Monitoring Porous Asphalt Stormwater Infiltration and Outflow

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Abstract: Performance of porous asphalt (PA) was evaluated on a parking lot of the Washington State University Puyallup campus that included three pavement treatments in triplicate: maintained impervious asphalt (MIA), maintained porous asphalt (MPA), and unmaintained porous asphalt (UPA). Maintained treatments were annually swept with a regenerative air street sweeper. Infiltration rates measured annually using an infiltration ring declined over the course of the study (2011–2015) from 118 to 39 mm/min for the MPA, and from 134 to 54 mm/min for UPA, respectively. Lower infiltration rates on maintained cells relative to unmaintained cells are ascribed to the air-blast and suction cycle that characterizes the type of street sweeper used. The authors hypothesize that particulate matter was forced deeper into the porous structure of the pavement wearing course, reducing infiltration rates in the maintained cells. Annual maintenance was shown to be too infrequent and did not prevent infiltration rates from declining, with parts of the pavement cells becoming clogged. However, performance of the pavement as a whole, measured by relating total storm inflow to storm outflow, did not decline over the study period with 99.5% of storm inflow infiltrating into the porous asphalt pavement surface. Time-series analysis showed that peak flow mitigation of stormwater was considerably superior with permeable pavements in comparison with impervious pavement surfaces. **DOI: [10.1061/(ASCE)IR.1943-4774.0001197](https://doi.org/10.1061/(ASCE)IR.1943-4774.0001197).** © 2017 American Society of Civil Engineers.

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Introduction

The management of stormwater using green stormwater infrastructure (GSI) is gaining importance in urban, suburban, and exurban watersheds across the country. The need to manage larger stormwater runoff volumes and peak flows is exacerbated in megapolitan regions (Lang and Nelson 2007) that face the dual threats of rapid urbanization and a changing climate (Grimm et al. 2008; Semadeni-Davies et al. 2008). In western Washington, stormwater has been identified as one of the principal threats to the Puget Sound ecosystem's health (Puget Sound Action Team 2007). GSI is a suite of stormwater management practices that harness ecosystem processes, treating the stormwater close to its source (USEPA 2016). Green stormwater infrastructure is gaining considerable favor in western Washington and is a National Pollutant Discharge Elimination System (NPDES) stormwater permitting requirement for certain new and redevelopment projects in western Washington (Washington State Department of Ecology 2014).

One such GSI practice that is seeing wider adoption in recent years is permeable pavement (Kayhanian et al. 2015). These pavements are designed to treat and infiltrate incident rainfall (Scholz and Grabowiecki 2007) and in many cases incident runoff or *run-on*. Permeable pavements comprise an upper wearing course

that both supports vehicular traffic and is permeable, and a supporting aggregate subbase over a soil subbase. The aggregate subbase acts as a temporary reservoir that facilitates a gradual exfiltration of stormwater into the soil subbase while keeping the roadway surface clear of standing water (USEPA 1999; Collins et al. 2008). In some cases, where exfiltration into the native soil is not desired or limited by poorly draining native soils or the presence of a seasonally high water table, perforated underdrain pipes can be used to convey drainage to nearby stormwater conveyance systems.

Porous asphalt is an alternative to traditional impervious pavements. Porous asphalt is suitable for low traffic uses such as parking lot, sidewalks, and driveways (Scholz and Grabowiecki 2007; Roseen et al. 2011; Al-Rubaei et al. 2013). Polymer additives have been used as porous asphalt amendments for heavier traffic such as airport runways (Hinman 2005; Scholz and Grabowiecki 2007). Porous asphalt differs from standard hot-mix asphalt in that finer aggregates are precluded (Dietz 2007) from the mix. For a review of types of permeable pavements, readers are referred to the work of Ferguson (2005) and Drake et al. (2013).

Runoff-Volume and Peak-Flow Reduction in Permeable Pavements

In a review of published studies that measured effectiveness of low-impact development (LID) practices, Ahiablame et al. (2012) reported that permeable pavements reduce runoff generation between 50 and 93% and may eliminate runoff completely in some cases (e.g., Bean et al. 2007; Roseen et al. 2011). Collins et al. (2008) showed a 99.9% reduction in surface runoff from rainfall depth for a pervious concrete section in North Carolina.

