hydrographs for the selected eight flood events (**a**) calibration period, (**b**) validation period.

According to Figure 3, it can be seen that the computed flood hydrographs agree well with the observed hydrographs for most flood events, except flood No. 19990622. As for flood No. 19990622, the simulated peak time was three days earlier than the observed result, but the flood hydrograph shape was basically consistent with the observed result. The *Dv* and *Dp* values for eight flood events are all below 20%. As for the calibration period, the average value of *R* and *NSE* is 0.960 and 0.890 respectively. As for the validation period, the average value of *R* and *NSE* is 0.960 and 0.870 respectively. Based on the above results, the HEC-HMS is applicable to the Qinhuai River basin for flood event simulation. The calibrated sub basin and sub reach parameters of the HEC-HMS model without polder can be seen in Table 5.

Table 5. Sub basin and reach parameters of the model without polder in the Qinhuai river basin.

Sub basin				Reach		
No.	**Lag Time (min)**	**Threshold Ratio to Peak**	**Recession Constant**	**No.**	***K* (h)**	***X***
W1	2542	0.10	0.01	R1	4.34	0.50
W2	2531	0.10	0.01	R2	4.02	0.28
W3	2533	0.90	0.01	R3	0.91	0.29
W4	2536	0.90	0.01	R4	4.79	0.50
W5	2625	0.10	0.01	R5	3.39	0.05
W6	2645	0.10	0.01	R6	1.71	0.01
W7	2813	0.10	0.01	R7	1.71	0.29
W8	2625	0.90	0.60	R8	2.85	0.02
W9	2843	0.90	0.88	R9	1.60	0.05
W10	2813	0.10	0.01	R10	5.68	0.10
W11	3000	0.95	0.01	R11	0.86	0.01
W12	3100	0.10	0.01	R12	2.60	0.19
W13	3000	0.10	0.01	R13	4.00	0.06
W14	3100	0.10	0.01	R14	2.17	0.29
W15	3000	0.95	0.99	R15	2.17	0.20
W16	3000	0.90	1.00	R16	0.91	0.29
W17	3000	0.95	0.88	R17	3.88	0.07
W18	2625	0.10	0.01	R18	2.99	0.13
W19	3000	0.10	0.01	R19	3.63	0.07

3.3. Urbanization Scenarios

According to the historical and present land use conditions of the Qinhuai River basin, five urbanization scenarios, i.e., the historical, current, and three assumed future urbanization scenarios, were constructed to analyze the hydrological effects. For the sake of brevity of scenario construction, the urbanized ratios of the scenarios constructed in this paper were 10% and its integral multiples. Since the existing layout of UAPFCP in the Qinhuai River basin took shape in 2009, the focus of the construction is on improving the flood control standards of the polders and inner regional urbanization levels, rather than enlarging the protection areas of the polders [19]. Under the with polder condition, for all the urbanization scenarios, the size and the distribution of the polders are unchanged. The bases of scenario construction are as follows.

Scenario A: The land use condition for 2002 of the Qinhuai River basin was used as reference scenario, where the urbanized areas occupy 8.4% of the research region. Then the historical level of the urbanization scenario (urbanized areas ratio: 10%) in the Qinhuai River basin was constructed.

Scenario B: The land use condition for 2016 of the Qinhuai River basin was used as reference scenario, where the urbanized areas occupy 25.3% of the research region. Then the current level of the urbanization scenario (urbanized areas ratio: 20%) in the Qinhuai River basin was constructed.

Scenario C and D: Shanghai is the most developed and urbanized city in the Yangtze River Delta, and it is an important template for the urbanization of other cities in this region. By the end of 2016, urbanized areas occupied 39.8% of Shanghai. The urbanized ratio of Shanghai in 2016 was used as reference, then two of the future levels of urbanization scenarios (urbanized areas ratio: 30% and 40%) in the Qinhuai River basin were constructed.

Scenario E: In the US, 50% is set as the warning line of the ratio of urbanized areas in the urban area [19]. If the urbanized areas ratio exceeds the warning line, ecological environment will be greatly affected. Thus, the warning line of the US was used as reference, then one of the future levels of urbanization scenarios (urbanized areas ratio: 50%) in the Qinhuai River basin was constructed.

