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Flood Mitigation by Permeable Pavements in Chinese Sponge City Construction

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Abstract: It is important to evaluate the effectiveness of permeable pavements on flood mitigation at different spatial scales for their effective application, for example, sponge city construction in China. This study evaluated the effectiveness of three types of permeable pavements (i.e., permeable asphalts (PA), permeable concretes (PC), and permeable interlocking concrete pavers (PICP)) on flood mitigation at a community scale in China using a hydrological model. In addition, the effects of clogging and initial water content in permeable pavements on flood mitigation performance were assessed. The results indicated that in 12 scenarios, permeable pavements reduced total surface runoff by 1–40% and peak flow by 7–43%, respectively. The hydrological performance of permeable pavements was limited by clogging and initial water content. Clogging resulted in the effectiveness on total surface runoff reduction and peak flow reduction being decreased by 62–92% and 37–65%, respectively. By increasing initial water content at the beginning of the simulation, the effectiveness of total runoff reduction and peak flow reduction decreased by 57–85% and 37–67%, respectively. Overall, among the three types of permeable pavements, PC without clogging had the best performance in terms of flood mitigation, and PICP was the least prone to being clogged. Our findings demonstrate that both the type and the maintenance of permeable pavements have significant effects on their performance in the flood mitigation.

Keywords: flood mitigation; surface runoff; peak flow; initial water content; clogging

1. Introduction

Urban flooding/waterlogging has been a serious problem in many cities around the world. For example, urban flood hazards caused huge damage in the last decades in China [1–3]. Due to climate change and rapid urbanization [4–6], the risks of urban waterlogging are very likely to increase in the near future. The traditional urban rainwater management approaches and existing flood disaster defense structures have been proven to be ineffective in extreme weather events [7]. Development of new approaches to supplement existing urban water management is urgently needed in many cities in the world. In 2014, the Chinese government proposed a plan of sponge city construction at the national scale, with the innovation of finding ecologically suitable alternatives to mitigate the impacts of water-related problems resulting from “too much water” or floods, “too little water” or water scarcity, and “too dirty water” or water pollution [8,9]. One of the core objectives of the construction of sponge cities is to control and mitigate the increasing challenges of urban flooding/waterlogging [10]. The Central Government of China has provided financial support to implement the sponge city plan in 30 pilot cities around China [9–11]. However, the sponge city concept is still a relatively new idea and it requires more research on urban hydrologic theory and different engineering approaches in many cities in China.

Permeable pavement is one such technology in sponge city construction that is highly recommended by the Chinese Ministry of Housing and Urban Rural Development (MHURD) [12]. This technology has been studied and implemented in many areas in the world to manage urban stormwater under different plans with terminologies such as sustainable urban drainage systems, low impact development, best management practices, and others [13–15]. Reductions in storm runoff peak, runoff volume and improvement in water quality by permeable pavement systems have been widely reported [16–19]. For example, Pyke et al. [16] reported that stormwater runoff was more sensitive to changes in impervious covers than changes in precipitation volume and intensity. Damodaram et al. [19] demonstrated that permeable pavements had good performance on flood mitigation and the effect was larger than other technologies, including rainfall harvesting and green roofs in two campuses of Texas A&M University, Texas, USA. Some studies have also been conducted in China on the effectiveness of permeable pavements in terms of flood mitigation [11,20–25]. For example, Huang et al. [21] reported that the implementation of permeable pavements reduced about 35.6% of total runoff and 28.7% of peak flow in the campus of Tianjin University, China. Hu et al. [11] found permeable pavements reduced inundated areas by 10–14% and areas of high risk hazard by 48–76% in a watershed in Nanjing, China. The peak flow of a designed five-year recurrence rainfall event decreased by 24.7% with the implementation of permeable pavements in a tourist village in Jurong, China [23]. Existing works on permeable pavements in relatively large areas in China were typically focused on long-term simulation or multi designed rainfall with different intensities and frequencies [22].

