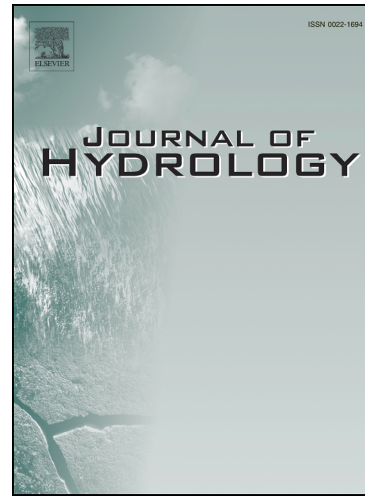
Accepted Manuscript



Research papers

Investigation clogging dynamic of permeable pavement systems using embedded sensors

Mostafa Razzaghmanesh, Michael Borst

PII:	S0022-1694(18)30012-X
DOI:	https://doi.org/10.1016/j.jhydrol.2018.01.012
Reference:	HYDROL 22494
To appear in:	*Journal of Hydrology*
Received Date:	5 September 2017
Revised Date:	15 November 2017
Accepted Date:	6 January 2018

Please cite this article as: Razzaghmanesh, M., Borst, M., Investigation clogging dynamic of permeable pavement systems using embedded sensors, *Journal of Hydrology* (2018), doi: https://doi.org/10.1016/j.jhydrol.2018.01.012

Investigation clogging dynamic of permeable pavement systems using embedded sensors

[1]Mostafa Razzaghmanesh, PhD*, [2]Michael Borst

[1]ORISE Postdoctoral Research Fellow at the U.S. EPA, Office of Research and Development (ORD) Edison, New Jersey, email: Razzaghmanesh.Mostafa@epa.gov, Corresponding author

[2]Principal investigator, the U.S. EPA Office of Research and Development (ORD) Edison, New Jersey, email: Borst.Mike@epa.gov

Postal Address: 2890 Woodbridge Ave. Building 10, Office of Research and Development (ORD), Edison, NJ 08837-3679- Phone: +1 (732) 321-6632

Abstract

Permeable pavement is a stormwater control measure commonly selected in both new and retrofit applications. However, there is limited information about the clogging mechanism of these systems that effects the infiltration. A permeable pavement site located at the Seitz Elementary School, on Fort Riley, Kansas was selected for this study. An 80-space parking lot was built behind the school as part of an EPA collaboration with the U.S. Army. The parking lot design includes a permeable interlocking concrete pavement section along the downgradient edge. This study monitored the clogging progress of the pavement section using twelve water content reflectometers and three buried tipping bucket rain gauges. This clogging dynamic investigation was divided into three stages namely pre-clogged, transitional, and clogged. Recorded initial relative water content of all three stages were significantly and negatively correlated to antecedent dry weather periods with stronger correlations during clogged conditions. The peak relative water content correlation with peak rainfall 10-min intensity was significant for the water content reflectometers located on the western edge away from the eastern edge; this correlation was strongest during transition stage. Once clogged, rainfall measurements no longer correlated with the buried tipping bucket rain gauges. Both water content reflectometers and buried tipping bucket rain gauges showed the progress of surface clogging. For every 6mm of rain, clogging advanced 1 mm across the surface. The results generally support the hypothesis that the clogging progresses from the upgradient to the downgradient edge. The magnitude of the contributing drainage area and rainfall characteristics are effective factors on rate and progression of clogging.

Keywords:

Green infrastructure, permeable pavement, clogging, Water content reflectometer, Tipping bucket rain gauge

1 Introduction

Replacing natural environment with impervious surfaces including roofs, roads, highways and bridges have led to increase of seasonal flooding and easy movement of pollutants into the receiving surface water and groundwater. The increased magnitude and the number of flooding events also caused the conventional urban drainage systems not to be able to control and convey all the runoff events throughout a whole year. Green infrastructure (GI) is one option to reduce the effects of urbanization (USEPA 2015, Rowe et al. 2016). GI can potentially reduce the runoff volume and the contaminant load reaching the receiving water. Permeable pavement is a GI technology that has multiple benefits for the urban environment. Permeable pavements have been implemented in the forms of porous asphalt, pervious concrete and permeable interlocking concrete pavement (Collins et al. 2008, Brown and Borst 2015). Research has indicated the potential of permeable interlocking concrete pavers (PICP) systems as a technology to reduce both the runoff volume and pollutant removals (Booth and Leavitt 1999, Fassman and Blackbourn 2011, Brown and Borst 2015). However, to maximize the stormwater quantity and quality performance of these systems and to better design and prepare maintenance guidelines, continuous monitoring is of interest to engineers and policy makers.

Permeable pavement is an infiltration system that passes stormwater runoff into the soil. Internal and external factors including native soil, weather and surrounding land-use can affect a permeable pavers site. Existing soil condition, particularly the infiltration rate, is an important internal factor that affects the performance of a permeable pavement system. While systems placed over permeable soils are expected to perform, studies of various types of permeable pavement systems have shown functionality even when installed over both low permeable and impermeable soils (Fassman and Blackbourn 2010, Drake et al. 2014).

During rainfall events, sediment washes from the surface of the upstream contributing drainage area and moves toward the permeable pavement sections and, as a result of infiltration, particles accumulate within the openings. This accumulation and addition of fine particles make the surface of a permeable pavement clog and generally progresses from the upgradient toward the down-gradient (Brown and Borst 2013). Permeable pavement's clogging is the main problem that reduces the surface infiltration of these systems and also is a barrier toward wider implementation of this technology (Welker et al. 2013). This ratio of the contributing drainage area to the working width of the permeable pavement is a design factor and the rate of clogging is expected to be faster with larger drainage areas than a smaller one (Brown and Borst 2013). Generally, clogging particles are from biological, chemical or physical sources (Yong et al. 2013).

Most field studies measured the initial infiltration rates and the changes over time as a metric to investigate the permeable pavement's hydrological performance and clogging progress (Booth and Leavitt 1999, Brattebo and Booth 2003, Brown and Borst 2014).

Different aspects of clogging mechanisms have been conducted by earlier studies through laboratory experiments (Haselbach 2010, Ehsaei 2013), field investigations (Bean et al. 2007, Pezzaniti et al. 2009, Lucke and Beecham 2011) and modelling (Deo et al. 2010).

Haselbach (2010) investigated the effects of extreme events and runoff with high loads of clay on pervious concrete clogging, concluding that the clay particles accumulated on the upper layers of the pavement and surface sweeping followed by rinsing was an efficient way to return infiltration to an acceptable level.

Welker et al. (2013) performed intensive vacuuming to collect materials from the opening of the pavers to investigate the types of deposited materials on the pore spaces and particle sizes. They found that most of the materials came from the raveled permeable pavement and few fines were associated with migration of particles and organic matter from the surrounding drainage area.

Yong et al. (2013) developed a regression model to predict physical clogging after a series of laboratory experiments. They concluded that clogging was highly correlated with runoff's volume and flow rate. Radfar and Rockaway (2016) developed a new model for clogging prediction using artificial neural networks. In this study, peak 5-min intensity, the previous rainfall depth, and the cumulative rainfall depth from the start of the study were the most effective parameters on predicting the hydrologic performance of the permeable pavement.

Stander et al. (2013) used water content reflectometers (WCRs) to measure permeable pavement and rain garden performance. It was concluded that WCRs successfully quantified size and timing of the wetting front as runoff moves through soil and non-soil media in low impact development (LID) practices. WCRs were also used by Ehsaei (2013) in a flume experiment at the Edison Environmental Center (EEC) designed to link the effect of slope and paver's gap sizes on creation and progress of clogging. In an earlier study by Brown and Borst (2013), unevenly distributed WCRs with higher density near the upgradient were used for a spatial infiltration study of clogging pattern and progression for permeable pavement strips along a street in Louisville, Kentucky.

However, there are limited studies on the continuous monitoring of PICP internal hydrologic processes and clogging mechanisms. This study monitored the mechanism and progress of clogging on a PICP pavement as part of a mild sloped parking lot at an elementary school using embedded WCRs (CS650-Campbell) and tipping bucket rain gauges (TB4-Campbell). This study also investigated the required maintenance to keep the PICP function within the accepted levels. The distribution of WCRs also provide the opportunity to study the clogging in two dimension as a secondary objective of this study.

2 Experimental set up

This study was conducted at the Seitz Elementary School, a LEED-silver certified building in the Camp Forsyth area of Fort Riley, Kansas. Fort Riley has a temperate continental climate characterized by hot summers, cold, dry winters, moderate winds, low humidity, and a pronounced peak in rainfall late in the spring and in the first half of summer. Prevailing winds are from the south to southwest during most of the year, but during February and March, the prevailing winds are from the north (USARMY 2014).

The Army designed and constructed an 80-space parking-lot with a PICP section (Figure 1). The PICP section captures direct rainfall, and parking lot runoff from the adjacent parking area and conveys it into the underground layers. The design of the PICP section's underground volume was based on the capture of 100% of the 5-year 24-hr rainfall event (107.70 cm) and assumes a nominal 40% aggregate porosity in the storage gallery. The contributing drainage area is 1833 m^2 and the area of the PICP section is 174 m^2. The parking lot has been mainly used by parents as a pickup / drop off area. To collect and treat the direct rainfall and run-on from the adjacent parking lot area, and also because of low-permeability of the native soil, the drainage area under the permeable pavement was designed in three sections. This design provided enough space and time for water to be infiltrated.

