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Rainfall Runoff Mitigation by Retrofitted Permeable Pavement in an Urban Area

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Abstract: Permeable pavement is an effective low impact development (LID) practice that can play an important role in reducing rainfall runoff amount in urban areas. Permeable interlocking concrete pavement (PICP) was retrofitted in a tremendously developed area of Seoul, Korea and the data was monitored to evaluate its effect on the hydrology and stormwater quality performance for four months. Rainfall runoff was first absorbed by different layers of the PICP system and then contributed to the sewage system. This not only helps to reduce the runoff volume, but also increase the time of concentration. In this experiment, different real rain events were observed and the field results were investigated to check the effectiveness of the PICP system for controlling the rainfall runoff in Songpa, Korea. From the analysis of data, results showed that the PCIP system was very effective in controlling rainfall runoff. Overall runoff reduction performance from the PCIP was found to be around 30–65% during various storm events. In addition, PICP significantly reduced peak flows in different storm events which is very helpful in reducing the chances of water-logging in an urbanized area. Research results also allow us to sum up that retrofitted PICP is a very effective approach for rainfall runoff management in urban areas.

Keywords: permeable interlocking concrete pavement; runoff mitigation; storm events; rainwater management; urban area

1. Introduction

Climate change and urbanization are two dominant factors that are altering the natural hydrological cycle as well as boosting the flash flooding in cities [1,2]. High speed urban growth increases the peak runoff, which involves the rapid discharge of rainfall to the conventional drainage system. The effect of climate change alters the rainfall intensity which results in raising the peak discharge and runoff volumes that might exceed the capacity of existing drainage infrastructure such as sewer systems. However, urbanization has replaced the natural surface with hard infrastructure such as roads, buildings and parking lots, which have decreased the natural infiltration rate of the soil [3–5]. These adverse impacts of urbanization have created multiple problems, such as flash flooding, stream bank erosion and water quality degradation [4,5]. Under these circumstances, our traditional storm water management approaches need to be redesigned to perform well under the extreme climate conditions [6]. To mitigate these adverse impacts of urbanization, there is an urgent need for development of new sustainable urban water management approaches around the globe.

Permeable pavement has been applied globally for the past years and it can reduce flooding and water quality degradation problems [7–9]. Permeable pavement is generally used to collect, treat, and absorb rainfall runoff; allow groundwater recharge; and prevent pollution [9,10]. Previous studies have shown that permeable pavements have an ability to reduce surface runoff by permitting the infiltration into the underground soil [11–13] (even though the infiltration rate is low) and enhancing the infiltrated water quality through different layers [14,15].

Typically, permeable pavement consists of permeable block pavers with open joint spaces that allow the infiltration of surface water. Underneath the pavers lies the storage layers (bedding aggregate + base course aggregate), which generally consists of open graded aggregate size varies from 2 mm to 20 mm [4]. The rainwater infiltrates through the bedding layers and infiltrates to the ground surface. Sometimes, geotextiles are used which helps for separation and strengthening layers under new roads and car parking lots. The lowest layer is the subgrade, which is a generally native soil. If the infiltration rate of permeable pavements is lower than the perforated drainage pipe, it can be applied to the subgrade layer in the pavement design [4,15]. Figure 1 below shows details of cross section of a permeable block pavement. It also shows the different layers of the permeable pavement system.

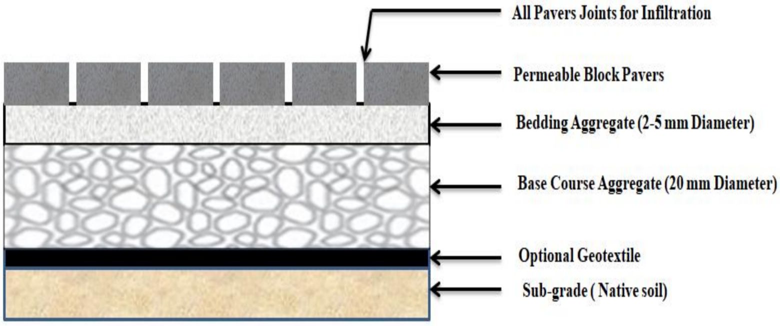

Figure 1. Shows the cross section of permeable block pavement.