This paper took scenario B as an example to illustrate the construction method of the scenarios. Based on the land use map for 2016 of the Qinhuai River basin, and the relative change of the urbanized areas ratio between scenario B and 2016 in the basin, the urbanized area ratio of each sub basin could be calculated, and this was set as the basis to adjust the proportions of other land use types. Figure 4 shows the areas of soil types and land uses in the sub basins of the Qinhuai River basin of scenario B, and the CN values of the five urbanization scenarios under without polder conditions.

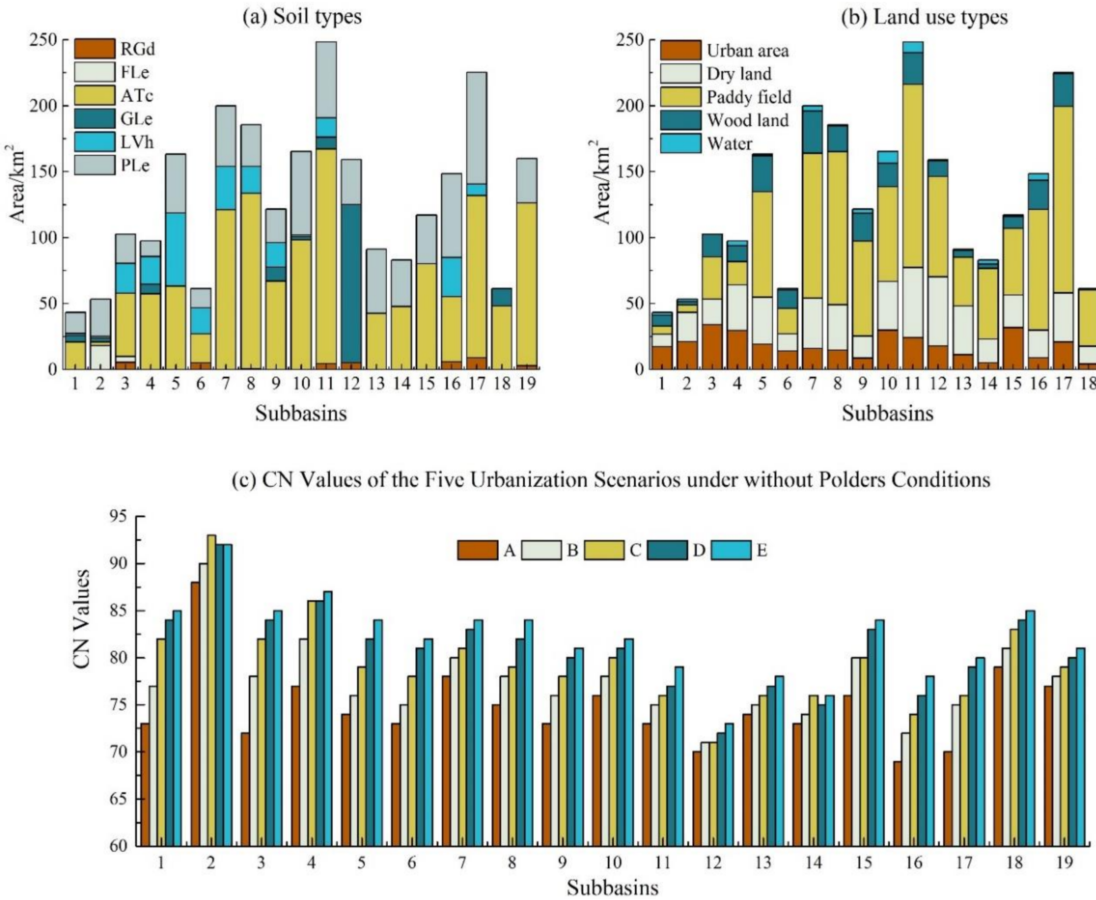

Figure 4. The areas of soil types and land uses in the sub basins of the Qinhuai River basin (scenario B) and the CN values of the five urbanization scenarios under without polder conditions(**a**) soil types (scenario B), (**b**) land use types (scenario B), (**c**) CN values under without polder conditions.