Figure 1 Parking lot with location of the embedded WCRs and rain gauges under the PICP section

The dimension of the underground is 3.20 m (width) × 54.90 m (length) × 3.30 m (depth). The three layers of the underground section from the top to the bottom are 5.10 cm thick bedding layer of American Association of State of Highway Transportation (ASHTO) No.8 aggregate, a 15.25 cm choker consisting of ASHTO No.57 and a 3.10 m storage gallery of ASHTO No.2 (Figure 2). The trench walls and bottom were covered by non-woven double needle punch geotextile layer. Based on previous research (Brown and Borst 2013) it was expected that the PICP surface would clog as solids carried by the runoff accumulated in the aggregate-filled paver gaps, initially filling the most upgradient gaps and forcing the water to gaps farther downgradient.

WCRs were embedded at the interface of the choker and storage gallery layers at the depth of 20.32 cm to monitor the clogging progress following the recommendation by Brown and Borst (2013). In this study, the WCRs were placed in rows of three at four locations equally spaced across the paver surface (see Figure 1). WCRs were designed to monitor moisture levels in mineral soils but they have been demonstrated to provide relative moisture content in aggregate (Brown and Borst 2013, Stander et al. 2013). The relative moisture levels indicated by the sensors can be used to distinguish when the surface above the sensor is receiving moisture from direct rainfall or the large influx associated with the progression of the wetting front to the surface above the sensor. The data loggers with hardwired sensors are programmed to send recorded volumetric water content, electrical conductivity, temperature, dielectric permittivity, period average, and voltage ratio data tables. The generated tables are sent in the form of 1-min and 10-min to the "master logger" at defined intervals using the radios connected to the loggers. The operation of the reflectometer can be adversely affected by large conductivities associated with winter salt operation (Campbell Scientific 2015) and in such cases, the recorded data were excluded from the analysis.

Figure 2 Side view of the PICP's section

This study used tipping bucket rain gauges as a second approach to investigate the clogging mechanism and progression. Three TB4 model tipping bucket rain gauges (Campbell Scientific 2010) were buried under the column 2 of WCRs numbered WCR4, WCR5 and WCR6 (Figure 1 & Figure 2).

A weather station was installed on the southwest corner of the school roof. The weather station monitored rainfall and other climatological parameters. The data logger was programed to record all readings at 1-minute intervals during rain events and 10-minute intervals otherwise. The 1-minute and 10-minute data were stored in separate data tables. The 1-minute data were continued until there were 12 hours without rain. Separately, time of tip files were also generated from the rain gauges. Each tip represented 2.54 mm (0.10 in.) of rainfall; the maximum capacity of the tipping bucket is 456 mm/hr. Definition of "event" in this study was a period with at least 2.54 mm of rainfall measured by tipping bucket rain gauge and dry inter-event of at least 6 hours (Brown and Borst 2013, Razzaghmanesh and Beecham 2014).

It was expected that the PICP surface infiltration rates would be similar to rainfall intensities before the clogging progressed to the buried tipping bucket rain gauge locations. As the clogging front reaches the rain gauge location, the measured rates were expected to increase dramatically as the rain gauge would be subject to both runoff and rainfall intensity. As the clogging front advances past the embedded rain gauge location, the measured rate of tips was expected to decrease. These rain gauges were hard wired to a data logger and similar to the WCRs from the significant events, 1-min and 10-min data were generated.

3 Statistical analysis

Initially, the datasets were tested for normality using Shapiro-Wilk tests. In addition, in case of non-normal distribution for correlation studies, a nonparametric test (Spearman rank order) was used for WCRs and tipping bucket rain gauges' correlation tests against rainfall intensity and antecedent dry weather period (ADWP). For comparisons between WCRs responses for runoff versus rainfall, nonparametric Kruskal-Wallis ANOVA & Median tests were used. Multiple comparisons p values (2-tailed) with a significance level of $\alpha = 0.05$ were used to test for difference between the variables. All statistical analyses were computed using Statistica 9.1 (Statsoft 2009).

4 Results

4.1 Rainfall events during this study.

The time between the finish of the last rainfall and start of the new event considered as ADWP. Fifty-two rainfall events were investigated in this study. Seventy-six percent of the total rainfall volume occurred from mid-spring to early fall of 2016. These events were divided into pre-clogged, transition, and clogged stages according to the selected threshold in section 4.2. Table 1 shows the rainfall characteristics.

Table 1 Rainfall event characteristics during this study

4.2 Selecting threshold

A simple approach to detect events is based on defining thresholds values to compare the sensor readings (Bahrepour et al. 2012). Because of the presence of linear relationship between cumulative rainfall and clogging progress along the pavement section, it is possible to find a threshold for determining the clogging rate across permeable pavement sections (Brown and Borst 2013, Kazemi 2014). According to the maximum relative water content (MRWC) recording from the WCRs along the PICP, the MRWC threshold to identify when surface runoff was infiltrating over the WCR was tested at 0.08 m^3/m^3 and in increments of 0.01 m^3/m^3 to 0.16 m^3/m^3. The first and last measurement exceeding each threshold were plotted against cumulative rainfall depth since installation of monitoring equipment for each WCR along the PICP. At 0.11 m^3/m^3 the largest correlation coefficient was calculated and then this threshold selected for this study. Figure 3 shows a least-squares linear regression of distance on cumulative rainfall computed for both the first and last measurement to exceed 0.11 m^3/m^3.

Figure 3 Selecting a WCR threshold to determine the progression of surface clogging

4.3 WCRs and correlation to rainfall- runoff characteristics

The ADWP and rainfall peak 10-min intensity are recognized as correlated parameters to WCRs initial and peak relative water content (Brown and Borst 2013). This study also tested correlation of the recorded initial relative water content (IRWC) against ADWP and results are reported in Table 2. Data were divided into three stages namely pre-clogged, transitional, and clogged, and then analyzed for correlation investigations. Pre-clogged condition was attributed to the period that MRWC readings of WCRs were < 0.11 m^3/m^3. Transitional stage was represented by the period from the start of clogging to the completely clogged condition or the period between the first and the last time that WCRs readings were > 0.11 m^3/m^3. All WCRs readings less than 0.11 m^3/m^3 after the transitional period were considered among clogged period.

All the IRWC measured by WCRs during clogged stage, and most of the sensor's initial relative water content during pre-clogged and transitional period, were significantly and negatively correlated to ADWP as shown in Table 2. During transition and clogged periods, stronger correlations resulted, and because of reduced infiltration rate, less water infiltrated from PICP surface.

Correlation among MRWCs with rainfall peak 10-min intensities were studied for the defined categories of pre-clogged, transition and clogged. WCR1, WCR3 to WCR10, and WCR12 showed positive correlation during transition period as reported in Table 2. In clogged stage WCR2, WCR3, WCR6 through WCR9 showed significant difference with rainfall peak 10-min intensities, while just few of the WCRs (WCR6, WCR9, WCR11 & WCR12) showed statistically significant difference during pre-clogged condition. The reason for not showing a significant correlation in the pre-clogged period is because the pavement was new and pristine and water infiltrated with various and predominantly larger rates than the rainfall intensities. For the clogged stage, few of the WCRs did not show significant correlation with 10-min rainfall intensities and this is mainly because of the progress of the clogging front across the PICP.

Table 2 RWVC correlation to rainfall characteristics

4.4 Clogging investigation using water content reflectometers

WCR recordings were used to investigate the clogging appearance and development across the PICP section. It was expected that contributing drainage area runoff carries solids and deposition of these materials cause the PICP section starts to clog. Progression of clogging from the upgradient edge toward a location just upgradient of a WCR, more water from the contributing drainage area will infiltrate over the WCR leading to larger corresponding response. As the clogging front progresses downgradient from a WCR location, the clogged surface allows less water to infiltrate over the WCR with a smaller corresponding response observed. Figure is a three-dimensional graph of MRWC of the fifty-two events for the rows of WCR (R1, R2 & R3) located at distance of 0.80 m, 1.60 m and 2.40 m from the upgradient edge. The results showed that from the event number 1, which was one of the largest rainfall events monitored and had 76.20 mm/h intensity (Table 1), clogging had already progressed 0.80 m from the upgradient edge when the average MRWC recorded 0.14 m^3/m^3. After events number 14, 15 and 16, it was evident the clogging front had already passed those WCRs located nearest to the upgradient edge.

The maximum 10-min rainfall peak intensity during this study happened for the event of 04/25/2016 with 102.10 mm/h. After this storm, the clogging front progressed further downgradient. The upgradient PICP was clogging and infiltration rates of this area of the permeable pavement section were reduced. The results of the recorded MRWC located at 1.60 m from the upgradient edge showed evidence of clogging after event of 05/23/2016. The clogging front advanced to distance of 2.40 m from the upgradient edge after events of 05/25/2016 and 05/27/2016. Figure 4 shows the condition of the PICP at the start of the study (A) and standing water on the PICP section because of clogging (B). The results indicate that nearly one year after the installation of PICP, maintenance is required to return the PICP infiltrating function.