In addition, the hydrological performance of permeable pavements depends on materials, usage, service life, environment and maintenance [26,27]. Collins et al. [28] found that concrete grid pavers generated the greatest surface runoff volumes compared with other kinds of permeable pavements through field observation in a parking lot in Carolina, USA. Kumar et al. [29] reported that the infiltration rates of three kinds of permeable pavements declined markedly from the second year due to clogging of pores by in situ measurement of infiltration performance over a four-year period. Previous studies on the performance of permeable pavements considering the effects of materials and external factors have primarily focused on laboratory-based analyses or field observations at small sites [30–32]. Chandrappa and Biligiri [33] measured and researched the permeability characteristics of pervious concrete at varying head levels. Turco et al. [34] studied the hydraulic behavior of permeable pavements with three materials using a HYDRUS-2D model at laboratory-scale. Few studies have discussed the effects of materials and external factors on the effectiveness of permeable pavements at the community or watershed scales [35]. In China, sponge city construction is at the infant stage, with pilot cities only in their second or third years. There is currently a scarcity of hydrological information on the evolution or life cycle of different permeable pavements. For example, clogging of permeable pavements is one of the problems which needs to be considered for future research and sponge city construction. This is particularly important as many cities suffer from high concentrations of particulate matter (PM) [36], and particle deposition on pavement surfaces can induce degeneration of permeable pavement performance.

This study investigates the effectiveness of permeable pavements in the sponge city construction for flood mitigation through an event-based case study in a residential district located in Nanjing, China. The main objectives are: (1) to evaluate the potential performance of different kinds of permeable pavements on flood mitigation; and (2) to estimate the impact of clogging and initial water content at the beginning of a storm event on permeable pavement performance. The results provide useful information on the effectiveness of permeable pavements in mitigating flood risks in Chinese sponge cities.

2. Materials and Methods

2.1. Research Site and Data

The research area is in a residential block with an area of about 0.58 km^2 in Nanjing, China (Figure 1). It is adjacent to the Qinhuai River, a tributary of the Yangtze River. Because of its elevation, being lower than the water level of the Qinhuai River in the rainy season, it is one of the most seriously waterlogged areas in Nanjing City. The impervious underlying surfaces of the study area account for 73.8% of the total area. Among them, there are 0.15 km^2 of rooftops, 0.046 km^2 of parking lots and squares, 0.085 km^2 of non-busy roads and 0.143 km^2 of busy roads (Table 1). The non-busy roads are defined as roads less than 10 m wide with low traffic. A typical 20-year recurrence storm event which occurred in Nanjing from 19:00 June 12 to 7:00 June 13 in 1991 was selected for this study. The hourly rainfall data at Nanjing Meteorological Station was shown in Figure 2. The 12-h precipitation was 113.8 mm and 72% of this precipitation amount fell within two hours.