3.4. Determination of Flood Magnitude

In order that the impact of the UAPFCP and potential change in response to urbanization can be conveniently and comprehensively assessed, it is necessary to select the representative flood events. The usual method is to choose flood events of different magnitudes. While determining the flood magnitude, the peak flow level and the flood volume level should be comprehensively analyzed. The peak flow level can reflect the flood intensity, maximum flood inundation range, and extent of the flood threat. The determination of flood volume level takes the flood peak height and flood duration into account, which can reflect the degree of flood disaster. Generally, flood control can be faced by a univariate approach relying on peak flow discharge statistics only when the main issue lies within the conveyance capacity of the river cross sections. Otherwise, flood volume is the most significant variable [25]. According to the terrain, river channels, and flood processes characteristics of the study area mentioned in Section 2.1, the flood disaster in the study area is mainly affected by the flood volume, thus, this paper used the flood volume level to determine the flood magnitude.

Based on historical flood observations (1986–2015) of the Qinhuai River basin, typical floods were divided into three orders of magnitude, based on the flood volume. Minor flood (200 mm or less, corresponding to 5-year flood or smaller), medium flood (200–350 mm, corresponding to 5-year flood to 20-year flood), major flood (350 mm or more, corresponding to 20-year flood or larger). Three different magnitude flood events, i.e., flood No. 19890803 (minor flood), 19870701 (medium flood) and 19910630 (major flood), were selected to assess the impact of the UAPFCP on flood events and the potential change in response to urbanization. Table 6 shows the results.

Table 6. Hydrological response to urbanization under with and without polder conditions.

Flood No.	Scenarios	Without Polder		With Polder		Increase Rate Compared with Scenario A under the without Polder Condition (%)		Increase Rate Compared with Scenario A under the with Polder Condition (%)		Relative Change between with and without Polder Conditions (%)	
		Q_v (mm)	Q_p ($m^3 \cdot s^{-1}$)	Q_v (mm)	Q_p ($m^3 \cdot s^{-1}$)	Q_v	Q_p	Q_v	Q_p	Q_v	Q_p
19890803	A	132	767	157	1014					18.94	32.20
	B	137	818	161	1040	3.79	6.65	2.55	2.56	17.52	27.14
	C	147	840	164	1067	11.36	9.52	4.46	5.23	11.76	26.98
	D	153	882	167	1093	15.91	14.99	6.37	7.79	9.47	23.89
	E	159	925	171	1119	20.45	20.60	8.92	10.36	7.18	20.96
19870701	A	307	828	336	977					9.45	18.00
	B	313	855	340	1000	1.95	3.26	1.19	2.35	8.63	16.96
	C	324	882	344	1023	5.54	6.52	2.38	4.71	6.11	15.92
	D	331	921	348	1045	7.82	11.23	3.57	6.96	4.90	13.51
	E	339	962	352	1068	10.42	16.18	4.76	9.31	3.83	11.00
19910630	A	497	1365	528	1500					6.24	9.89
	B	503	1393	532	1524	1.21	2.05	0.76	1.60	5.77	9.40
	C	515	1420	536	1549	3.62	4.03	1.52	3.27	4.14	9.04
	D	522	1461	540	1573	5.03	7.03	2.27	4.87	3.40	7.63
	E	530	1506	544	1597	6.64	10.33	3.03	6.47	2.68	6.07

3.5. Hydrological Response to Urbanization of UAPFCP on Flood Events

According to Table 6, for different magnitude floods, the UAPFCP increased Q_v and Q_p compared to the results of the without polder conditions. Under the current urbanization scenario (scenario B), for the selected flood events, Q_v increased from 5.77% to 17.52%, and Q_p increased from 9.40% to 27.14%. Besides, it is also clear to see that with the improvement of the urbanization level, Q_v and Q_p increased correspondingly for all the flood events. Taking flood No. 19870701 (under with polder condition) as an example, as the urbanization level increases from scenario B to Scenario E, the flood volume and peak flow increase from 1.19% to 4.76%, and from 2.35% to 9.31% respectively, compared with scenario A.

This can be explained by the following reasons. The land use conditions change inside the polder, especially the increased proportion of urbanized areas, compared with the same area without polder. These changes result in increase of the impervious ratio. Under similar rainstorm conditions, the increases of runoff inside the polder and drainage volume from the polder result in increase of Q_v. With the increase of water volume inside the polders, considering the flood control security of the urban area inside the polders, the polder needs to drain out the water timely. The polder's drainage time may overlap with the peak arrive time of the main river channel, and different polders' drainage times may overlap. Besides, the construction of river dikes of the polder makes the river course narrower than the condition without polder. Because of the above reasons, Q_p would increase. Moreover, with the improvement of the basin's overall urbanization level, the proportion of urbanized areas increases, which leads to an increase of the impervious ratio. Because of the above analyses, Q_v and Q_p would gradually increase compared with scenario A.