Figure 4 Maximum relative water content versus time (Event number) (A) distance from upgradient edge=0.80 m, (B) distance from upgradient edge=1.60 m & (C) distance from upgradient edge=2.40 m for WCRs

Figure 4 Standing water over PICP section after progression of clogging

4.5 Differences in Response for Runoff versus Direct Rainfall

In order to investigate the WCRs responses to rainfall versus runoff, the WCRs were analyzed using nonparametric Kruskal-Wallis ANOVA for the three distinguished conditions of pre-clogged, transitional, and clogged and results are presented in Table 3. There was not a statistical significant difference among WCRs during pre-clogged stages while all showed significant difference during transitional and clogging periods. This indicates that during pre-clogging the WCRs near the contributing drainage area were receiving surface runoff and the WCRs that located far from the upgradient received direct rainfall. Significant difference during clogging period shows non-uniform distribution of clogging front over the PICP section and at this condition the WCRs located in eastern side of the PICP showed less recording.

Table 3 WCRs response for runoff versus rainfall

4.6 Tipping bucket rain gauges and correlation to rainfall- runoff characteristics

Similar to WCRs, the correlations among the roof rain gauge and three buried tipping bucket rain gauges were investigated using the same three periods of pre-clogged, transition and clogged, with the goal to distinguish these three periods. Table 4 shows the results of correlation investigation for 10-min rainfall and runoff intensities.

Table 4 rainfall and runoff intensities correlations

There was a significant correlation between the roof's rain gauge and middle and south buried tipping rain gauge during pre-clogged stage. A similar result was evident for the roof's rain gauge and north buried tipping rain gauge during transition period. However, there was not a significant correlation among roof rain gauge 10-min peak rainfall intensity and all three buried tipping rain gauge peak 10-min runoff intensities during clogged period.

4.7 Clogging investigation through buried tipping bucket rain gauges

As shown in Figure 1 & Figure 2, the tipping bucket rain gauges were buried under WCR4, WCR5 and WCR6. Both continuous and event-based cumulative rainfall and runoff were recorded from the roof rain gauge and the three buried tipping bucket rain gauges. Figure 5 shows that all four rain gauges initially recorded similar amounts of water until start of the event of 12/13/2015, when the north rain gauge cumulative runoff curve rises faster. This signifies the beginning of clogging of the PICP upgradient of the north rain gauge.

The data were normalized by dividing the cumulative recording of each buried rain gauge per event by the cumulative recording of the roof rain gauge in each event. The results are reported in Figure 6. The north rain gauge cumulative recording during each event gradually increased (Figure 5) and the normalized ratio also increased from 4.70 to 7.60, 9.20 and then 18.20 after event of 04/20/2016 (Figure 6). The ratio increased until it reached a maximum of 103 during the event of 04/25/2016. After this stage, the clogging front passed the north rain gauge location. The normalized ratio value of the north rain gauged then dropped to 8.90 and then 1.80 after the events of 05/17/2016 to 05/27/2016 indicating the surface above the north rain gauge clogged. This result generally showed that although the northern zone of the PICP is clogged, it still allows a small amount of water to infiltrate. Early on, for both the middle and south rain gauges, normalized ratio values increased from about 1.00 to values approaching 4.00. Then as the surface above the north rain gauge clogged, the normalized values increased to 27.70 for middle rain gauge and 26.40 for the south rain gauge after events of 05/24-25/2016 similar to north rain gauge increase on 4/20/2016. The increased ratio for the middle and south rain gauge also mean that the clogging front was progressing to the middle rain gauge. The event-based normalized values for the middle rain gauge decreased to smaller values but then increased to 22.40 on 08/07/2016, 46.60 on 08/26/2016 and then a maximum value of 114.60 during the event of, 09/14/2016 indicating that the area above the middle rain gauge would soon be clogged. The south rain gauge showed its peak value during the event of 12/04/2016 when it reached the value of 65.80. These results support the hypothesis that clogging progressed from the upgradient to downgradient.

Figure 5 cumulative rainfall and runoff recorded from the roof rain gauge and the three buried tipping bucket rain gauges since start of the study

Figure 6 Event based normalized cumulative runoff to rainfall

4.8 Clogging rate

The slopes for the first and last response to exceed the 0.11 m^3/m^3 threshold were 0.615 and 0.008 m/mm, and the coefficients of correlation were 0.99 and 0.94, respectively. In the studies by Brown and Borst (2013) and Kazemi (2014), the larger correlation coefficient was observed for the last time exceeded the selected threshold. As explained earlier, installing WCRs in three rows and four columns provides the opportunity to study the clogging rate in two dimensions. The same threshold limit of 0.11 m^3/m^3 was used and the clogging rate was calculated for each row and column for the first and last time that MRWC exceeded this threshold limit separately. The results of average clogging rate for the first and last time exceeded threshold are reported in Table 5. The rows and columns shown in Figure 1.

Table 5 Clogging rates of WCRs rows and columns

4.9 Effect of drainage area on clogging

The results of this study were used with the results of two earlier studies (Table 6) to investigate the effects of design parameters of contributing drainage area and rainfall characteristics. From the earlier studies that were conducted in Louisville, Kentucky and Edison, New Jersey sites, the former had a larger and the latter a smaller contributing drainage area located upstream of the permeable pavement section (Brown and Borst 2013). Results of all three studies were used to find a relation between the contributing drainage area and the number of the required maintenance events per year as shown in Figure 7.

Table 6 Contributing drainage area and observed rainfall of various sites

Figure 7 Relation between ratio of contributing drainage area to pavement width versus number of yearly required maintenance

5. Discussion

In this study, WCRs and buried tipping bucket rain gauges were employed to investigate the progression of clogging on a permeable interlocking concert pavement section. The permeable section was part of an 80-space parking lot in Seitz Elementary School in Fort Riley, Kansas. The rainfall pattern in the study area showed non-uniform distribution with fewer storm events during winter and most of the large storm events occurring from mid spring through early fall. As a result, more runoff generated from the contributing drainage area and more likely the potential for clogging of the PICP is larger after large events of mid spring through summer. Three periods of namely pre-clogged, transition, and clogged were defined to evaluate the results of both embedded sensors.

There was negative correlation among the WCRs initial relative water content with ADWP during all three stages of pre-clogged, transition, and clogged stages. The significant negative correlation between IRWC and ADWP confirmed that WCRs can measure drying between events, similar to what occurs in soil. The calculated correlation was stronger during the clogged and the pre-clogged stages than transitional stage. These results are similar to the results of TDRs that used to monitor a permeable pavement strips in Louisville, KY by Brown and Borst (2013).

WCR1, and WCR3 to WCR10 & WCR12 showed statistically positive correlation between WCRs peak relative water contents and rainfall peak 10-min intensities during the transitional period while 33% and 50% of the WCRs that were located farther from the upgradient edge showed significant correlation during pre-clogged and clogged periods. The reason for non-significant correlation in the pre-clogged period for the WCRs located farther from the upgradient edge is because the downgradient pavement initially had larger infiltration rates. During the clogged period the PICP infiltration was less than rainfall intensity.

From the WCRs recording, it was possible to distinguish whether the area above the WCRs is receiving water from direct rainfall or runoff from the contributing drainage area. These results are similar to the results of earlier studies by Brown and Borst (2013) and Stander et al. (2013) for the WCRs.

As recommended by Brown and Borst (2013), WCRs were evenly distributed across the PICP. This arrangement also gave the opportunity to monitor the clogging in two dimensions of upgradient toward down-gradient and from western edge to eastern edge. The results showed that the clogging started from the upgradient and progressed into the downgradient and west edge direction. Also, a lateral progression of clogging was evident in a direction from west edge into the east edge of PICP. At a Louisville site with a permeable pavement strip system located along a road with a curb, the progression of clogging was perpendicular to the contributing drainage area runoff flow direction.

During the design and construction of the parking lot, efforts were made to direct all of the contributing drainage area's runoff to spread uniformly over the pavement section width. However, the results showed that some of the WCRs located on the far east side of the pavement section received less runoff during this study. These results are similar to the finding of Ehsaei (2013) that conducted wetting and clogging front on a pavement section with underlying layers in a laboratory scale experiment. Another possibility for smaller recording of the far east sensors could be the deposition of the particles and debris from the earlier events, thus changing the runoff direction and hence the runoff did not infiltrate over these reflectometers during the following events.

Feasibility of using buried tipping bucket rain gauges as a tool to investigate the mechanism and progression of clogging was conducted in this study. Peak 10-min rainfall and runoff intensities were compared. During the pre-clogged stage, 10-min runoff intensity of both the middle and south buried tipping bucket rain gauge showed a significant correlation with rainfall peak 10-min intensity. In the transition period, the north rain gauge showed a significant correlation with rainfall intensities. The clogged stage peak 10-min run off recorded by all three buried tipping bucket rain gauges did not show correlation with 10-min peak rainfall intensity. Similar to WCRs, the buried tipping rain gauges were also installed in the direction of the upgradient toward the opposite gradient. The buried tipping bucket rain gauges were able to show the generation and advancement of clogging along the PICP section in consistent with WCRs. Before clogging at each rain gauge location, the recorded infiltration by rain gauges was similar or larger than the rainfall intensities, while after clogging the infiltration rates calculated from buried rain gauges were remarkably smaller.

The WCRs measurement provide useful information for clogging investigation and also for recommending the required yearly maintenance. Recordings of buried tipping bucket rain gauges and WCRs confirmed that PICP was not completely clogged and showed some degrees of infiltration.