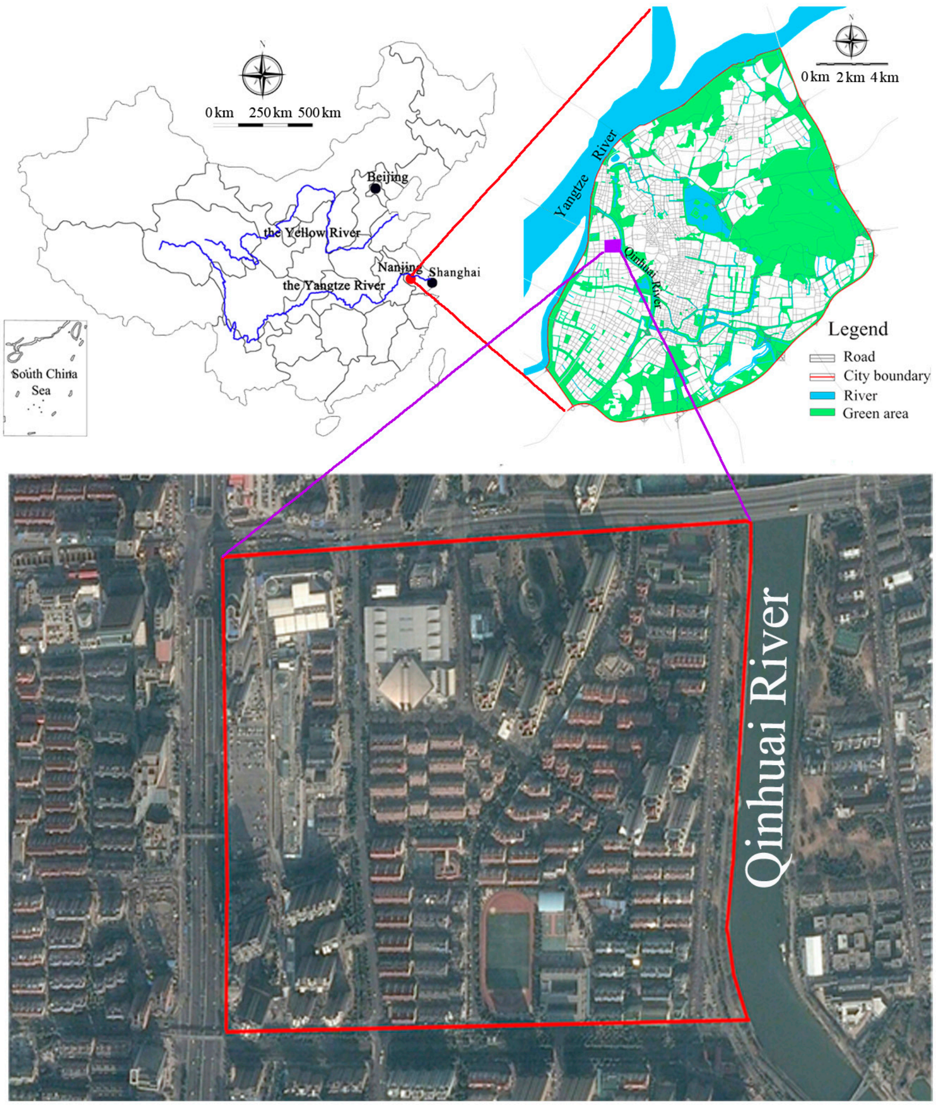

Figure 1. Study area of the residential block in Nanjing, China.

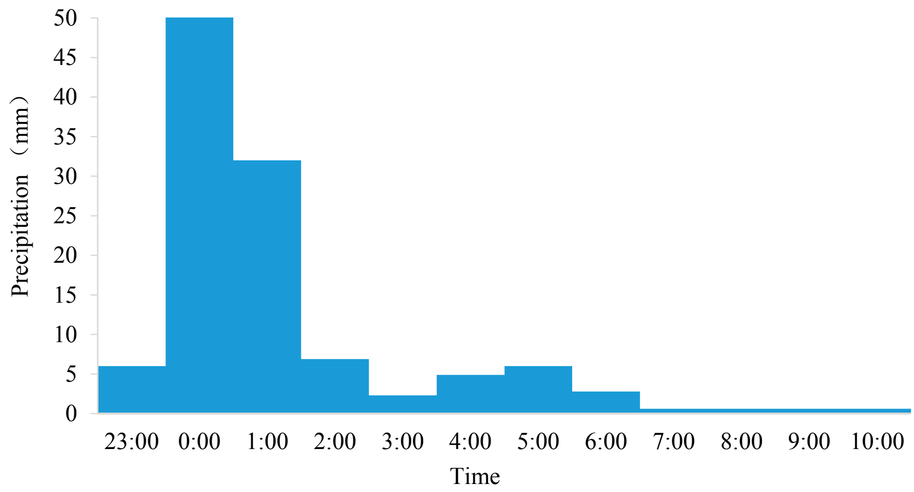

Figure 2. Hourly precipitation at Nanjing Meteorological Station from June 12 to June 13 in 1991.

Table 1. Underlying surface types and proportions in the study area.

Type	Roof	Non-Busy Road	Busy Road	Parking Lots and Squares	Green Land	Water
Area (km^2)	0.153	0.085	0.143	0.046	0.150	0.001
Percentage (%)	26.4	14.7	24.7	8.0	26.0	0.2

2.2. Flow Calculation

A hydrological model which includes impervious and pervious modules was used to simulate the hydrological processes. The impervious module is based on the soil conservation service (SCS) curve number method [37] and the pervious module is based on Horton's infiltration model [38]. The model has the advantages of less requirements of parameters and observation data (only precipitation).