A study by Wardynski et al. (2012) on permeable interlocking concrete pavers (PICP) with underdrains showed that the available volume for water storage in the aggregate subgrade determined the volume of outflow in the underdrains. Underdrain outflow volumes ranged from 0 to 22% of total rainfall, with variability of outflow volume dependent upon the elevation of the underdrain invert with

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respect to the bottom of the coarse aggregate reservoir layer. Abbott and Comino-Mateos (2003) showed that for a system of porous concrete pavers in a parking lot, peak flows were considerably attenuated such that outflow from the system occurred over a period that was on average 14 times as long as the rainfall event. Fassman and Blackbourn (2010) showed that in a comparison of permeable pavement and regular asphalt pavement, permeable pavement produced runoff peak flows at levels comparable to predevelopment irrespective of antecedent moisture conditions.

Effect of Maintenance on Permeable Pavement Performance

As with most GSI practices, operations and maintenance of permeable pavement systems underpin the practice's performance (Benedict and McMahon 2006). The performance of permeable pavements to manage stormwater has been shown to be a function of maintenance and proximity to sources of particulate material that might clog the pores (Abbott and Comino-Mateos 2003; Bean et al. 2007; Dietz 2007; Sansalone et al. 2008). Lucke and Beecham (2011) showed that the majority of clogging particulate matter within a PICP system accumulated within and immediately below the upper wearing course. A study by Haselbach (2009) on clogging of permeable pavements by clay particulate matter showed that most clogging occurred within a few centimeters of the top wearing course. The formation of a particulate matter layer in permeable pavements was referred to as a *Schmutzdecke* by Sansalone et al. (2012). The ability of permeable pavement to infiltrate incident rainfall was shown by Stotz and Krauth (1994) to be related to axle weight and speed, with areas of pavement experiencing heavier and slower-moving traffic exhibiting lower rates of infiltration.

Different approaches have been reported to maintain or restore initial hydraulic conductivity rates of permeable pavements. Winston et al. (2016) showed that for porous asphalt, a restoration of designed infiltration rates was best effected through industrial handheld vacuum cleaning, pressure washing, and milling. In a study of the effect of high pressure washing and vacuum cleaning of porous asphalt installations in Sweden, Al-Rubaei et al. (2013) found that the effects of maintenance were dependent on the age of the pavement and winter maintenance regime. Sansalone et al. (2012) reported that sonication and vacuuming of a pervious concrete pavement system restored initial hydraulic conductivity rates. Chopra et al. (2009) showed that pavement rejuvenation was best effected through high-pressure washing when compared to vacuuming.

The objectives of this study were to measure infiltration rates of porous asphalt over time, to test how maintenance with a regenerative air street sweeper affects infiltration rates, and to determine how stormwater flow rate is attenuated by flow through porous asphalt in comparison to impervious pavement.

Site Description

A parking lot on the campus of Washington State University's Research and Extension Center in Puyallup, WA (47° 11′20.57″ N, 122° 19′49.59″ W) was retrofitted with 0.32 ha of permeable asphalt (PA). The PA section comprised nine cells, where the dimensions of each cell were 18.3 by 2.7 m, and each cell was isolated from adjacent cells by a 0.2 m concrete wall. The only source of runoff to these systems came from direct rainfall with no run-on from adjacent impermeable surfaces. The PA experiment consisted of three treatments: unmaintained porous asphalt (UPA), maintained porous asphalt (MPA), and maintained impervious asphalt (MIA).

Maintained cells were cleaned annually in two passages with a regenerative air street sweeper (Schwarze A4000, Schwarze Industries, Huntsville, Alabama) set to 2,000–2,200 rpm. Treatments were randomized for each of the three blocks [Fig. 1(a)]. Rainfall was measured in 5 min increments with a rain-gauge tipping bucket (Model TB3, Hydrological Services, Sydney, Australia) located 75 m from the test pavement cells.

Construction and Instrumentation of Porous Asphalt

Soil in each porous asphalt cell was excavated and each cell was laid out with an impermeable cell liner with protective nonwoven geotextile. Slotted PVC pipes (102 mm diameter) were installed on the geotextile to drain the porous cells (underdrain). A 76 mm layer of porous asphalt was poured on a 457 mm layer of crushed stone #57 [Fig. 1(c)]. Soil in MIA cells was excavated and a 76 mm layer of hot-mix asphalt was poured on a 102 mm layer of crushed stone #57 [Fig. 1(d)].