For a series of WCRs along the PICP, the timing of the measureable change in response by the WCR versus similar rainfall intensities can be used to indicate surface clogging progression rate. This can help to establish a maintenance schedule. Selecting the proper threshold for MRWC to differentiate between direct rainfall infiltration compared to surface runoff is critical. As mentioned earlier, it is likely that the threshold is location and instrument specific (Brown and Borst 2013) and may also be influenced by construction materials.

Clogging rate results showed that clogging progressed at the average rate of 0.006 m/mm (0.50 ft/in) from upgradient to downgradient and also the average rate of 0.211 m/mm (17.58 ft/in) from the west edge to the east edge of PICP. The results from a series of WCRs installed in the direction of expected clogging in Louisville indicated that surface clogging was advancing at a rate of about 0.123 m/mm of rainfall based on the first three months of monitoring (Brown and Borst 2013). Based on this rate of surface clogging and the annual rainfall depth in Louisville, the 36.6 m long control required about four maintenance events per year in Louisville, whereas in Fort Riley annual maintenance is required. It can be concluded that clogging rate is dependent on the size of the contributing drainage area and rainfall characteristics. Further investigation of the WCRs and tipping bucket data showed that the clogging progress was slower on the northern half of the PICP and quicker on the south half. This happened mainly because of the increase in drainage area and because of the greater frequency of rainfall events in late spring and summer. It can be concluded that rainfall characteristic is one of the main drivers of the clogging. These results are in agreement with findings of Yong et al. (2013) that found clogging was highly correlated with runoff's volume and flow rate. Additionally, Radfar and Rockaway (2016) concluded the previous rainfall depth, and the cumulative rainfall depth from the start of the study were the most effective parameters on the hydrologic performance of the permeable pavement. It is recommended when the clogging front reached the 75% of the width of the PICP or when the transition stage started, the maintenance should be scheduled.

The ratio of the contributing drainage area to permeable pavement area is an important factor for recommending maintenance. This ratio was largest for the Louisville study and it was smallest at the Edison site. This helps explain why Louisville needed maintenance after three months, Fort Riley after 12 months and why Edison required no maintenances even after seven years of use.

It is recommended for designing a parking lot system that includes PICP section, the ratio of contributing drainage area to the PICP area should be between 2:1 to 5:1 (NJDEP 2004, Smith 2006). However, in this study the ratio was 10.50 which helps explain the progression of clogging in less than a year. A cost- benefit study would help to select which options of narrow-deep or wider-shallow of GI is useful.

Lack of flexibility and adaptability is one of the weakness of the threshold-based classifications techniques (Bahrepour et al. 2012). It has been suggested for the studies that when early detection of the event is necessary, data mining methods can be used for data interpretation. Novel reputation-based voting and the decision tree is one of the applied method of machine learning techniques to detect many real world events that show specific patterns (Bahrepour et al. 2012).

The embedded sensors such as water content reflectometer have been used in earlier study by Brown and Borst (2013) on non-array placement. In this study sensors were installed in an array pattern for further investigations. Results of earlier studies showed if the sensors installed properly those can work for several years. One important issue with the embedded sensor is the careful installation of the sensors. If those installed correctly there will not be any communication issues during the study. In this study, two data loggers were used for recording and transferring the data. The results of this study showed that the embedded sensors can be used in the larger area. However, validating the recorded data is one of the common issues of the large wireless networks. A method has been proposed by Chen et al. (2017) to reduce the traffic and required communications and to increase validity of the recorded data.

6. Conclusion and recommendations

Permeable pavement is generally designed to treat stormwater that falls on the actual pavement surface area and accept run-on from adjacent impervious areas. Monitoring of clogging progression of the surface of a PICP section that was part of a parking lot was conducted in this study. With WCR placement that was spread out across the PICP, it was possible to monitor the clogging in two dimensions. One along the upgradient edge into the opposite edge and one from the west edge along the east edge or generally, along the length of the PICP section.

WCRs and buried tipping rain gauges were consistent in predicting the clogging progression of PICP section. These instruments are useful tools for monitoring the permeable pavement performance in remote areas.

Developing a mobile application and connecting the sensors recording with the application will provide useful information regarding clogging and scheduling maintenance for the owners.

Both embedded WCRs and buried tipping bucket rain gauges were located at 25%, 50% and 75% from the upgradient edge and in this study with this placement it was possible to track progression of clogging. It is recommended when the clogging front reached the 75% of the width of the PICP or when the transition stage started, the maintenance should be scheduled because of increased contributing drainage area potentially the clogging will progress quicker after this point.

Further studies on the rainfall characteristics, the ratio of the contributing drainage area, the drainage area land-use, and economy of the permeable pavements are helpful for scheduling more accurate maintenance practice and success of the project. Additionally, studies on pavement section evaporation before and after clogging may be useful

7 Acknowledgments

This article was supported in part by an appointment to the ORISE Research Participant Program supported by an interagency agreement between EPA and DOE and may not necessarily reflect the views of EPA. The writers also would like to thank the following parties for their assistance with this project: US Army, School District, EPA Region 7, Corps of Engineers.

8 Disclaimer

The U.S. EPA, through its Office of Research and Development, funded and managed, or partially funded and collaborated in, the research described in this paper. It has been subjected to the Agency's administrative review and has been approved for external publication. Any opinions expressed in this paper are those of the writers and do not necessarily reflect the views of the Agency; therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

9 References

Bahrepour, M., N. Meratnia, M. Poel, Z. Taghikhaki and P. J. M. Havinga (2012). "Use of wireless sensor networks for distributed event detection in disaster management applications." International Journal of Space-Based and Situated Computing **2**(1): 58-69.

Bean, E. Z., W. F. Hunt and D. A. Bidelspach (2007). "Field Survey of Permeable Pavement Surface Infiltration Rates." JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING **133**(3): 249-255.

Booth, D. B. and J. Leavitt (1999). "Field evaluation of permeable pavement systems for improved stormwater management." Journal of the American Planning Association **65**(3): 314-325.

Brattebo, B. O. and D. B. Booth (2003). "Long-term stormwater quantity and quality performance of permeable pavement systems." Water Research **37** 4369–4376.

Brown, R. A. and M. Borst (2013). "Assessment of Clogging Dynamics in Permeable Pavement Systems with Time Domain Reflectometers." Journal of Environmental Engineering **139**: 1255-1265.

Brown, R. A. and M. Borst (2014). "Evaluation of Surface Infiltration Testing Procedures in Permeable Pavement Systems." Journal of Environmental Engineering **140**(3): 04014001.

Brown, R. A. and M. Borst (2015). "Nutrient infiltrate concentrations from three permeable pavement types." Journal of Environmental Management **164**: 74-85.

Campbell Scientific (2010). TB4 and TB4MM Rain Gage instruction manual. C. Scientific. North Logan, Utah, USA**:** 22.

Campbell Scientific (2015). CS650 and CS655 Water Content Reflectometers instruction manual. I. CAMPBELL SCIENTIFIC. North Logan, Utah, USA**:** 58.

Chen, L., L. Liu, X. Qi and G. Zheng (2017). "Cooperation forwarding data gathering strategy of wireless sensor networks." International Journal of Grid and Utility Computing **8**(1): 46-52.

Collins, K. A., W. F. Hunt and J. M. Hathaway (2008). "Hydrologic Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina." Journal of Hydrologic Engineering **13**(12): 1146-1157.

Deo, O., M. Sumanasooriya and N. Neithalath (2010). "Permeability Reduction in Pervious Concretes due to Clogging: Experiments and Modeling." Journal of Materials in Civil Engineering **22**(7): 741-751.

Drake, J., A. Bradford and T. V. Seters (2014). "Hydrologic Performance of Three Partial-Infiltration Permeable Pavements in a Cold Climate over Low Permeability Soil." Journal of Hydrologic Engineering **19**(9): 04014016.

Ehsaei, A. (2013). Effect of slope and paver characteristics on performance of permeable pavement GI. Department of Civil and Environmental Engineering. Louisville, Kentucky, University of Louisville. **PhD dissertation:** 393.

Fassman, E. A. and S. Blackbourn (2010). "Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils." Journal of Hydrologic Engineering **15**(6): 475-485.

Fassman, E. A. and S. D. Blackbourn (2011). "Road runoff water-quality mitigation by permeable modular concrete pavers." JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING **137**(11): 720-729.

Haselbach, L. M. (2010). "Potential for Clay Clogging of Pervious Concrete under Extreme Conditions." Journal of Hydrologic Engineering **15**(1): 67-69.

Kazemi, H. (2014). Evaluating the effectiveness and hydrological performance of green infrastructure stormwater control measures. Civil and Environmental Engineering. Louisville, Kentucky, University of Louisville. **PhD:** 231.

Lucke, T. and S. Beecham (2011). "Field investigation of clogging in a permeable pavement system." Building Research & Information **39**(6): 603-615.

NJDEP (2004). NJ Stormwater Best Management Practices Manual. New Jersey Department of Environmental Protection Division of Watershed Management. Trenton, NJ.

Pezzaniti, D., S. Beecham and J. Kandasamy (2009). "Influence of clogging on the effective life of permeable pavements." Proceedings of the Institution of Civil Engineers-Water Management **162**(3): 211-220.

Radfar, A. and T. D. Rockaway (2016). "Clogging Prediction of Permeable Pavement." JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING **142**(4): 04015069.

Razzaghmanesh, M. and S. Beecham (2014). "The hydrological behaviour of extensive and intensive green roofs in a dry climate." Science of The Total Environment **499**: 284-296.