3.6. Sensitivity of Flood Changes to Increasing Urbanization of UAPFCP

According to the results of percentage increases in Q_v and Q_p compared with scenario A under the with and without polder condition for different flood magnitudes in Table 6 the potential changes can be drawn in Figure 5. According to Figure 5, within the urbanization scope of this paper, the potential changes of percentage increase in Q_v and Q_p from scenario A under the with polder condition for different flood magnitudes all follow a linear rate law. The results are coincident with Bhaduri et al. [26], Calhoun et al. [27], and Choi et al. [28], but different from Brun and Band [29] and Wissmar et al. [30]. Brun and Band's study reveals both a logistic relationship between runoff ratio and impervious ratio, and an exponential relationship between baseflow and imperviousness can be observed under the condition where the impervious ratio increases up to 90%. In the study of Wissmar et al., the flood magnitude for urban watersheds tends to increase nonlinearly when the impervious ratio reaches 43%–74% levels in the lower Cedar River drainage in the US. In this study, the urbanization level might be still not high enough to result in nonlinearity.

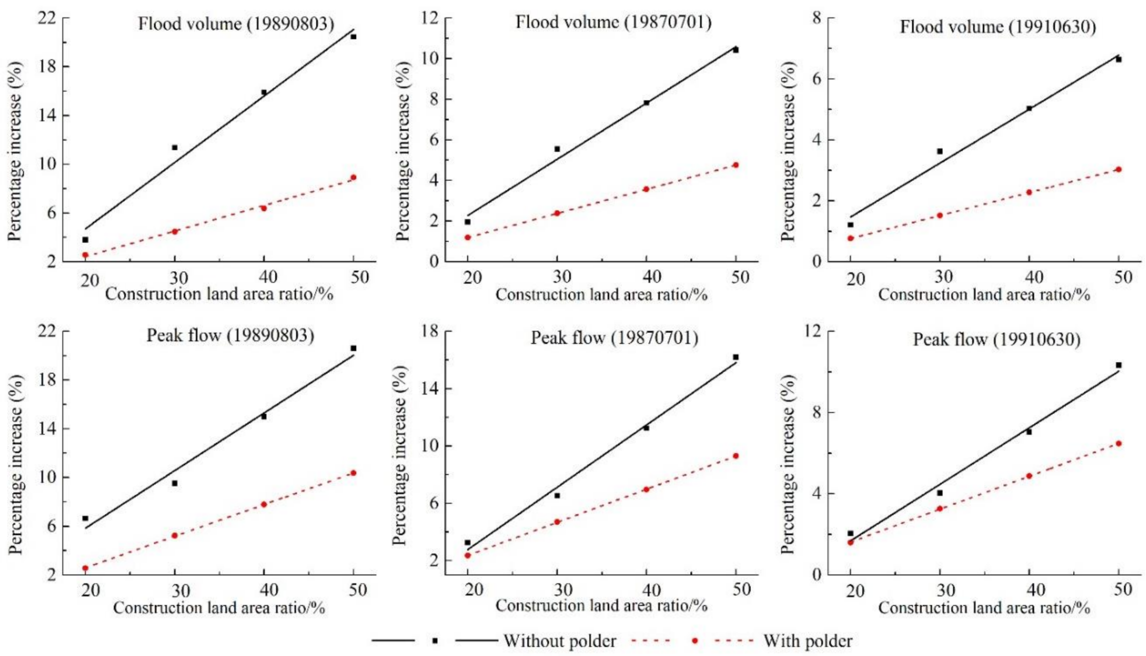

Figure 5. The potential changes of percentage increases in Q_v and Q_p from scenario A under the without polder and with polder conditions for different flood magnitudes.