Permeable pavement is referred to as permeable concrete (PC), permeable interlocking concrete pavers (PICP), porous asphalt (PA), or concrete grid pavers (CGP). Numerous studies have suggested permeable pavement as a sustainable stormwater management practice because it helps manage stormwater quantity as well as the quality [14,15]. Permeable pavement allows the rainfall runoff to infiltrate through the pores which help to reduce the small flash flood in developed areas. Different studies showed that the permeable pavement reduces the runoff volume and peak flow and also increases the time of concentration [8,15]. Brattebo and Booth [9] evaluated the four permeable pavements and found that if the rainfall is less than 5 mm, permeable pavements can reduce peak runoff by 95% and total runoff volume by 90%.

Researchers have indicated that rainfall runoff from permeable pavement is notably less as compared to traditional pavement (asphalt pavement) [13,16,17]. Collins et al. [16] investigated the hydrological performance of four different permeable pavements. Results indicated that the all four permeable pavements reduce runoff volume by 36–67% and peak flow by 60–70% as compared to the asphalt pavements. Palla et al. [17] studied the hydrological properties of permeable pavements in a laboratory. This study utilized two types of permeable pavements: concrete cell (CC) and deep pervious brick (PB). Results showed that there was no runoff observed from both permeable pavements in the first 15 min of constant rainfall intensity. In addition, the study indicated that the higher slope and bigger aggregate size enhanced the drainage [17]. Similarly, Drake [18] investigated permeable pavement performance and showed it can reduce runoff volumes by up to 43% in urban areas. Infiltration rates of the permeable pavement system greatly enhance its performance for controlling runoff in an urban area. Research shows that the newly constructed permeable pavement has higher infiltration rates and hence is more effective in managing stormwater in the urban area [19].

Some studies showed the efficiency of the permeable pavements in case of flood reduction [20,21]. For instance, Huang et al. [20] indicated that the application of permeable pavements decreased 35.6% of total rainfall runoff and 28.7% of peak flow in Tianjin University, China. The peak flow of designed five-year recurrence storm events was reduced by approximately 24.7% with the application of permeable pavements in the small village of Jurong, China [21]. Additionally, the rainfall runoff reduction performance of permeable pavements counts on the types of materials, the life of pavement, usage, operation and maintenance [16,22]. Collins et al. [16] indicated that the concrete grid pavers produced the more rainfall runoff volumes than the other kinds of permeable pavements in a field test of a parking lot in Carolina, USA. On the other hand, Kumar et al. [22] found that the infiltration rates of the pavement system depend on the service life of the pavement. From the field experiment, he found that the infiltration rates of three kinds of permeable pavements were decreased significantly from the second year because of clogging effect. Few studies also have discussed the material's effects on the efficiency of permeable pavements in controlling runoff quantity and quality at the small scale [23]. In real world applications, clogging of the pavement system is one the serious issue which needs to be investigated further for coming years [24]. In this way, we can develop a sustainable design for permeable pavements that can solve urban water related problems in the future.

Previous studies have shown that permeable pavements are very effective in controlling a large amount of rainfall runoff in urban areas. From a water quantity perspective, permeable pavements cited above mostly showed the promising results in capturing larger rain events in their sub-base layer. This process not only reduces the surface runoff but also decreases the risks of flash flooding. This study investigates the effectiveness of retrofitted permeable interlocking concrete pavement (PICP) in controlling the runoff in a populated area of Seoul, Korea. The main objectives of the paper are: (1) to investigate the performance of permeable interlocking concrete pavement in retaining runoff in different storm events; and (2) to estimate the capability of the permeable interlocking concrete pavement system to decrease the chances of flash flooding in an urban area of Seoul, Korea.