The PA section had a 2% grade to the west to ensure that surface and subsurface flow drained to sampling locations located on the western boundary of the test facility. V-notches installed on the downstream (western) end of each cell channeled surface flow, while subsurface flows were channeled to subsurface underdrains [Fig. 1(c)]. Stormwater from the V-notches on the MIA cells and stormwater from the underdrain of the UPA and MPA cells were routed to tipping-bucket flowmeters (Model TB1L, Hydrological Services, Sydney, Australia) to measure flow rates. Additionally, total surface runoff volume from UPA and MPA cells were estimated for some qualifying storms by collecting all the water that flowed through the surface level V-notches. The tipping-bucket flowmeters were calibrated annually and the outflow rate measurements were corrected for instrument bias when detected.

Street Dirt Application

The parking lots of the PA research site experienced lower traffic usage compared to most other asphalted roadways primarily because the research site was an overflow parking lot for a conference center at the Washington State University's Puyallup campus. To mimic typical debris and pollutant loads commonly seen in residential areas in western Washington, street dirt was applied quarterly using a lawn fertilizer spreader. Street dirt was received from the City of Puyallup, sieved through a 2 mm sieve, and stored until application. Street dirt was applied at 75 g/m^2 in 2013 (March 29, June 28, July 26, October 9) and 2014 (March 4, September 9) and at 37.5 g/m^2 in 2014 (October 30) and 2015 (January 13, May 15, August 25, November 12). Application rates were the average rate of street dirt that was collected by street sweepers in the City of Puyallup. In fall 2014, application rates were reduced after infiltration rates started to decline to prevent complete clogging that might jeopardize a secondary study that was also under way. In that secondary and as-yet-unpublished study, the authors examined the fate and transport of stormwater pollutants through this permeable pavement system—a complete clogging of cells would have prematurely ended that secondary study. Fig. 1(a) shows the section of PA where street dirt was applied. No street dirt was applied on the control cells C1 and C2. MIA and MPA cells were maintained annually as described in the section Site Description above.

In 2016, all porous asphalt cells were cleaned with a single pass of a water-based vacuum cleaning system (MCV, Triverus, Palmer, Arkansas) in order to test the efficacy of this newer method in improving 5 years of clogging and use. All cells were cleaned including those previously designated as unmaintained cells (UPA).
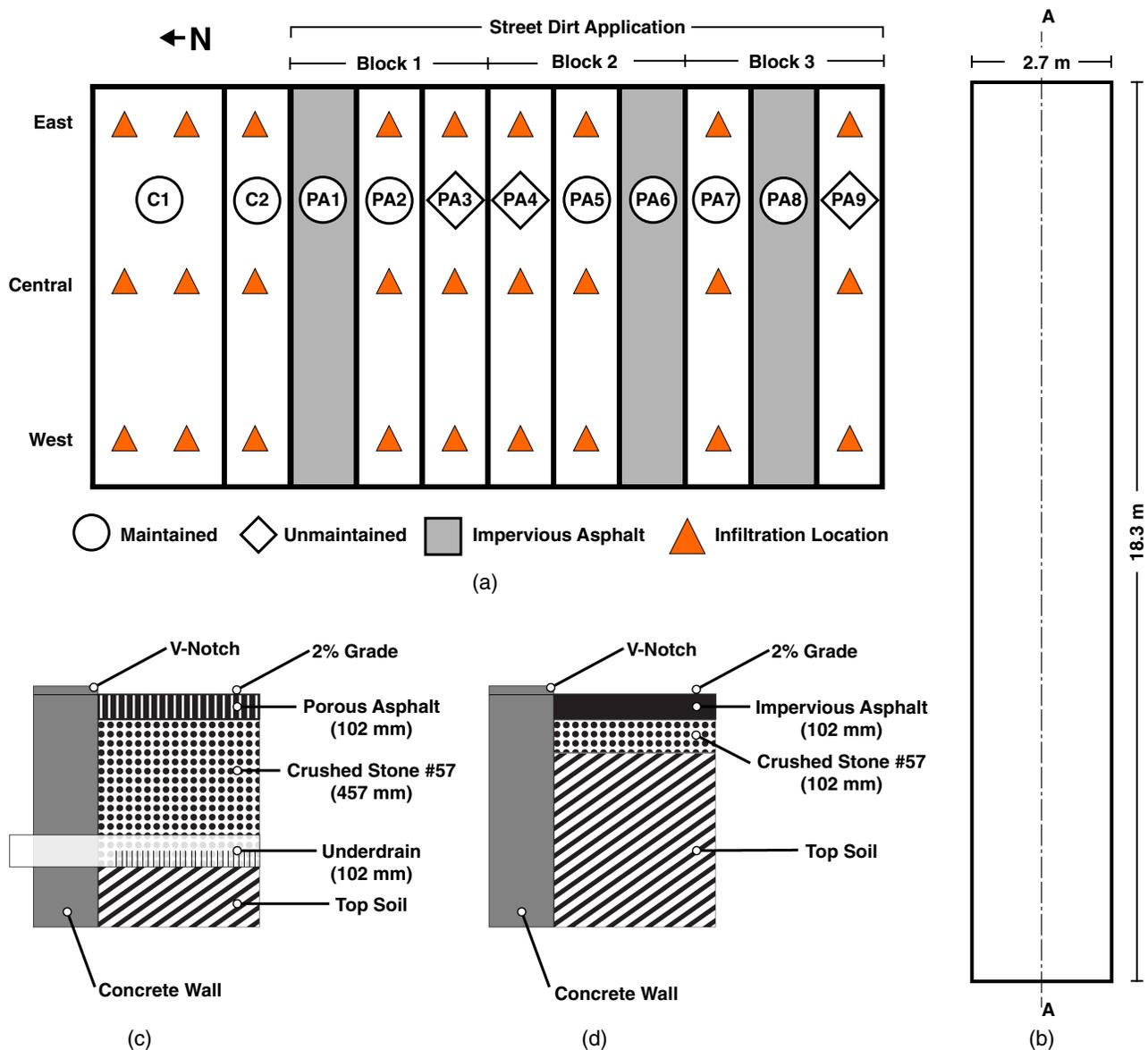
Fig. 1. (a) Site plan of the porous asphalt cells; maintained cells were cleaned annually with a regenerative air street sweeper; the dashed line (b) indicates the cross section shown in (c) for porous asphalt and in (d) for impervious asphalt cells