3.7. Interaction between Urbanization and Urban Agglomeration Polders on Flood Events

According to Figure 5, it is also clear to see that the curve slopes of flood volume and peak flow under the without polder condition are steeper than those under the with polder condition for all the flood events, thus, the following conclusion can be drawn. In the Qinhuai River basin, with the constant improvement of the urbanization level, the increase degree of Q_v and Q_p under the with polder conditions are lower than those under the without polder conditions. That is, the effect of urbanization on the flood process is weakened due to the existence of the urban agglomeration polders.

Figure 6 shows the relative change in Q_v and Q_p with increasing urbanization level between with and without polder conditions for various floods. According to Table 6 and Figure 6, for the selected flood events, with the constant improvement of urbanization level in the Qinhuai River basin of UAPFCP, the differences between with and without polder conditions in Q_v and Q_p gradually decrease. All these curves follow the linear rate law. Taking flood No. 19870701 as an example, as the urbanization level increases from scenario A to scenario E, the differences between with and without polder conditions in Q_v and Q_p decrease from 9.45% to 3.83%, and from 18.00% to 11.00% respectively.

Based on the above analyses, under the UAPFCP, the increase of the Q_v and Q_p is mainly due to the existence of urban agglomeration polders. With the constant improvement of the urbanization level of the whole basin, the urbanization level of the area outside the polder gradually approaches the urbanization level of the area inside the polder, thus, the effects on floods caused by polders are gradually weakened. That is, with the constant improvement of the urbanization level, the effect on the flood process caused by urban agglomeration polders is gradually weakened.

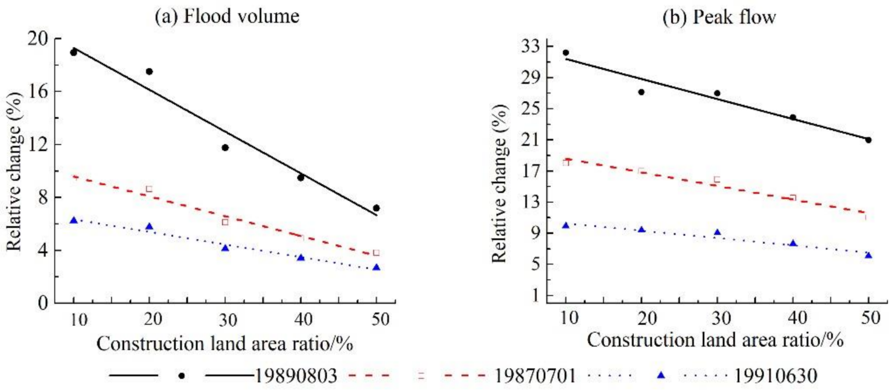

Figure 6. The potential changes of relative change in Q_v and Q^P between with and without polder conditions for different flood magnitudes under different urbanization scenarios (**a**) flood volume, (**b**) peak flow.

4. Summary and Conclusions

A case study was conducted in this paper to examine the effects of urbanization on flood events of UAPFCP in the Qinhuai River basin by utilizing Remote Sensing (RS), Geographic Information System (GIS), and the HEC-HMS model. Five urbanization scenarios (the historical, current, and three future urbanization scenarios) were constructed based on the historical and present land use conditions of the Qinhuai River basin. The main conclusions are drawn as below.

First, with the constant improvement of the urbanization level in the Qinhuai River basin of UAPFCP, Q_v and Q_p gradually increase for all flood events.

Second, within the urbanization scope of this paper, the potential changes in Q_v and Q_p under the with polder condition with increasing urbanization level show linear relationships. The possible cause for the linearity is that the proportion of urbanized areas is not large enough to lead to nonlinearity.

Third, with the constant improvement of the urbanization level in the Qinhuai River basin, the degrees of increase of Q_v and Q_p under the with polder condition are lower than those under the without polder condition. That is, the effect of urbanization on the flood process is weakened because of the existence of the urban agglomeration polders. Moreover, the effect on the flood process caused by urban agglomeration polders is gradually weakened.