2. Materials and Methods

2.1. Site Detail Description

Permeable pavements were retrofitted in series in a highly developed area of Songpa, (Seoul, Korea, 37°49′11.33″ N 127°13′29.05″ E). Seoul perceives an average of 1300 mm of precipitation every year [25]. The research area is near the residential apartments in Songpa, Seoul, Korea (Figure 2). Because of the highly developed urban area, there are more chances of flash flooding in the rainy season. The non-busy residential road is selected for this study. This site was studied and it was found that it is composed of sandy loam soils. Eight different permeable pavement sections (permeable pavement, reinforced permeable pavement, asphalt pavement, block pavement) were retrofitted with the total length of 180 m and width of about 7 m. Lengths of each section of pavement are about 20 m and about 7 m wide. The infiltration rate of the PICP system was found to be around 0.7 mm/s during this study. The main purpose of these permeable pavements was to reduce the stormwater runoff as well as to improve the water quality performance in that area. In this study, we had selected the permeable interlocking concrete pavement (PICP) section to check the rainfall runoff reduction and water quality performance in Seoul, Korea. The PICP system consisted of different aggregate size (3–20 mm) in the sub-base with a native sandy loam soil as the sub-grade. Permeable block pavers were used on the top surface with the slope of 3%. Perforated pipe was used in the sub-grade layer to capture the infiltrate stormwater and move it to the sewer system. This PICP was designed to capture rainfalls ranging in intensity from about 20 to 50 mm/h as occurs with various storm events.

Figure 2. Study area of the permeable interlocking concrete pavement (PICP) in Seoul, Korea.

Figure 3, below shows the rainfall of Seoul, Korea throughout the year. It also shows that the maximum rainfall occurred in July of every year.

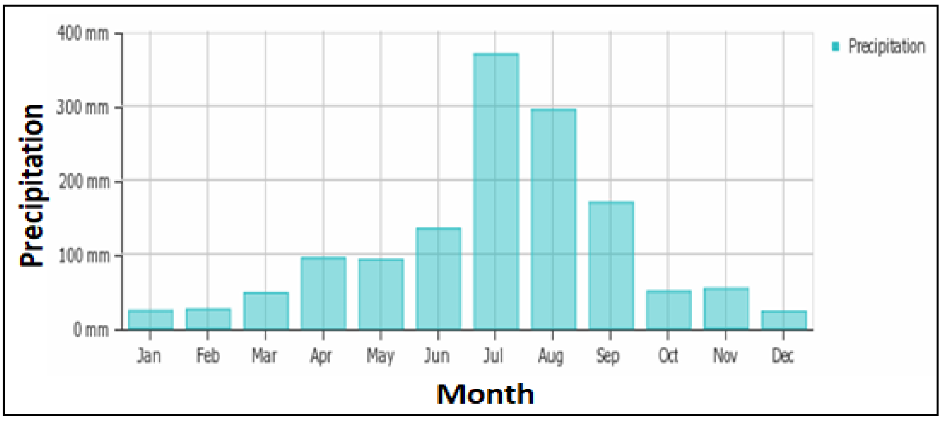

Figure 3. Monthly precipitation of Seoul, Korea in 2016 [25].

Figure 4, below, shows the permeable pavement site before the permeable pavement when it was an asphalt pavement road. This also shows the construction stage and retrofitted permeable pavement in Songpa permeable pavement systems. The construction of this site was completed in December 2017. Overall parameters of the PICP system are explained in Table 1 given below.

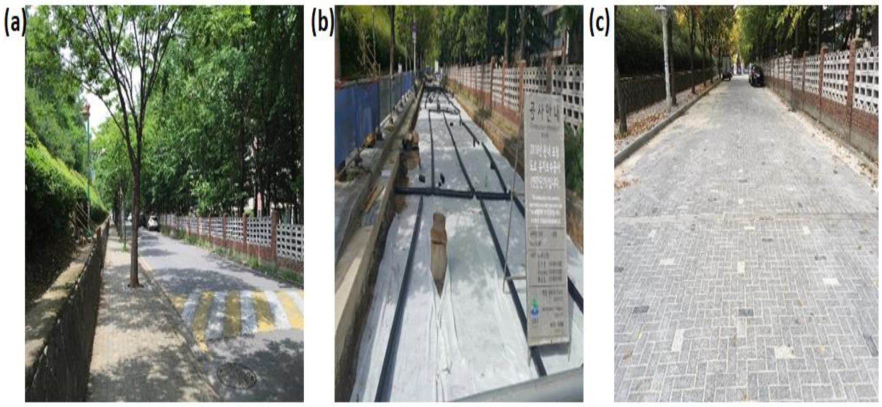

Figure 4. Shows the site of permeable pavement before and after construction; (**a**) Site before permeable pavement (asphalt pavement); (**b**) Site under the construction of permeable pavement; (**c**) Retrofitted permeable pavement (PICP).