2.2.1. Impervious Module

The SCS curve number method has been widely used in permeable pavement studies with acceptable model performance [18,39]. The key parameter of the SCS method is the curve number (CN) value, which is determined by a series of factors including land use, soil type and antecedent moisture condition. According to a previous study [18] and the reference CN values given in the manual of the model [37], a CN value of 94 was set for the impervious surfaces in this study. The terminal equation for impervious surface runoff computation is:

$$RF = \frac{(P - I_a)^2}{P - I_a + S} = \frac{(P - 3.24)^2}{P + 12.97}, \quad P > 3.24 \tag{1}$$

where S is the potential maximum soil moisture retention, equal to $\frac{25400}{CN} - 254$; I_a is the initial abstraction, equal to 0.2 S; P is the precipitation (mm) and RF is the surface runoff volume (mm). When P is less than 3.24 mm, there is no surface runoff.

2.2.2. Pervious Module

Horton's infiltration model [38] was applied to determine the infiltration rate:

$$f(t) = f_c + (f_0 - f_c)e^{-kt} = f_0 e^{-kt} + f_c\left(1 - e^{-kt}\right) \tag{2}$$

where f (t) is the infiltration rate (mm/h) at time t; k is the decay constant for the Horton curve; f_0 is the maximum infiltration rate (mm/h) and f_c is the minimum infiltration (mm/h). Soil moisture was from the infiltration by the force of capillary action [40]. Then, the capillary action and gravity infiltration rates (f_1 and f_2) can be obtained using the following equations:

$$W(t) = \int_0^t f_1 dt = \int_0^t f_0 e^{-kt} dt \tag{3}$$

$$WM = \int_0^\infty f_1 dt = \frac{f_0}{k} \tag{4}$$

$$f_1 = f_0 e^{-kt} = f_0 \left(1 - \frac{W(t)}{WM}\right) \tag{5}$$

$$f_2 = f_c \left(1 - e^{-kt}\right) = f_c \frac{W(t)}{WM} \tag{6}$$

where W (t) is the soil moisture (mm) at time t; WM is the storage capacity (mm). Then, surface runoff intensity (R_s) and subsurface flow intensity (R_g) have the following relations with precipitation intensity (I):

$$R_s = \begin{cases} 0 & , I < f_1 + f_2 \\ I - f_1 - f_2 & , I > f_1 + f_2 \end{cases} \tag{7}$$

$$R_g = (I - R_s) \frac{f_2}{f_1 + f_2} \tag{8}$$

If soil moisture (W) is known at the beginning of a precipitation event, surface runoff yield (h_s), subsurface runoff yield (h_g) and increased soil water (F) at any duration (x) of the event can be calculated using the following equations:

$$h_s = \int_0^x R_s dx \tag{9}$$

$$h_g = \int_0^x R_g dx \tag{10}$$

$$F = P - h_s - h_g \tag{11}$$

In the pervious module, the mandatory parameters are f_0, f_c, k and W at the beginning of a precipitation event.

2.3. Permeable Pavement Scenarios and Model Setting

Three kinds of permeable pavements (permeable asphalts (PA), permeable concretes (PC) and permeable interlocking concrete pavers (PICP)) were installed into non-busy roads, parking lots and squares in the study area. Nanjing is one of the cities suffering air pollution, which resulted in a high concentration of PM2.5, thus the performance of permeable pavements is markedly affected by clogging over their service life. Considering the impact of clogging, two conditions (good and poor) of permeable pavements in terms of infiltration and void rate differences were evaluated. The good permeable pavements have high infiltration and void rates without the impact of fine particles. The poor condition of permeable pavements is due to the effect of the deposition of fine particles. The good and poor infiltration rates and void rates of all the three permeable pavements were set according to the recommendations by MHURD [12] and the previous studies [29,30,33–35]. The values are given in Table 2. Two settings of the initial water in permeable pavements are used (no water and 50% of maximum water storage capacity). All the simulated scenarios are listed in Table 3. Permeable pavements are implemented on all non-busy roads, parking lots and squares. The total implementation area is 0.13 km^2. Permeable pavements are assumed to be continuous pavement systems and no infiltration water goes into soils under the layer of permeable pavements.