Materials and Methods

Qualifying Storms

The Washington State Department of Ecology has published guidelines for evaluating emerging stormwater treatment technologies (Washington State Department of Ecology 2011). These guidelines require a minimum storm duration of 1 h, a minimum precipitation of 3.8 mm, an antecedent dry period of 6 h with less than 1 mm of precipitation, and a period of at least 6 h with less than 1 mm of precipitation after the storm to ensure representativeness of the collected stormwater data. 277 qualified storms were identified between October 1, 2011, and December 31, 2015.

Infiltration Tests

Infiltration rates of PA were measured annually over the period of study using the ASTM C1701 method (ASTM 2009). In brief, a 298 mm-diameter PVC pipe was fastened to the permeable surface

and the infiltration time t of the water volume V was determined. Fig. 1(a) shows the measurement locations. Per ASTM (2009), the infiltration rate was calculated as

$$I = \frac{V}{D^2 t} \qquad (1)$$

where I = infiltration rate (mm/min); V = infiltrated volume (mm^3); D = diameter of the PVC tube (mm); and t = infiltration time (min).

Statistical Analysis

Porous asphalt infiltration data were analyzed using nonparametric statistical tests because of the lack of data normality. The paired Wilcoxon signed rank test was used to assess differences between infiltration rates of maintained and unmaintained asphalt. Infiltration data were paired for maintained and unmaintained matched by block (1, 2, or 3) and location (east, central, or west; Fig. 1).

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For example, a sample pair in Block 1 and east location comprised infiltration rates measured in Cells PA2 (maintained) and PA3 (unmaintained).

Street dirt was only applied on Blocks 1–3 on the PA and no street dirt was applied on the Control Cells C1 and C2 [Fig. 1(a)]. This resulted in 18 infiltration locations on the PA in Blocks 1–3 and 9 infiltration locations in the Control Cells C1 and C2. A Mann-Whitney U test was used to test whether the control cells without street dirt application had higher infiltration rates compared to the PA cells with street dirt application.

The authors compared the infiltration rates of the different locations to check for effects between east and central, east and west, and central and west. The central location is most trafficked by vehicles entering and leaving the parking lot. This analysis was performed with a Mann-Whitney U test to test if this increased trafficking affects the infiltration rate in the central location. The effect of wet vacuum–based cleaning was assessed by testing paired pre-2016 cleaning and post-2016 cleaning infiltration data using the paired Wilcoxon signed rank test. Pre- and post-2016 cleaning were performed within 2 months.