Table 1. Parameter values used for the study of PICP system.

Parameter	PICP System
PICP total drainage area	Around 200 (m^2)
Hydraulic conductivity of sub-grade soil	6.5 (mm/s)
Watershed land use	Residential and asphalt pavement
Drainage area: PICP area	3:1
Underlying soil classification	Sandy loam
Rainfall intensity	30–120 (mm/h)
PICP system length	20 m
PICP system width	7 m
Monitoring period	22 April 2017–16 July 2017

2.2. Monitoring and Data Calculation

The Hydrological performance of the PICP system was investigated from 22 April 2017–16 July 2017. Regular data readings were collected to evaluate the PICP system in mitigating the rainfall runoff during various storm events in the highly urbanized area of Seoul, Korea. Measured precipitation readings were calculated from the Korea Meteorological Administration (KMA) online site by though the nearest rain gauge [25]. The uncertainty in the collected storm data from the KMA site was estimated to be less than 13% during the study investigation. Continuous rainfall runoff water flow measurements were taken during the different rain events. In this field study, a Stingray 2.0 (Greyline instruments Inc., Largo, FL, USA) portable level velocity logger was placed at the PICP site to investigate the water flows of the PICP system during the analysis period. PICP system rainfall runoff was calculated at the side of the vertical infiltration trench. Figure 5 below shows the point of PICP system where the rainfall runoff was calculated. After rainfall, rainwater first infiltrates in the ground soil through the PICP system, and the extra water becomes surface runoff and collects in the vertical infiltration trench where the surface rainfall runoff is calculated. Field tests carry out during real rain conditions for a period of about four months to evaluate the runoff mitigation performance of the PICP system in Korean geographical conditions.

Figure 5, shows (a) the mechanism of rainfall runoff distribution within the PICP system; (b) indicated the location of the instrument where water flow is measured. Stingary 2.0 portable level velocity logger was installed in the PICP system to check the water flow of the PICP system during different storm events.

Figure 5. (**a**) Permeable block runoff collecting mechanism; (**b**) location of data collection and permeable infiltration trench.

Figure 6 below, shows the stormwater management mechanism on the site. It also shows that the permeable pavements have a vertical underground infiltration trench on the left side of the pavement system that is collected the infiltrated water through the underground porous pipe which further infiltrates water to the ground surface. In the middle of a permeable pavement system, the perforated porous pipe installed, which is used to gather all the infiltrated rainwater from all permeable pavements and throw extra water into the sewer system. This system helps to absorb more rainfall runoff into the ground surface in many different ways and is very effective in controlling flooding in urban areas.

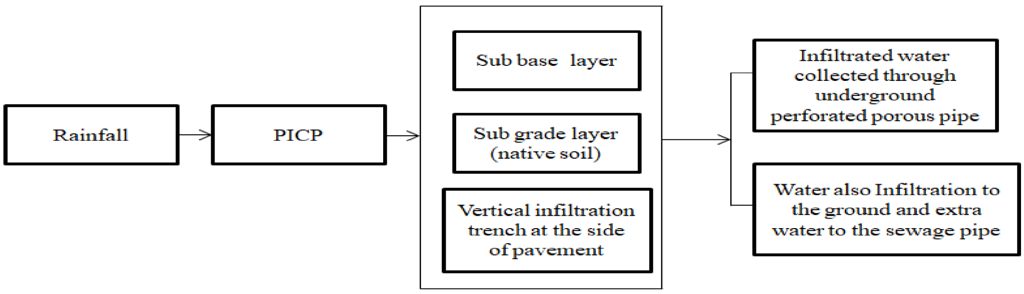

Figure 6. Shows the mechanism of stormwater management of the retrofitted PICP system.