Table 2. Parameters of three permeable pavements.

Parameter	Permeable Asphalts		Permeable Concretes		Permeable Interlocking Concrete Pavers	
	Good	Poor	Good	Poor	Good	Poor
Permeability (mm/h)	15,000	130	15,000	160	10,000	530
Void ratio	0.3	0.1	0.32	0.12	0.3	0.14
Thickness (mm)	450		450		430	

Note: Void ratios are the average values of all layers.

Table 3. Simulation scenarios of permeable pavements.

Type	Condition	Scenario	Initial Water Content of Permeable Pavements
Permeable asphalts	Good	Scenario 1	No water
		Scenario 2	50% of water storage capacity
	Poor	Scenario 7	No water
		Scenario 8	50% of water storage capacity
Permeable concretes	Good	Scenario 3	No water
		Scenario 4	50% of water storage capacity
	Poor	Scenario 9	No water
		Scenario 10	50% of water storage capacity
Permeable interlocking concrete pavers	Good	Scenario 5	No water
		Scenario 6	50% of water storage capacity
	Poor	Scenario 11	No water
		Scenario 12	50% of water storage capacity

In this study, the mandatory parameters for original condition simulation were obtained from Gao [40] who studied urban flooding with the same storm event in a watershed in which our study area is located. The values of f_0, fc and k are 199.8 mm/h, 12 mm/h and 1.98, respectively. The initial soil moisture at the beginning of the storm event was set to be half of the maximum water storage capacity. The parameters for permeable pavement scenarios were calculated based on the attribute values listed in Table 2. The value of f_0 was equal to permeability and k was calculated using Equations (4) and (12). All the mandatory parameters were listed in Table 4.

$$WM = VR \times TK \tag{12}$$

where VR is the void ratio of permeable pavements and TK is thickness (mm).

Table 4. Mandatory parameters for all scenarios in model simulation.

Parameter	Original Condition	Permeable Asphalts		Permeable Concretes		Permeable Interlocking Concrete Pavers	
		Good	Poor	Good	Poor	Good	Poor
f_0 (mm/h)	199.8	15,000	130	15,000	160	10,000	530
k	1.98	111.11	2.89	104.17	2.96	77.52	8.8
f_c (mm/h)	12	-		-		-	

3. Results and Discussion

3.1. Effectiveness of Permeable Pavements on Flood Mitigation

Table 5 indicates the results of the total 12-h surface runoff under original conditions without permeable pavement implementation and 12 scenarios with different permeable pavements. Rainfall falling on permeable pavements and the flow from the impervious surface to permeable pavements could be stored in the pavements. The total runoff was reduced by 1–40% (Figure 3). This is consistent with other studies. For example, Luan et al. [41] reported that permeable pavements can reduce 2–12% of runoff for different rainfall intensities in a watershed in Beijing, China. Ahiablame and Shakya [42] found that permeable pavements reduced 15–41% of flood events under different implementation areas in a watershed in Illinois, USA. Also, it was found that peak flow decreased by 7–43% with the implementation of permeable pavements (Figure 4). Nine of the 12 scenarios had a lag time on peak flow, with the exception of Scenarios 8, 10 and 12 (Figure 5). Similar findings were also found by other studies [21,23]. For example, Huang et al. [21] reported an approximately 29% decrease in peak flow with the implementation of permeable pavements in the new campus of Tianjin University, China.

Table 5. Total 12-h surface runoff under original condition and all scenarios.