Temporal Statistics

Recall that PA cells comprised impervious and porous asphalt cells, where outflow from the impervious cells was measured at the cell surface (surface runoff), while outflow from the porous cells was measured at the underdrain. Time-series data for rainfall and outflow from the PA cells were analyzed using temporal statistics. The two time series were tested for temporal relationships, and the lag times between the onset of rainfall and the onset of runoff were calculated (Shumway 1988). The authors hypothesized that the lag time between the onset of rainfall and the onset of PA outflow would increase over time with application of street dirt, because they expected street dirt application to influence infiltration and therefore water movement through the PA cells. For the impervious PA cells, the surface runoff was considered as outflow; for the porous PA cells, the stormwater moving through the cell and draining out on the west location was considered as outflow.

The authors identified five time spans related to five distinct patterns of street dirt application [Fig. 2(a)]. No street dirt was applied during the first two time spans. In the subsequent three time spans [Time Spans III, IV, and V in Fig. 2(a)], the cumulative amount of applied street dirt was 300, 488, and 638 g/m^2, respectively.

Because the duration and precipitation depth of qualifying storms varied considerably, the authors grouped storms by similarities in duration and precipitation depth. This grouping was performed by assigning x- and y-coordinates to each storm's duration and precipitation depth [Fig. 2(b)]. Then a distance matrix between the single storms was developed using the fossil package in R (Vavrek 2011). Storms that were closely grouped based on Cartesian distance measured in the x-y space were considered similar [Fig. 2(b)]. For each qualified storm, the authors selected the most similar storms from the other four time spans. The subplot in Fig. 2(b) shows the five storms that are most similar in duration and precipitation depth—one storm in each group.

This resulted in 20 groups of five storms that shared similarities in duration and depth—one from each of the five time spans [Fig. 2(a)]. Single storms were only part of one of the 20 groups. For each of the five time spans, the authors constructed synthetic time series of rainfall and flow data that *stacked* the 20 storms of one time span one after the other with each storm separated by a period of 96 h [Fig. 2(c)]. Storms were spaced out at uniform intervals to allow for a consistent rainfall signal in the temporal
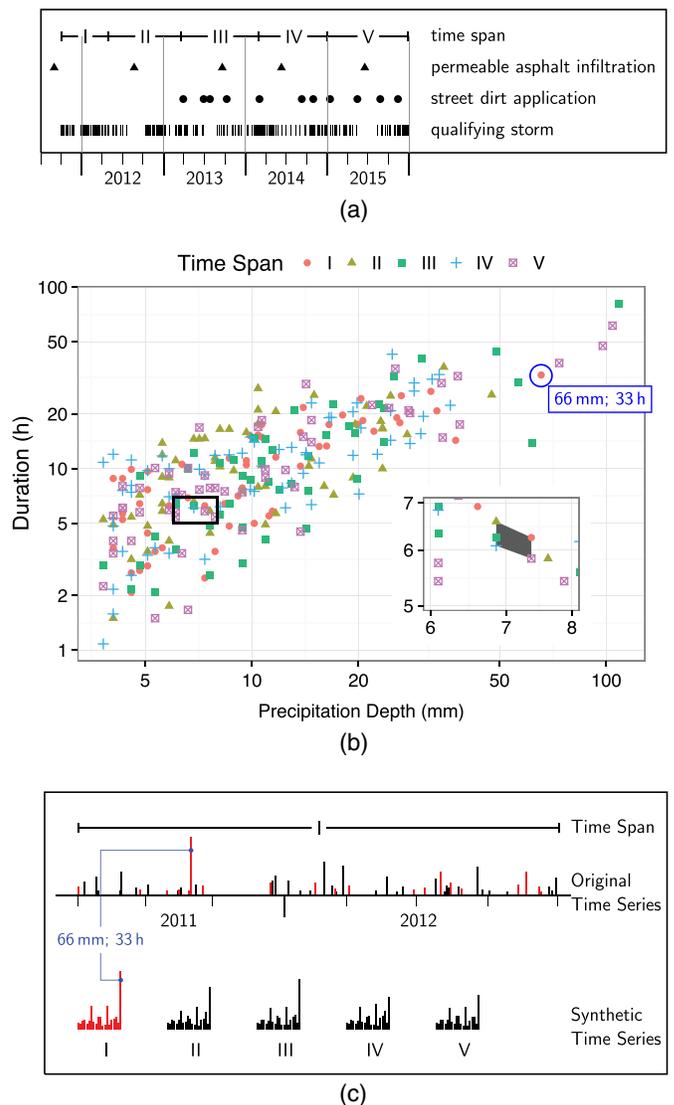
Fig. 2. (a) Timeline that indicates when qualifying storms were detected, when street dirt was applied, and when infiltrations test have been performed; roman numbers show time spans used to create synthetic time series; each time span represents an amount of cumulative street dirt (0, 0, 300, 488, and 638 g/m^2 for the Time Spans I–V, respectively); (b) storms similar in duration and precipitation were identified by plotting duration over depth and measuring the distance to the other storms; the subplot shows the five storms (one from each time span) that are most similar connected through the gray polygon; (c) original and synthetic time series