3. Results and Discussion

Runoff Reduction Performance of PICP System

During the four-month period, a number of storm events were observed with rainfall intensity about 30, 60 and 120 mm/h. Infiltration of the underlying subgrade soil was the main factor for the rainfall runoff reduction through the PICP. Every rain event, hydrological properties for the inflow (INFLOW), PICP outflow (OUTFLOW) after infiltration the outflow runoff and peak flow reduction were calculated by using the volume reduction (VR, Equation (1) [26]), and the peak flow reduction (QR, Equation (2) [26]) as shown below.

$$VR = \frac{\sum_{i=1}^{n} V_{INFLOWi} - \sum_{i=1}^{n} V_{OUTFLOWi}}{\sum_{i=1}^{n} V_{INFLOWi}} \times 100 \quad (1)$$

$$QR = \frac{Q_{PINFLOW} - Q_{POUTFLOW}}{Q_{PINFLOW}} \times 100 \quad (2)$$

Equations (1) and (2) were used to analyze the runoff reduction performance of the PICP system during different time intervals. When the rainfall runoff falls on the PICP system, the water infiltrates the underlying soil and if the rainfall intensity is higher than the infiltration rate of the PICP, then runoff occurs on the surface. Different runoff volume reduction calculated on the basis of storm events and the analysis shows that the PICP system would have reduced 30–65% of the volume, which shows that it is a very effective technique to control flash flood issues in developed areas like Songpa, Seoul, Korea. Table 2 below shows that the permeable pavement is very effective in case of small rain events (of intensity about 40 (mm/h). It absorbed all rainwater and no discharge took place during these rain events. However, in case of bigger rain events, permeable pavement reduced rainfall runoff up to around 30–50% as shown in Table 2.

Table 2. Volume reduction of PICP system during different storm events.

Rainfall Events	Runoff Volume Reduction Performance
Rainfall intensity: 40 (mm/h)	100%
Rainfall intensity: 120 (mm/h)	30–50%
All storm events	Around 30–65%

During the field data analysis of the PICP system, the rain events hydrograph data give the details of the permeable interlocking concrete pavement response to the various storm event inputs. Hydrographs of various rain events were exhibited by the capture of rainwater runoff (Figures 7 and 8). The hydrographs responses indicate the variations in rainfall runoff outflow with various rain events. However, in a 40 mm/h small rain event, no discharge (rainfall runoff outflow) was found from the PICP system. It means that all the rainwater infiltrated through the PICP system. Another storm event on 3 July 2017 with rainfall intensity of 120 mm/h shows the larger rainfall runoff outflows of 3.2 L/s as shown in Figure 7 below. From the analysis during big storm events, the rainfall runoff outflow of PCIP system was found to about 3.5 L/s, which shows that PCIP system helps to control the surface runoff in urban areas. During the various storm events, the rainfall runoff outflows from PICP system varies from 1.0 L/s to 5.5 L/s. In this way, rainwater infiltrates to the ground surface and reduces the surface rainfall runoff. From the analysis, it was proven that PCIP can reduce the rainfall runoff about 35% to 65% of during small rain events. This is due to the ability of the PICP system to store large amount of rainwater in different layers.

In addition to reducing rainfall runoff, the PICP system notably decreased the peak flow on an average 10–25% as shown in Figures 7 and 8. This is because of the storage and infiltration of rainwater rainfall in the PICP system. Figure 8 shows the rainfall outflow from the PICP during different rain events of intensity 30–120 mm/h. This also shows that in case of small storm events of less than 40 mm/h rainfall intensity, the PICP system captures all the rainfall runoff and thus there was no runoff outflow found during these time periods.