Scenario	Total Surface Runoff (mm)	Scenario	Total Surface Runoff (mm)
Original condition	71.3	Scenario 7	65.1
Scenario 1	44.6	Scenario 8	70.4
Scenario 2	60.0	Scenario 9	63.0
Scenario 3	43.0	Scenario 10	69.1
Scenario 4	58.9	Scenario 11	61.6
Scenario 5	46.0	Scenario 12	68.5
Scenario 6	60.6		

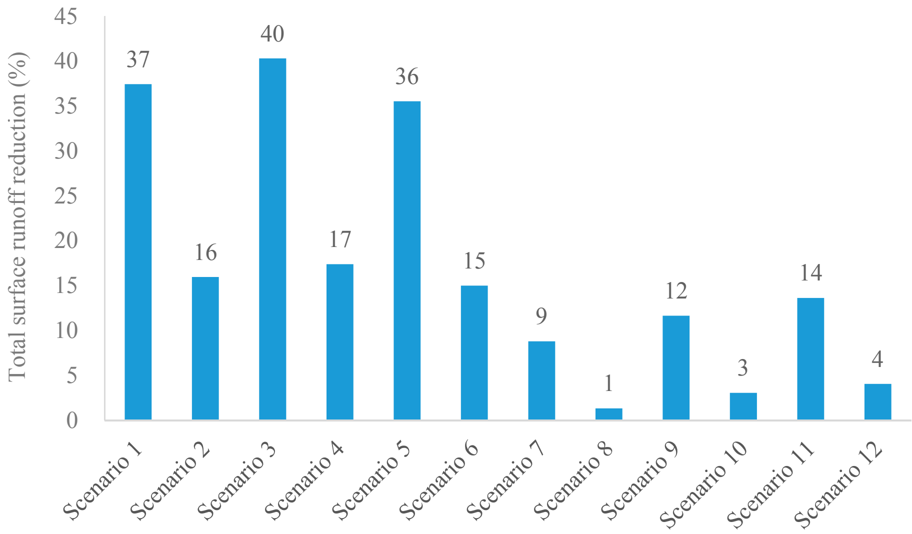

Figure 3. Percent of total surface runoff reduction by implementation of different permeable pavements.

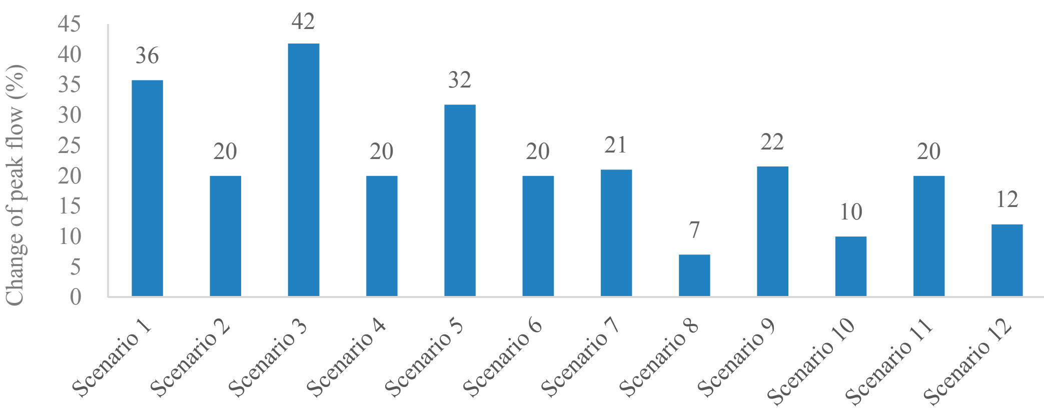

Figure 4. Percent of peak flow reduction by implementation of different permeable pavements.