The above conclusions are helpful for flood mitigation and drainage control, as well as for water resources planning and management in the Qinhuai River basin. The construction of city circle polders is beneficial to the flood control of the areas inside the polders, but it increases the flood risk of the overall basin. Thus, while formulating the basin flood control policy, the flood control standard of the main river courses in the middle and lower basin should be increased to ensure overall flood control safety. Besides, in future development of urban agglomeration polders, on the premise of ensuring flood control safety of the areas inside the polders, the regulation and storage capacity of the polders should be taken into consideration to reduce the impact of polders on the overall flood control safety, especially the peak flow. Thus, flood control measures need to be considered based on the whole system. Besides, according to the above third conclusion, with the improvement of the urbanization level, the adverse effects of UAPFCP and urbanization on the whole basin flood control are weakened. This illustrate that under the conditions of higher urbanization level in the future, UAPFCP is an effective flood control pattern to ensure flood safety in urban agglomeration areas. Considering the many similar city circle polders planned in the Yangtze River Delta region, and the possibility of other new position of this kind in other rapidly urbanizing regions, the change rules of hydrological responses to urbanization on flood events with UAPFCP are important for further study. This paper can provide useful information and helpful reference for these regions.

Author Contributions: Conceptualization, Y.G. and Y.Y.; Methodology, G.F.; Software, Y.Y.; Validation, Y.Y. and Y.G.; Formal Analysis, Y.Y.; Investigation, X.H.; Resources, Y.G.; Data Curation, Y.Y.; Writing-Original Draft Preparation, Y.Y.; Writing-Review & Editing, X.H.; Visualization, Y.G.; Supervision, G.F.; Project Administration, Y.G.; Funding Acquisition, G.F. and Y.Y.

Funding: This research was funded by the Fundamental Research Funds for the Central Universities (No. 2017B686X14), the Postgraduate Research & Practice Innovation Program of Jiangsu Province (No. KYCX17_0427), the National Natural Science Foundation of China (No. 51309076), the Fundamental Research Funds for the Central Universities (No. 2014B05814), the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions, the Water Conservancy Science and Technique of Hunan Province (No. [2015]245-13), and the Key Project of Water Conservancy Science and Technique of Hunan Province (No. [2016]194-21).

Acknowledgments: The writers would like to thank Youpeng Xu for his help in the conceptualization of the research and Chengxuan Lu for her help in the statistical analysis of the simulation results.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ji, X.; Xu, Y.; Han, L.; Yang, L. Impacts of urbanization on river system structure: A case study on Qinhuai river basin, Yangtze river delta. *Water Sci. Technol. J. Int. Assoc. Water Pollut. Res.* **2014**, *70*, 671–677. [CrossRef] [PubMed]
2. Ahn, G.-C. *The Effect of Urbanization on the Hydrologic Regime of the Big Darby Creek Watershed*; The Ohio State University: Columbus, OH, USA, 2007.
3. Salvadore, E.; Bronders, J.; Batelaan, O. Hydrological modelling of urbanized catchments: A review and future directions. *J. Hydrol.* **2015**, *529*, 62–81. [CrossRef]
4. Nirupama, N.; Simonovic, S.P. Increase of flood risk due to urbanisation: A Canadian example. *Nat. Hazards* **2007**, *40*, 25–41. [CrossRef]
5. Beighley, R.E.; Melack, J.M.; Dunne, T. Impacts of California's climatic regimes and coastal land use change on streamflow characteristics. *J. Am. Water Resour. Assoc.* **2003**, *39*, 1419–1433. [CrossRef]
6. Zhou, F.; Xu, Y.; Chen, Y.; Xu, C.Y.; Gao, Y.; Du, J. 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. *J. Hydrol.* **2013**, *485*, 113–125. [CrossRef]
7. Remondi, F.; Burlando, P.; Vollmer, D. Exploring the hydrological impact of increasing urbanisation on a tropical river catchment of the metropolitan Jakarta, Indonesia. *Sustain. Cities Soc.* **2016**, *20*, 210–221. [CrossRef]
8. Gao, Y.; Yuan, Y.; Wang, H.; Schmidt, A.R.; Wang, K.; Ye, L. Examining the effects of urban agglomeration polders on flood events in Qinhuai river basin, china with HEC-HMS model. *Water Sci. Technol.* **2017**, *75*, 2130–2138. [CrossRef] [PubMed]
9. Meenu, R.; Rehana, S.; Mujumdar, P.P. Assessment of hydrologic impacts of climate change in Tunga-Bhadra basin, India with HEC-HMS and SDSM. *Hydrol. Process.* **2013**, *27*, 1572–1589. [CrossRef]
10. Yuan, Y.; Gao, Y.; Wu, X. Flood simulation of flood control model for polder type based on HEC_HMS hydrological model in Qinhuai river basin. *J. China Three Gorges Univ. (Nat. Sci.)* **2015**, *37*, 34–39.
11. Zhao, G.; Hörmann, G.; Fohrer, N.; Gao, J.; Li, H.; Tian, P. Application of a simple raster-based hydrological model for streamflow prediction in a humid catchment with polder systems. *Water Resour. Manag.* **2011**, *25*, 661–676. [CrossRef]
12. Ren, L.; Liu, X.; Fei, Y.; Jing, X.; Wei, L. Quantitative analysis of runoff reduction in the Laohahe basin. *Hydrol. Res.* **2012**, *43*, 38–47. [CrossRef]
13. Zhang, S.; Hou, L.; Wei, C.; Zhou, X.; Wei, N. Study on water quantity and quality-integrated evaluation based on the natural-social dualistic water cycle. *Pol. J. Environ. Stud.* **2015**, *24*, 829–840. [CrossRef]