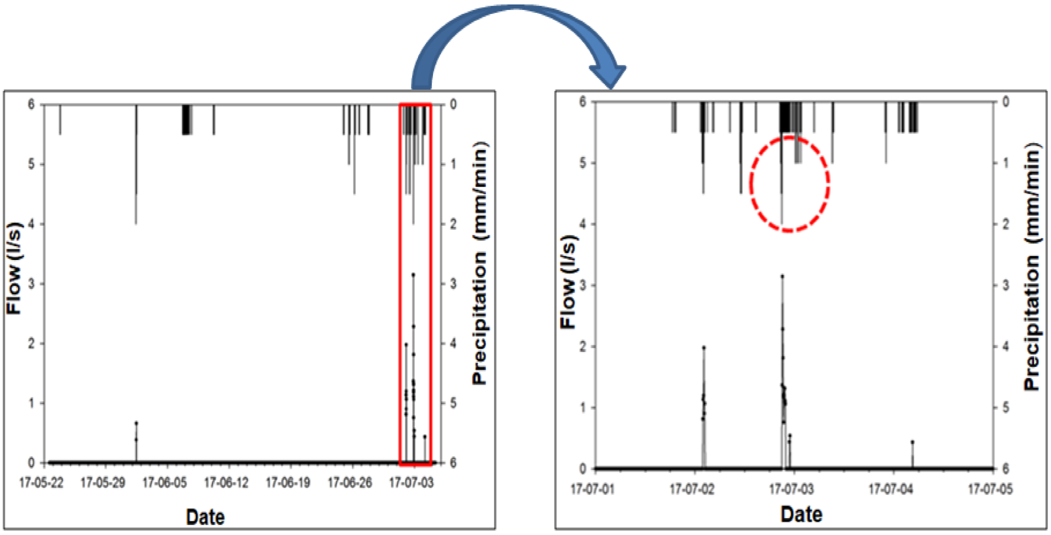

Figure 7. Indicates the rainfall runoff outflows (L/s) response during to the various storm events of 5 April–5 July 2017.

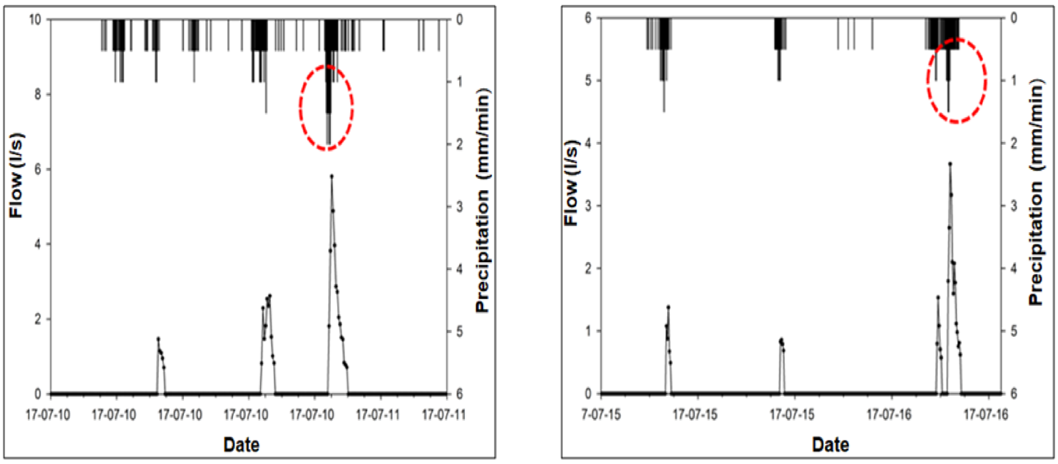

Figure 8. Shows the rainfall runoff outflows (L/s) response of the PICP system to the various rain events of 10–16 July 2017 with different rainfall intensities around 30–120 mm/h.

PICP system layers promote the infiltration of rainwater to the underground that helps to control the stormwater in urban areas. The runoff outflows were around 3–5 L/s during the big rain events of around 100–120 mm/h. This is because; during big storm events, the PICP system cannot detain and infiltrate all the rainwater in the underlying layers. From the analysis, it was found that the PICP system detain a significant amount of rainfall runoff. Therefore, a PICP technique is useful to control and infiltrate the rainfall runoff the ground surface and thus helps to enhance the ground water recharge in urban areas. If the depth of permeable pavement sub-base is greater, then it can capture and absorb more rainwater as compared to smaller depth sub-base. The results of rainfall runoff volume reduction showed that the PICP system is a very effective practice to retrieve the hydrological conditions of the urban area.