Rowe, A. A., P. Rector and M. Bakacs (2016). "Survey Results of Green Infrastructure Implementation in New Jersey." Journal of Sustainable Water in the Built Environment **2**(3): 04016001.

Smith, D. R. (2006). Permeable Interlocking Concrete Pavements, Selection, Design, Construction and Maintenance. I. C. P. Inistitute. Washington, D.C**:** 62.

Stander, E. K., A. Rowe, M. Borst and T. O'Connor (2013). "Novel Use of Time Domain Reflectometry in Infiltration-Based Low Impact Development Practices." JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING **139**(8): 625-634.

Statsoft (2009). Statistica. V. 9.1. Tulsa, OK.

USARMY (2014). Programmatic environmental assessment military engineering Fort Riley, Kansas.

USEPA (2015). "Green Infrastructure Research."

Welker, A. L., J. K. G. Jenkins, L. McCarthy and E. Nemirovsky (2013). "Examination of the material found in the pore spaces of two permeable pavements." JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING **139**(4): 278-284.

Yong, C., D. McCarthy and A. Deletic (2013). "Predicting physical clogging of porous and permeable pavements." Journal of Hydrology **481**: 48-55.

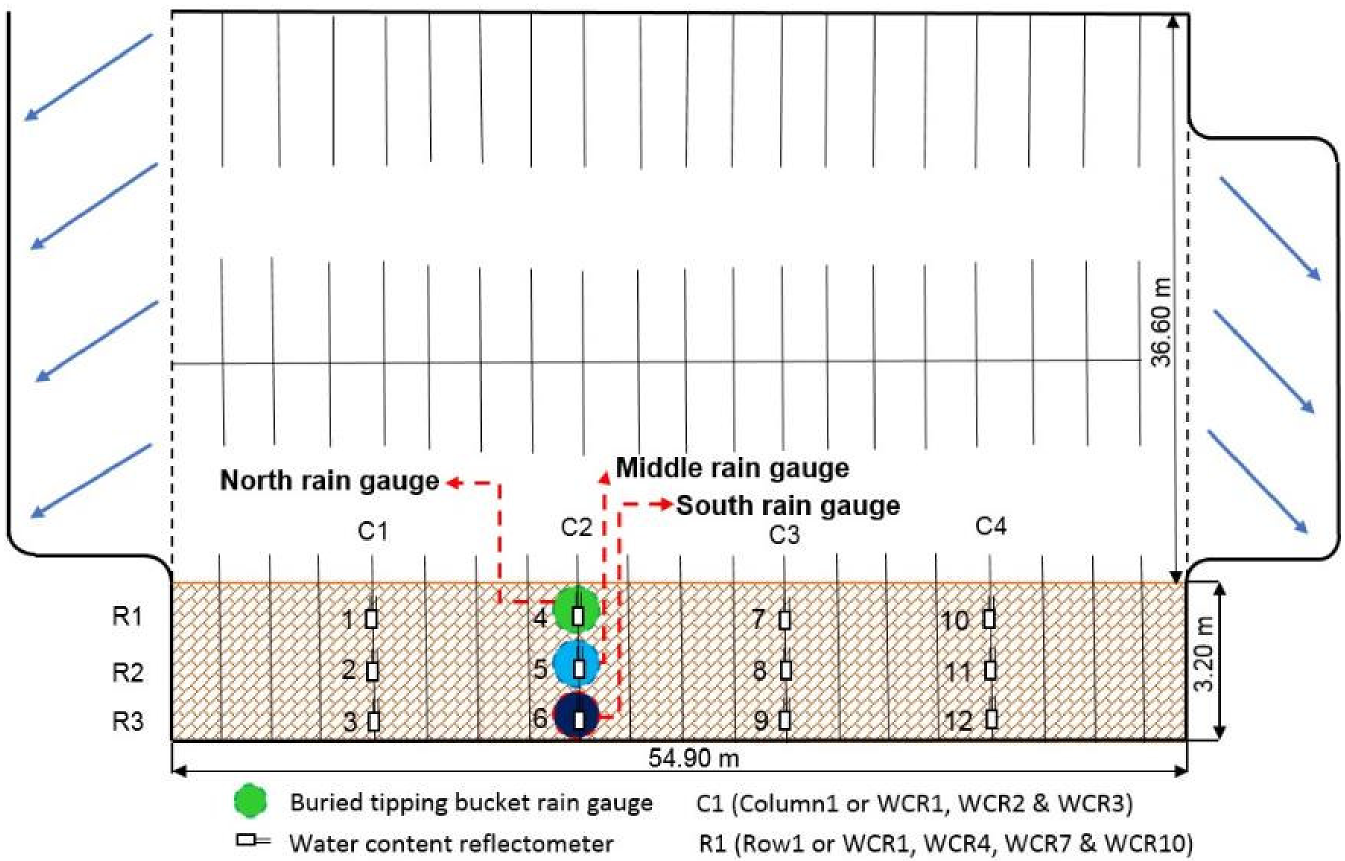


Figure 1 Parking lot with location of the embedded WCRs and rain gauges under the PICP section