domain, a critical aspect of lag detection using spectral analysis of rainfall data (Shumway and Stoffer 2011). The 96 h period was chosen as this time frame ensured that outflow from the test cells had ceased, thereby obviating between-storm overlap of flow data. Through this construction of synthetic rainfall and flow time series data, it was possible to constrain the time-series analysis to efficiently detect lag times between rainfall and PA outflow.

The relationships between rainfall and the PA stormwater outflow were analyzed using a cross-correlation function and then applying a cross-spectral analysis on all of the five synthetic time series. First, the cross-correlation function between the two time series of interest, i.e., rainfall and outflow of a PA cell, was computed (Nielsen and Wendroth 2003)

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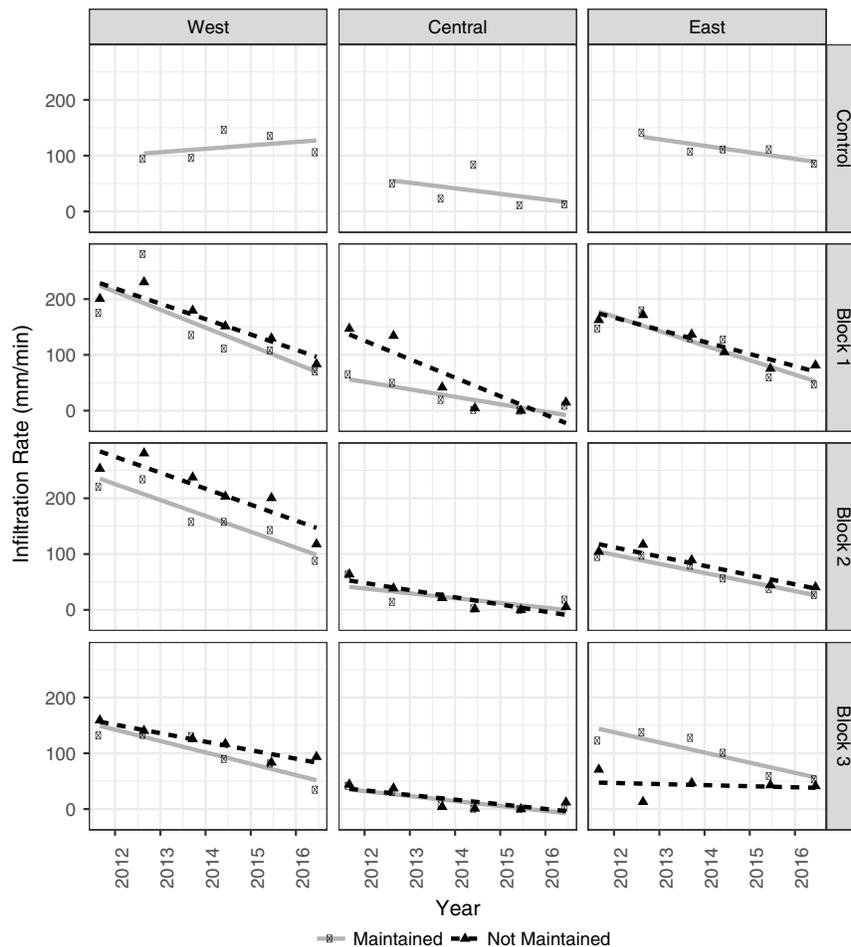
Fig. 3. Infiltration rates for the porous asphalt test; the results from 2016 show the rates after the pavement was cleaned with a water-based vacuum cleaning system; trend lines are based on linear regression

$$r_c(h) = \frac{\text{cov}[A_i(t_i), B_i(t_i + h)]}{\sqrt{\text{var}[A_i(t_i)]}\sqrt{\text{var}[B_i(t_i + h)]}} \qquad (2)$$

where cov = covariance of the rainfall time series A_i and of the drainage time series B_i; var = variance; and h = time lag between two observations in a time series. The cross-correlation analysis revealed over what distance in time two measurements are related to each other (Nielsen and Wendroth 2003, Fig. 3.1)