This field study manifested the capability of permeable pavements on rainfall runoff mitigation in an urban area. It gives useful information for stakeholders regarding the benefits of using the permeable pavements for controlling rainfall runoff in urban areas of Seoul, Korea. This research study mirrors the other field results [16] and indicates that the PICP system was very effective strategy in capturing a large amount of rainwater in a developed area. From the data analysis of field tests, PCIP system performance in controlling rainfall runoff was found to be higher than other studies Drake [18] and Huang et al. [20]. Therefore, this PICP system is very effective for urban rainfall runoff management. However, in line with several research studies, there are certain limitations to the current field study. These research shortfalls the long term evaluation of the PICP system because long term field evaluation will also help to investigate the clogging of permeable pavement. As clogging is the factor which greatly affects the performance of permeable pavement over the time. Therefore, a long term evaluation of the PICP system should be carried out. There is also a need to select the best materials for the subgrade of the PICP system so that it can decrease the more rainfall runoff as well as to enhance the infiltrated water quality. In the future, to enhance the PCIP system in terms of rainfall runoff quantity and quality performance, it is necessary to combine the PICP system with other suited LID facilities [26] in such a way that it can provide multiple benefits (hydrological + water quality improvements) in the urban area.

4. Concluding Remarks

This research presented the hydrological performance of PICP in the urban catchment, in order to check their potential to mitigate the peak discharge in flood risk areas. The results have demonstrated that the retrofitted PICP system is very effective in handling the storm events to decrease chances of flash floods in the developed area of Seoul. The hydrology and stormwater quality performance provided by a retrofitted permeable interlocking concrete pavement was evaluated for about four consecutive months of (April–July) in 2017. Through this study, the following outcomes are drawn:

(1) Permeable interlocking concrete pavement showed the tremendous performance in controlling a large amount of rainfall runoff in urban areas. The overall runoff volume reduction was around 30–65% during various storm events. This not only decreases the rainfall runoff volume, but also the peak flow discharge which is very helpful in lowering flash flooding in urban areas.

(2) The hydrological performance of the PICP system was enormously influenced by the type of underlying native soil. This is because the native soil has higher infiltration rates and is thus capable of absorbing a large amount rainfall runoff. Because of this, it prevents the ponding on the surface of the pavement.

Above results showed that PICP system is an effective technique to reduce the rainfall runoff in a developed area of Seoul, Korea. However, to get multiple results, there is a need to connect the PICP system with other nearby LID facilities such as rain gardens, grass swales, etc. This will not only help to control more runoff volume but help in treating more pollutants in different ways.

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

References

1. Franczyk, J.; Chang, H. The effects of climate change and urbanization on the runoff of the rock creek basin in the Portland Metropolitan Area, Oregon, USA. *Hydrol. Process.* **2009**, *23*, 805–815. [CrossRef]
2. Booth, D.; Hartley, D.; Jackson, R. Forest cover, impervious surface area, and the mitigation of storm-water impacts. *J. Am. Water Resour. Assoc.* **2002**, *38*, 835–845. [CrossRef]
3. Line, D.; White, N. Effects of development on runoff and pollutant export. *Water Environ. Res.* **2007**, *79*, 185–190. [CrossRef] [PubMed]
4. Moglen, G. Hydrology and impervious areas. *J. Hydrol. Eng.* **2009**, *14*, 303–304. [CrossRef]