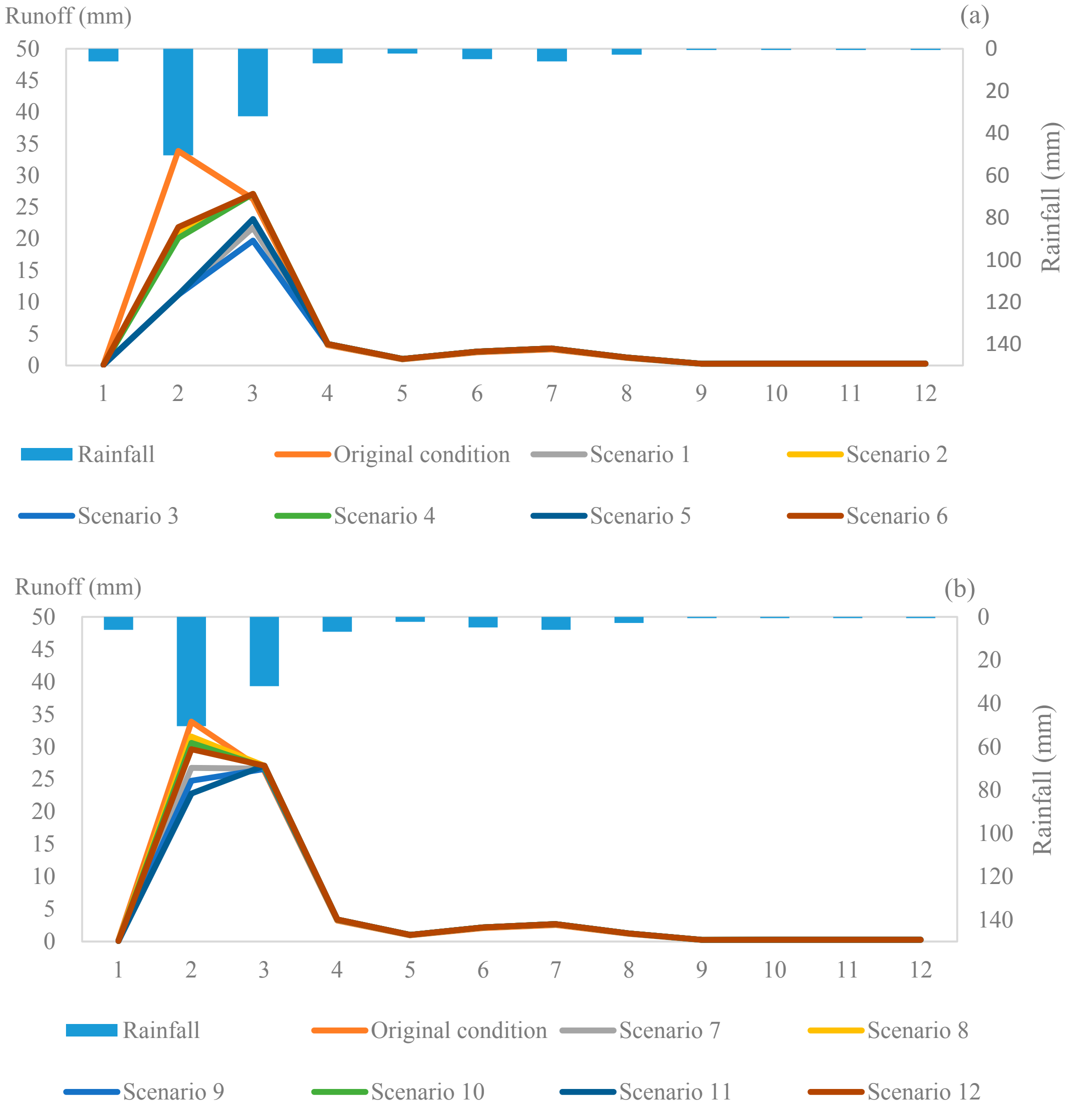

Figure 5. Simulated hourly surface runoff of original condition and all scenarios, (**a**) Scenarios 1–6; (**b**) Scenarios 7–12.

The flood mitigation performance varied with the types of permeable pavement. PA reduced 1–37% of total surface runoff and 7–36% of peak flow; PC reduced 3–40% of total surface runoff and 10–42% of peak flow; and PICP reduced 4–36% of total surface runoff and 12–32% of peak flow. Overall, PC showed the best performance (maximum decrease of 40% of total runoff and 42% of peak flow), followed by PA (maximum decrease of 37% of total runoff and 36% of peak flow) and PICP (maximum decrease of 36% of total runoff and 32% of peak flow) under good conditions. Similarly, Collins et al. [28] found different effects of four kinds of permeable pavements on runoff generation in Carolina, USA.