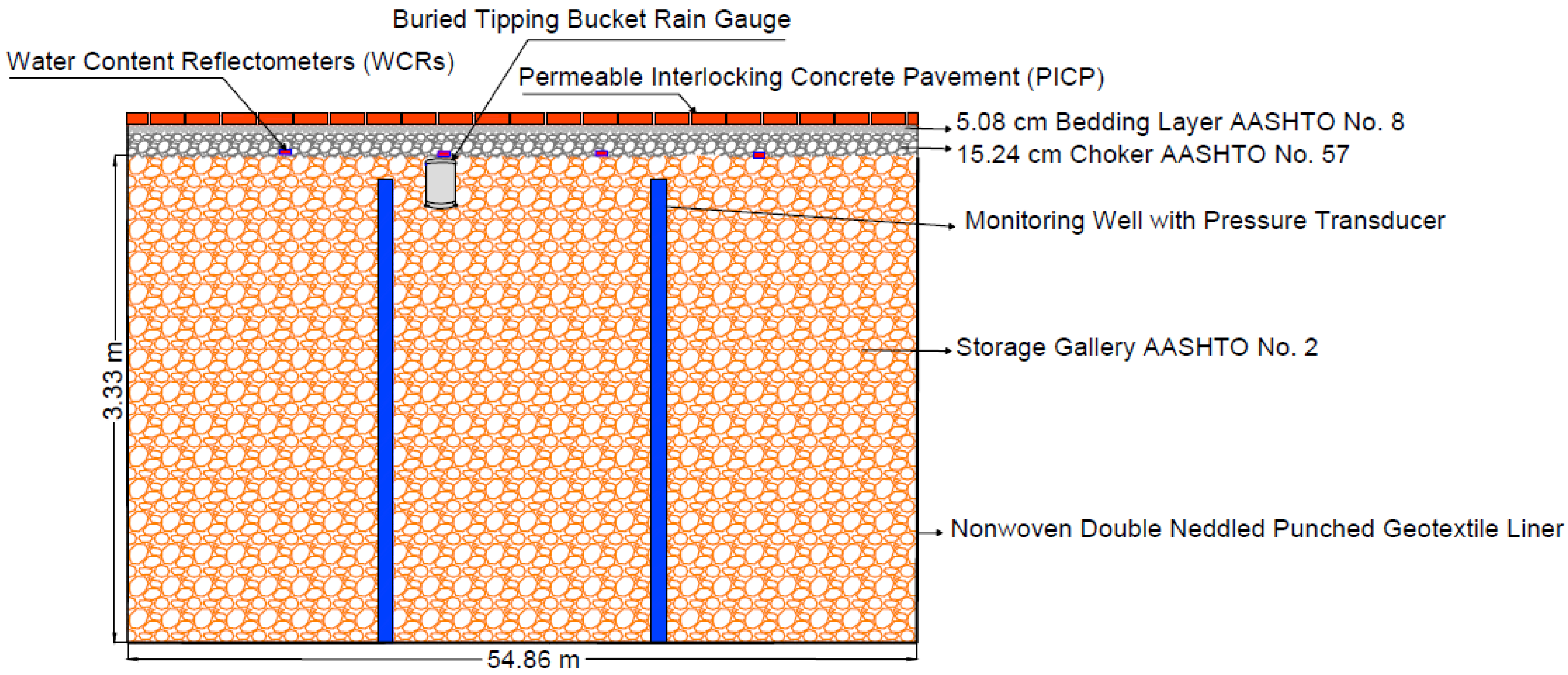


Figure 2 Side view of the PICP's section

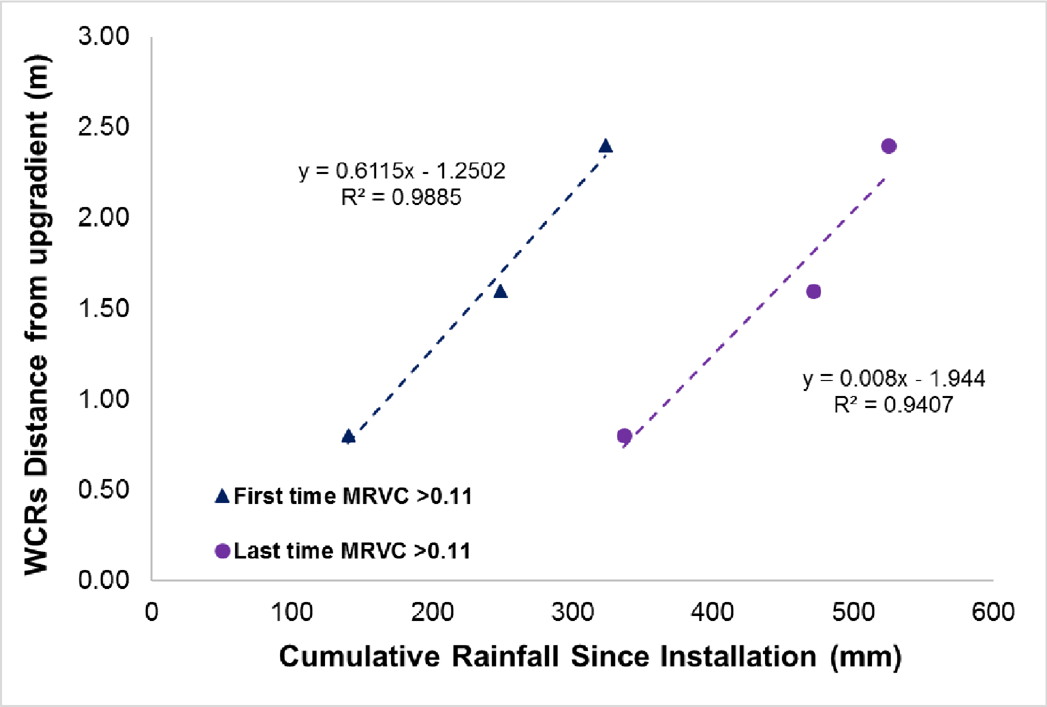
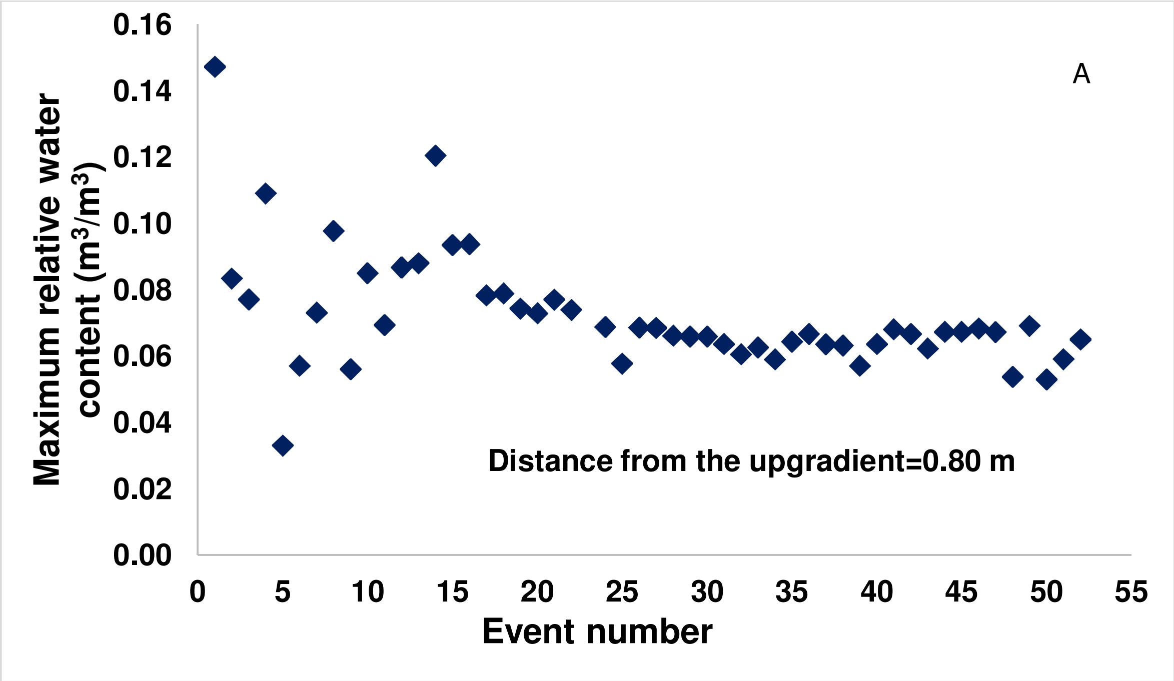
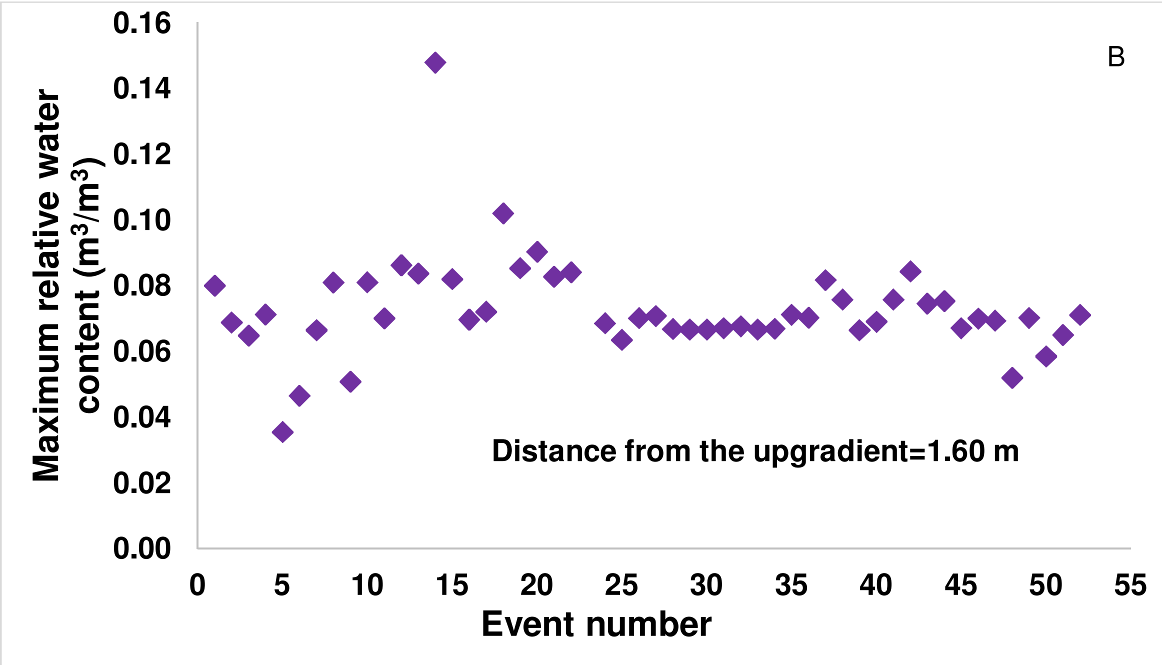


Figure 3 Selecting a WCR threshold to determine the progression of surface clogging


A
Maximum relative water content (m3/m3)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Distance from the upgradient=0.80 m
0
5
10
15
20
25
30
35
40
45
50
55
Event number


B
Maximum relative water content (m3/m3)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Distance from the upgradient=1.60 m
0
5
10
15
20
25
30
35
40
45
50
55
Event number

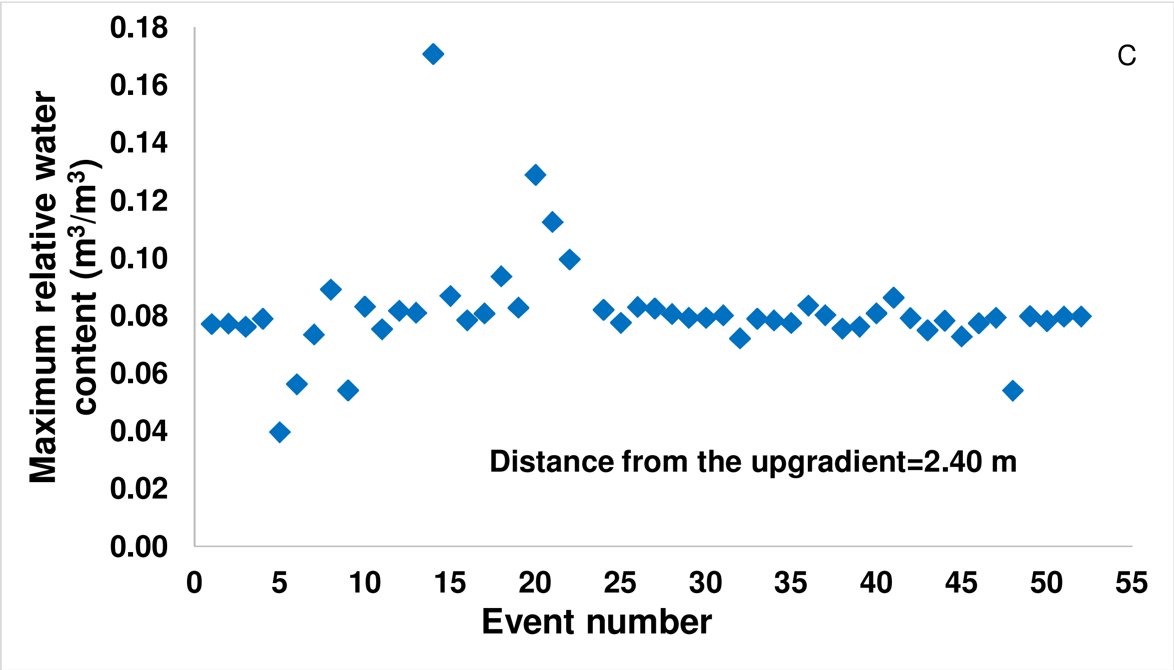


Figure 4 Maximum relative water content versus time (Event number) (A) distance from upgradient edge=0.80 m, (B) distance from upgradient edge=1.60 m & (C) distance from upgradient edge=2.40 m for WCRs