14. Suriya, S.; Mudgal, B.V. Impact of urbanization on flooding: The Thirusoolam sub watershed—A case study. *J. Hydrol.* **2012**, *412*, 210–219.
15. Du, J.; Li, Q.; Rui, H.; Zuo, T.; Zheng, D.; Xu, Y.; Xu, C.Y. Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China. *J. Hydrol.* **2012**, *464–465*, 127–139. [CrossRef]
16. Yong, B.; Zhang, W.; Zhao, D.; Zhu, Q. Application of hydrological modeling system HEC-HMS to Baohe catchment of Hanjiang basin. *Bull. Soil Water Conserv.* **2006**, *26*, 86–90.
17. Halwatura, D.; Najim, M. Application of the HEC-HMS model for runoff simulation in a tropical catchment. *Environ. Model. Softw.* **2013**, *46*, 155–162. [CrossRef]
18. Fu, S.; Wang, X.; Wang, H.; Wei, X.; Yuan, A. Meathod of determining CN value in the SCS-CN method. *Arid Land Geogr.* **2012**, *35*, 415–421.
19. Xu, Y. *The Effects of Urbanization on Water System and Hydrological Process in the Yangtze River Delta*; Science Press: Beijing, China, 2012.
20. Rui, H. *Land Use Changes and Its Hydrological Responses in the Qinhuai River Basin*; Nanjing University: Nanjing, China, 2012.
21. Che, Z. Discussing the empirical formula and graph of soil permeability coefficient. *Water Resour. Hydropower Northeast China* **1995**, *9*, 17–19.
22. Liang, R. *Application of HEC-HMS in the Beizhangdian Watershed*; Tai Yuan University of Technology: Taiyuan, China, 2012.
23. Li, Q. *Changing of Spatial Pattern and the Hydrological Response of Urbanization in Qinhuai River Basin*; Nanjing University: Nanjing, China, 2012.
24. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models part I—A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [CrossRef]
25. Balistrocchi, M.; Orlandini, S.; Ranzi, R.; Bacchi, B. Copula-based modeling of flood control reservoirs. *Water Resour. Res.* **2018**, *53*, 9883–9900.
26. Bhaduri, B.; Minner, M.; Tatalovich, S.; Harbor, J. Long-term hydrologic impact of urbanization: A tale of two models. *J. Water Resour. Plan. Manag.* **2001**, *127*, 13–19.
27. Calhoun, D.L.; Frick, E.A.; Buell, G.R. *Effects of Urban Development on Nutrient Loads and Streamflow, Upper Chattahoochee River Basin, Georgia, 1976–2001*; Georgia Institute of Technology: Atlanta, GA, USA, 2003.
28. Choi, W.; Deal, B.M. Assessing hydrological impact of potential land use change through hydrological and land use change modeling for the Kishwaukee river basin (USA). *J. Environ. Manag.* **2008**, *88*, 1119–1130. [CrossRef] [PubMed]
29. Brun, S.E.; Band, L.E. Simulating runoff behavior in an urbanizing watershed. *Comput. Environ. Urban Syst.* **2000**, *24*, 5–22. [CrossRef]
30. Wissmar, R.C.; Timm, R.K.; Logsdon, M.G. Effects of changing forest and impervious land covers on discharge characteristics of watersheds. *Environ. Manag.* **2004**, *34*, 91–98. [CrossRef] [PubMed]

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