3.2. Impact of Clogging on the Performance of Permeable Pavements

The clogging of permeable pavement has a negative impact on flood mitigation. Permeable pavements under good conditions reduced total runoff by 15–40% (Scenarios 1–6), whereas under poor conditions runoff was only reduced by 1–14% (Scenarios 7–12). The effectiveness of runoff reduction decreased by 62–92%. Also, the peak flow was reduced by 37–65% under poor conditions. This is because that the fine particles in permeable pavements have reduced the total void and blocked the pores, with the result of reducing infiltration rates. Some studies have reported a significant reduction in infiltration rates of permeable pavements within several years due to clogging [17,43,44]. This could be reduced to certain levels, such as 1% of runoff reduction in our study within several years without proper maintenance. In addition, PICP was the least prone to clogging among the three types of permeable pavements. PICP showed the best performance under poor conditions (decreased by 4–14% of total runoff and 12–20% of peak flow), followed by PC (maximum decrease by 3–12% of total runoff and 10–22% of peak flow) and PA (maximum decrease by 1–9% of total runoff and 7–21% of peak flow). Similarly, Bean et al. [30] found that PICP was less prone to being clogged when compared with other permeable pavements in a survey of 40 permeable pavement sites in the USA.

3.3. Impact of Initial Water Content on the Performance of Permeable Pavements

The effectiveness of permeable pavements in terms of flood mitigation is affected by initial water content at the beginning of a storm event. The reduction in total runoff and peak flow decreased by 57–85% and 37–67% due to the increase of initial water content at the beginning of the simulation. For example, PA under good conditions with maximum void at the beginning (Scenario 1) reduced 37% of the surface runoff, which was more than twice the value (16%) in the case of 50% initial water content (Scenario 2).

In addition, the effect was intensified by the interaction of initial content and clogging. For example, the performance of PA on peak flow reduction decreased by 44% between Scenarios 1 and 2. This value increased to 67% between Scenarios 7 with 8. Similarly, there was a 42% decrease in PA effectiveness of peak flow reduction between Scenarios 1 and 7 and this value rose to 65% between Scenarios 2 and 8. Also, the changes in lag time of the peak flow were not evident under the integrated impacts of clogging and initial water content (Scenarios 8, 10 and 12, see Figure 5).

3.4. Implications and Limitations

As a case study in Nanjing, China, this research demonstrated the effectiveness of permeable pavements on flood mitigation and indicated the impact of type, clogging and initial water content on the hydrological performance of permeable pavements. It provides valuable information for decision makers regarding the effectiveness of permeable pavements for sponge city construction in Nanjing and other cities in China. With increasing challenges regarding water resources, the Chinese government has invested more money in environmental protection in recent years [45,46]. However, to develop an achievable plan for permeable pavement implementation, economic considerations should be taken into account.

In line with numerous other studies, there are several limitations to the current research. This study lacks data for model calibration and validation, which would lead to biases in the absolute values of runoff reductions. However, model parameter values were obtained from the published literature and the main conclusions of the impact of types, clogging and initial water content were conducted from scenario comparisons. The impact of model uncertainties is not significant and will not change the conclusions of this study. Consideration of these factors in future studies will increase our understanding of urban floods in China and other countries.

4. Conclusions

This study evaluated the role of permeable pavements in mitigating urban floods in the context of sponge city construction in China. It was found that the hydrological effects of permeable pavements on flood mitigation were highly dependent on the types of permeable pavements, the clogging situation of permeable pavements, and the initial water content at the beginning of the storm event. The major findings include:

(1) Permeable pavements reduced surface runoff by 1–40% and peak flow by 7–43% in a 12-h storm event with rainfall of 113.8 mm.

(2) The hydrological performance of permeable pavements varied widely depending upon whether their function was fully applied. Without the impact of clogging, PC showed the best performance, followed by PA and PICP.
(3) Clogging reduced the hydrological performance of permeable pavements. PICP was the least prone to being clogged, followed by PC and PA. PA, PC and PICP reduced the total surface runoff by 77–92%, 71–82% and 62–73%, respectively; and reduced peak flow by 41–65%, 48–50% and 37–40%, respectively.
(4) The hydrological performance of permeable pavements decreased with increasing initial water content. Compared to permeable pavements without initial water content, the effectiveness of the cases with 50% initial water content decreased the total runoff by 57–85% and peak flow by 37–67%, respectively.

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