Figure 5 Standing water over PICP section after progression of clogging

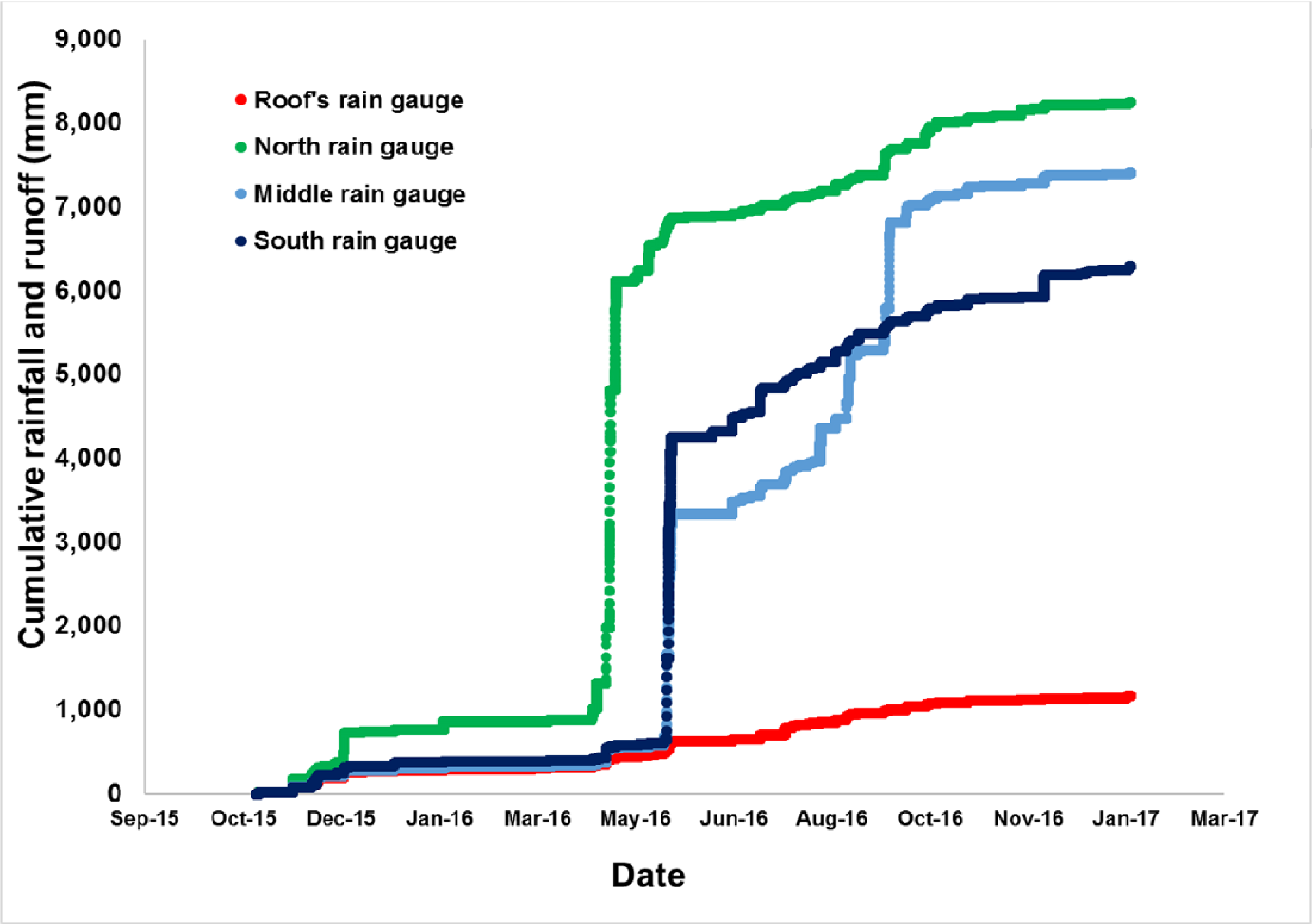


Figure 6 cumulative rainfall and runoff recorded from the roof rain gauge and the three buried tipping bucket rain gauges since start of the study

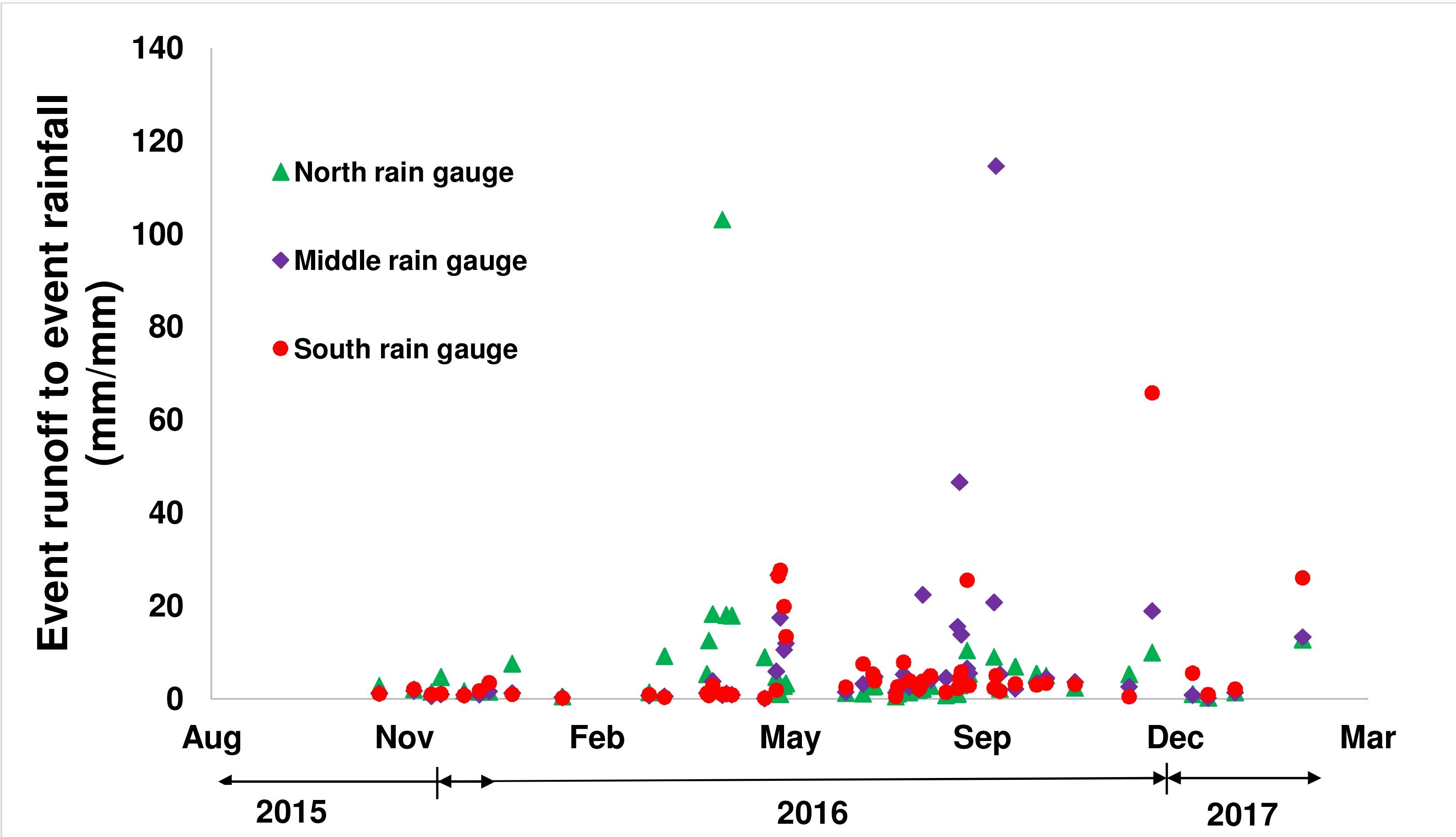


Figure 7 Event based normalized cumulative runoff to rainfall

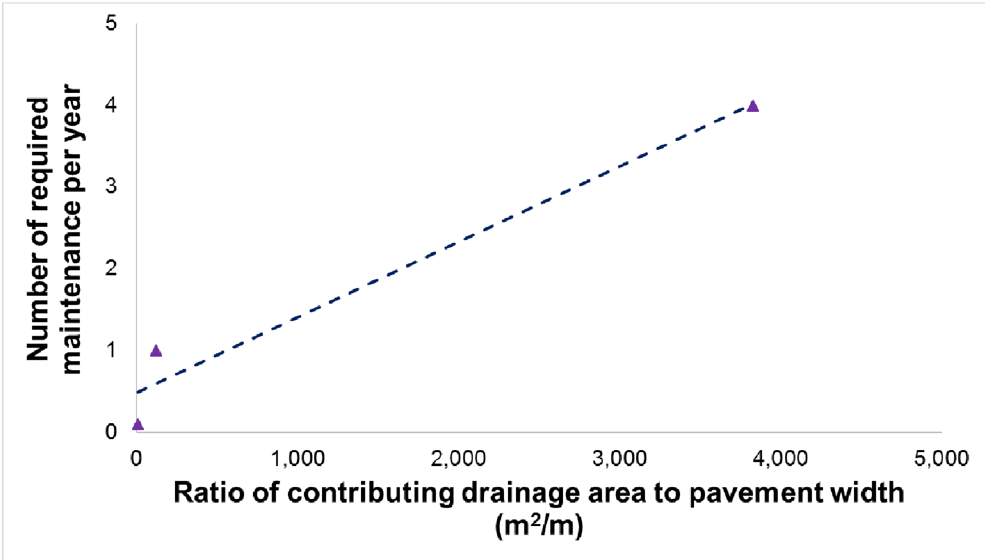


Figure 8 Relation between ratio of contributing drainage area to pavement width versus number of yearly required maintenance