Then the frequency domain variance components are determined with a cross-spectral analysis, which is a form of Fourier transformation (Shumway 1988)

$$\text{Co}(f) = 2 \int_0^\infty r_c(h) \cos(2\pi f h) dh \qquad (3)$$

where Co = cospectrum; f = frequency as f = period^{-1}; and the cross-correlation r_c is averaged as $r_c(h) = 0.5[r_c(h > 0) + r_c(h < 0)]$. This analysis identifies common periods in two time series as peaks in the cospectrum (Wendroth et al. 2011). The quadrature spectrum is a measure to determine the time lag between two time series (Shumway 1988):

$$Q(f) = 2 \int_0^\infty r'_c(h) \sin(2\pi f h) dh \qquad (4)$$

where r'_c = cross-correlation averaged as $r'_c(h) = 0.5[r_c(h > 0) - r_c(h < 0)]$. Cospectrum and quadrature spectrum are then used to

calculate the phase lag $h_\phi(f)$ between two time series at a certain frequency f

$$h_\phi(f) = \frac{1}{2\pi f} \tan^{-1}\left[\frac{Q(f)}{Co(f)}\right] \qquad (5)$$

In practice, the cospectrum is checked for maxima at frequencies that make sense. In this case, the authors constructed time series with 20 storms, with one storm starting after every 96 h. Hence, the period of the time series is 96 h and the authors expected peaks in the cospectrum at a frequency of $f = 1$. At the same time, the quad-spectrum should have a minimum at a frequency of $f = 1$. This indicates that there is a lag between the two time series of interest. In that case, the cospectrum Co(1) and the quad-spectrum $Q(1)$ are then used to compute the phase lag $h_\phi(f)$. The authors refer to the work of Shumway (1988) and Nielsen and Wendroth (2003) for a detailed description of time-series analysis. The authors used the *astsa* package (Stoffer 2014) in R (R Development Core Team 2016) to perform the temporal statistics.

Results and Discussion

Porous Asphalt Infiltration: Long-Term Locations

Fig. 3 shows the PA infiltration rates. For all locations, blocks, and maintenance treatments, with the exception of the west location in

Table 1. Infiltration Rates of the Porous Asphalt Test Site

Year	Control (mm/min)	Maintained (mm/min)	Unmaintained (mm/min)
2011	N/A	118 ± 19 (9)	134 ± 23 (9)
2012	95 ± 30 (9)	128 ± 30 (9)	129 ± 30 (9)
2013	75 ± 29 (6)	90 ± 19 (9)	98 ± 26 (9)
2014	114 ± 30 (9)	72 ± 20 (9)	127 ± 38 (9)
2015	86 ± 29 (9)	54 ± 17 (9)	64 ± 23 (9)
2016[a]	68 ± 23 (9)	39 ± 9 (9)	54 ± 14 (9)

Note: Error terms are standard errors of the mean; the numbers in parentheses are the number of observations n.
[a]Data acquired after pavement was cleaned in 2016.

the control treatment, the infiltration rates decreased with time. Infiltration rates also differ between locations, with the west locations having the highest infiltration rates, followed by the east locations and the central locations. Infiltration rates decreased noticeably in the central locations, with all central locations being clogged by 2015. Reasons for the spatial variability are discussed in the sections below.

In 2011, the infiltration rate was 118 and 134 mm/min for maintained and unmaintained PA, respectively (Table 1). By 2015, the infiltration rate decreased to 54 and 64 mm/min for maintained and unmaintained PA, respectively. Street dirt was applied to PA Cells 1–9 but not on Control Cells C1 and C2 [Fig. 1(a)]. The infiltration rates in the control cells not receiving any street dirt were lower than in the plots with street dirt application in the years 2012 and 2013; however, in 2014 and 2015 maintained PA cells had the lowest infiltration rates compared to the control cells and unmaintained PA. By the end of the study in 2016, the cells with the lowest infiltration rates were the maintained PA, while the control cells had the highest infiltration rates.