5. Todeschini, S. Hydrologic and environmental impacts of imperviousness in an industrial catchment of Northern Italy. *J. Hydrol. Eng.* **2016**. [CrossRef]
6. Shafique, M.; Kim, R. Recent Progress in Low-Impact Development in South Korea: Water-Management Policies, Challenges and Opportunities. *Water* **2018**, *10*, 435. [CrossRef]
7. Pratt, C.J.; Wilson, S.; Cooper, P. Source control using constructed pervious pavements. In *Hydraulic, Structural and Water Quality Performance Issues*; CIRIA: London, UK, 2002.
8. Bean, E.Z.; Hunt, W.F.; Bidelspach, D.A. Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts. *J. Irrig. Drain. Eng.* **2007**, *133*, 583–592. [CrossRef]
9. Brattebo, B.O.; Booth, D.B. Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Res.* **2003**, *37*, 4369–4376. [CrossRef]
10. Scholz, M.; Grabowiecki, P. Review of permeable pavement systems. *Build. Environ.* **2007**, *42*, 3830–3836. [CrossRef]
11. Ahiablame, L.; Engel, B.; Chaubey, I. Effectiveness of low impact development practices: Literature review and suggestions for future research. *Water Air Soil Pollut.* **2012**, *223*, 4253–4273. [CrossRef]
12. Shafique, M.; Kim, R. Green stormwater infrastructure with low impact development concept: A review of current research. *Desalination Water Treat.* **2017**, *83*, 16–29. [CrossRef]
13. Dreelin, E.A.; Fowler, L.; Carroll, C.R. A test of porous pavement effectiveness on clay soils during natural storm events. *Water Res.* **2006**, *40*, 799–805. [CrossRef] [PubMed]
14. Park, S.B.; Tia, M. An experimental study on the water purification properties of porous concrete. *Cement Concr. Res.* **2004**, *34*, 177–184. [CrossRef]
15. Bernot, M.J.; Calkins, M.; Bernot, R.J.; Hunt, M. The influence of different urban pavements on water chemistry. *Road Mater. Pav. Des.* **2011**, *12*, 159–176. [CrossRef]
16. Collins, K.A.; Hunt, W.F.; Hathaway, J.M. Hydrologic comparison of four types of permeable pavement and standard asphalt in Eastern North Carolina. *J. Hydrol. Eng.* **2008**, *13*, 1146–1157. [CrossRef]
17. Palla, A.; Gnecco, I.; Carbone, M.; Garofalo, G.; Lanza, L.; Piro, P. Influence of stratigraphy and slope on the drainage capacity of permeable pavements: Laboratory results. *Urban Water J.* **2015**, *12*, 394–403. [CrossRef]
18. Drake, J. Performance and Operation of Partial Infiltration Permeable Pavement Systems in the Ontario Climate. Ph.D. Thesis, University of Guelph, Guelph, ON, Canada, 2013.
19. Gilbert, J.K.; Clausen, J.C. Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. *Water Res.* **2006**, *40*, 826–832. [CrossRef] [PubMed]
20. Huang, J.J.; Li, Y.; Niu, S.; Zhou, S.H. Assessing the performances of low impact development alternatives by long-term simulation for a semi-arid area in Tianjin, northern China. *Water Sci. Technol.* **2014**, *70*, 1740–1745. [CrossRef] [PubMed]
21. Xie, J.; Wu, C.; Li, H.; Chen, G. Study on storm-water management of grassed swales and permeable pavement based on SWMM. *Water* **2017**, *9*. [CrossRef]
22. Kumar, K.; Kozak, J.; Hundal, L.; Cox, A.; Zhang, H.; Granato, T. In-situ infiltration performance of different permeable pavements in a employee used parking lot—A four-year study. *J. Environ. Manag.* **2016**, *167*, 8–14. [CrossRef] [PubMed]
23. Gao, M.; Carmichael, G.R.; Saide, P.E.; Lu, Z.; Yu, M.; Streets, D.G.; Wang, Z. Response of winter fine particulate matter concentrations to emission and meteorology changes in North China. *Atmos. Chem. Phys.* **2016**, *16*, 11837–11851. [CrossRef]
24. Razzaghmanesh, M.; Beecham, S. A review of permeable pavement clogging investigations and recommended maintenance regimes. *Water* **2018**, *10*. [CrossRef]
25. Korea Meteorological Administration (KMA) 2018. Available online: http://web.kma.go.kr/eng/weather/climate/worldclimate.jsp (accessed on 19 January 2018).
26. Braswell, A.S.; Anderson, A.R.; Hunt, W.F. Hydrologic and water quality evaluation of a permeable pavement and biofiltration device in series. *Water* **2018**, *10*. [CrossRef]