List of figures

Table 1 Rainfall event characteristics during this study

Event no.	Event date	Rainfall depth (mm)	Rainfall duration (hh:mm)	Peak 10-min Intensity (mm/h)	Dry period (Days)	Event no.	Event date	Rainfall depth (mm)	Rainfall duration (hh:mm)	Peak 10-min Intensity (mm/h)	Dry period (Days)
1	11/17/2015	56.38	02:20	76.20	00.65	**27**	7/24/2016	10.67	00:45	42.70	10.85
2	11/26/2015	36.83	20:42	12.20	05.08	**28**	7/25/2016	77.00	07:09	79.00	0.84
3	12/1/2015	27.94	23:11	7.60	04.00	**29**	7/28/2016	23.62	01:44	68.60	3.38
4	12/13/2015	62.99	20:43	22.90	12.27	**30**	7/31/2016	03.30	02:33	3.00	2.42
5	12/21/2015	02.54	03:44	13.70	08.10	**31**	8/5/2016	13.70	08:17	9.10	4.83
6	12/26/2015	04.06	02:30	15.20	05.20	**32**	8/7/2016	09.65	02:52	15.20	2.08
7	01/07/2016	09.65	26:11	4.60	11.41	**33**	8/12/2016	16.00	01:42	35.00	4.56
8	02/02/2016	11.68	08:20	36.60	26.22	**34**	8/19/2016	27.20	02:57	57.90	7.82
9	3/18/2016	03.81	04:36	2.50	15.00	**35**	8/25/2016	43.94	04:25	73.10	5.42
10	3/26/2016	09.65	19:39	9.10	02.06	**36**	8/26/2016	13.50	06:35	19.80	2.67
11	4/17/2016	07.87	08:47	4.60	11.68	**37**	8/27/2016	11.20	03:38	35.00	0.67
12	4/18/2016	12.95	08:06	9.10	00.32	**38**	8/30/2016	02.80	04:11	4.60	3.37
13	4/20/2016	17.02	12:33	7.60	01.48	**39**	8/31/2016	02.55	10:40	1.50	0.51
14	4/25/2016	47.25	13:02	102.1000	04.65	**40**	9/13/2016	21.60	21:15	13.70	12.620
15	4/27/2016	22.35	16:02	16.80	01.79	**41**	9/14/2016	16.30	04:22	19.80	0.67
16	4/30/2016	17.27	31:07	9.10	02.34	**42**	9/16/2016	08.10	05:26	9.10	1.91
17	5/17/2016	16.80	17:06	4.60	04.65	**43**	9/24/2016	34.80	21:09	53.33	8.22
18	5/23/2016	18.00	05:40	30.50	7.00	**44**	10/5/2016	20.00	10:50	136.800	9.17
19	5/24/2016	10.20	02:00	15.20	00.74	**45**	10/10/2016	13.20	08:40	7.60	5.78

20	5/25/2016	25.65	01:18	41.10	00.78	**46**	10/25/2016	21.40	20:00	13.70	15.85
21	5/27/2016	61.50	10:16	48.70	00.72	**47**	11/22/2016	03.00	02:40	3.00	27.00
22	5/28/2016	33.80	13:10	15.20	00.58	**48**	12/4/2016	16.25	12:30	4.60	11.42
23	6/28/2016	14.50	01:41	27.40	10.12	**49**	12/25/2016	03.80	03:30	6.10	22.00
24	7/7/2016	02.54	05:43	4.60	04.30	**50**	1/2/2017	03.80	01:20	6.10	07.80
25	7/12/2016	40.38	01:47	105.200	04.85	**51**	1/16/2017	35.60	27:00	9.20	13.10
26	7/13/2016	12.70	01:38	44.20	01.15	**52**	2/20/2017	10.20	04:10	9.20	35.00

Table 2 RWVC correlation to rainfall characteristics

Sensor	Initial MRWC versus ADWP			Peak MRWC versus rainfall peak 10-min intensity		
	Pre-Clogged (n)	Transition (n)	Clogged (n)	Pre-Clogged (n)	Transition (n)	Clogged (n)
WCR1	-	**-0.70 (14)** [b]	**-0.82 (38)** [c]	-	**0.83 (14)** [c]	0.24 (38)
WCR2	**-0.72 (14)** [b]	**-0.86 (23)** [c]	**-0.71 (14)** [b]	0.34 (14)	0.27 (23)	**0.53 (14)** [a]
WCR3	-0.51 (14)	**-0.85 (07)** [a]	**-0.77 (31)** [c]	0.36 (14)	**0.78 (07)** [a]	**0.41 (31)** [a]
WCR4		**-0.79 (17)** [c]	**-0.84 (35)** [c]	-	**0.84 (17)** [c]	0.27 (35)
WCR5	**-0.64 (13)** [a]	-0.59 (07)	**-0.80 (32)** [c]	0.51 (13)	**0.85 (07)** [a]	0.51 (32)
WCR6	**-0.59 (11)** [a]	**-0.92 (08)** [b]	**-0.72 (33)** [c]	**0.56 (11)** [a]	**0.95 (08)** [c]	0.26 (34)
WCR7	-	-0.52 (14)	**-0.80 (38)** [c]		**0.72 (14)** [b]	**0.51 (38)** [b]
WCR8	**-0.55 (13)** [a]	**-0.89 (24)** [c]	**-0.57 (15)** [b]	0.28 (13)	**0.54 (24)** [b]	**0.58 (15)** [a]
WCR9	**-0.60 (13)** [a]	**-0.85 (07)** [b]	**-0.80 (31)** [c]	**0.78 (13)** [b]	**0.93 (07)** [c]	**0.37 (31)** [a]
WCR10		**0.68 (15)** [b]	**-0.84 (37)** [c]		**0.62 (15)** [c]	0.22 (37)
WCR11	**-0.62 (14)** [b]	**-0.72 (38)** [c]	**-**	**0.70 (14)** [c]	0.12 (38)	

WCR12	-0.48 (14)	**-0.86 (38)** [c]	**-**	**0.60 (14)** [a]	**0.36 (38)** [a]

Highlighted correlations are significant at p <0.050 (a), p <0.01 (b) and p <0.001 (c)

(n) Number of events

Table 3 WCRs response for runoff versus rainfall

Comparison	**Period**	**Difference of means statistical test (p-value)**
WCR2, WCR3, WCR5, WCR6, WCR8, WCR9, WCR11 & WCR12	Pre-clogged	P= 0.33
WCR1 to WCR12	Transition	P< 0.0001
WCR1 to WCR10	Clogged	p<0.001

Table 4 rainfall and runoff intensities correlations

Buried Rain gauge	Rainfall peak 10-min intensity versus runoff peak 10-min intensity		
	Pre-clogged (n)	Transition (n)	Clogged (n)
North rain gauge	na	**0.50 (18)**	0.10 (36)
Middle rain gauge	**0.87 (13)**	0.21 (07)	0.32 (33)
South rain gauge	**0.59 (13)**	0.33 (08)	0.07 (32)

*Highlighted correlations are significant at p <0.050

Table 5 Clogging rates of WCRs rows and columns

Parameter	Locations						
	Upstream to down-stream				West to east edge		
	C1	C2	C3	C4	R1	R2	R3
Average clogging rate for the first time exceeded threshold (mm/mm)	6.72 (-1.41-14.96*)	6.72 (-1.41-14.96)	6.72 (-1.41-14.96)	7.03 (-0.38-14.44)	287.04 (-69.48-643. 60)	73.68 (3.60-143.79)	68.40 (12.20-124.69)
Average clogging rate for the last time exceeded threshold (mm/mm)	3.24 (0.11-6.37)	2.88 (0.31-5.46)	2.64 (-0.07-5.32)	3.96 (na)	58.32 (-31.39-147.97)	52.08 (-10.20-114.32)	36.24 (-3.43-76.09)

*95% Confidence of interval

Table 6 Contributing drainage area and observed rainfall of various sites

Site	Contributing drainage area to pavement width ratio (m^2/m)	Rainfall (mm)	Maintenance (per/year)
Edison, NJ	8	1245	0.1
Fort Riley, KS	120	864	0.8
Louisville, KY	3829	1169	4.0

Highlights

- Water content reflectometers and buried rain gauges showed the progress of clogging
- For every 6mm of rain, clogging advanced 1 mm across the surface
- Results showed the clogging progresses from the upgradient to the downgradient edge
- The size of drainage area and rainfall were effective on rate and progression of clogging