The authors tested the hypothesis that the maintained PA cells would have higher infiltration rates than the unmaintained PA cells. The paired Wilcoxon signed rank test yielded p-values that were >0.6 for each experimental year (Table 2), which suggests that maintenance of PA with a regenerative air street sweeper did not improve or preserve infiltration rates in comparison with the unmaintained PA cells. While statistical analyses of infiltration data suggest that annual maintenance with a regenerative street sweeper did not maintain infiltration rates, the act of street sweeping actually appeared to worsen infiltration rates on PA. This counterintuitive result suggests that the type of maintenance practice deployed during this study requires further scrutiny. The authors hypothesize that during cleaning with the air regenerative sweeper, some particulate matter was in fact forced deeper into the porous structure of the pavement wearing course, thereby reducing infiltration rates in the maintained cells. Air regenerative street sweepers employ a
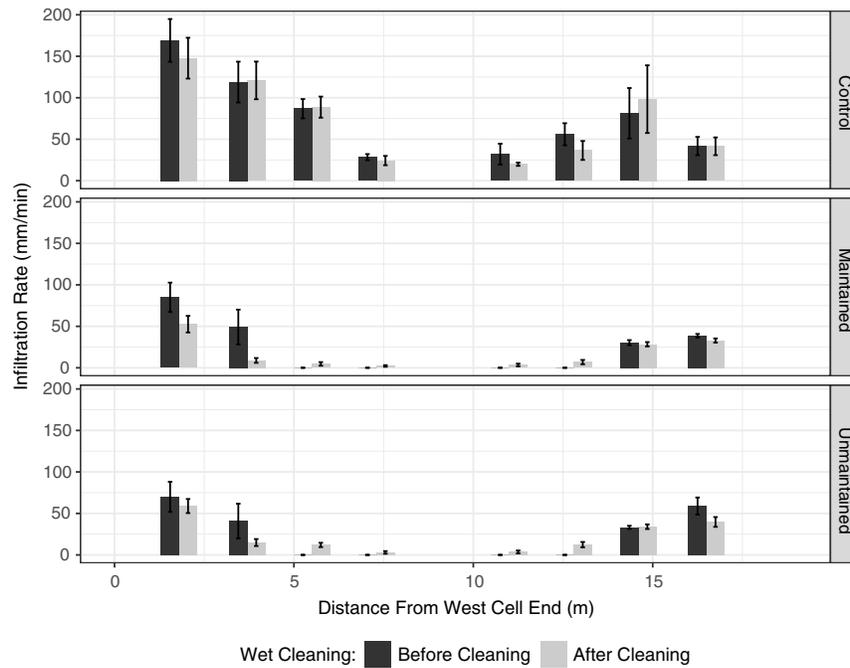
two-phase *blast and suction* cycle to remove particulate matter from pavement surface. The first phase comprises a controlled air blast that is designed to dislodge particulate matter off the pavement surface so that a suction nozzle can then entrain the dust particles as part of a second phase (Chow et al. 1990). Particle entrainment in the second phase is dependent upon the maintenance of an adequate negative pressure between nozzle and pavement that in turn is a function of the quality of contact between the pavement surface and a confining rubber curtain that surrounds the suction nozzle. The authors speculate that the air-blast phase (primarily designed for impervious pavements) actually caused particulate matter to be driven into the pores of the permeable pavement surface instead of being dislodged from the surface. Additionally, the porous nature of the pavement surface precipitated poor contact between the nozzle curtain and the pavement that impeded sweeper efficacy. A comparison of a regenerative air street sweeper and a rotary brush sweeper on an asphalt road in Florida by Tobin and Brinkmann (2002) showed that the rotary brush sweeper was more effective in removing particulate matter. Hunt et al. (2015) suggested using a true vacuum-based street sweeper over a regenerative street sweeper for highly clogged permeable pavements. Al-Rubaei et al. (2013) showed that high-pressure washing or vacuum cleaning was able to restore infiltration rates of a PA pavement that had experienced significant clogging.

The authors tested the hypothesis that infiltration rates in the control cells that did not receive street dirt were higher than maintained and unmaintained PA cells that were treated with street dirt. *P*-values of the Mann-Whitney U test were 0.31 and higher in every experimental year and for both maintained and unmaintained treatments (Table 2). These results indicate that street dirt applications on the treatment cells did not *worsen* infiltration rates in comparison to the control. Natural debris from traffic and from the surrounding landscape may have contributed to declining infiltration rates and the street dirt application may not have had an effect additionally to the natural debris. Annual maintenance intervals may have also been too infrequent to reverse effects of street dirt.

Statistical testing showed that, for each year, the infiltration rate was significantly higher in the east location in comparison to the central location (Table 2) at α-levels of 0.05 (2011–2012) and 0.01 (2013–2015). Infiltration rates of the east and west locations differed significantly for the years 2011 and 2015 at α-levels of 0.05 and 0.01, respectively. For all years, the infiltration rate was significantly higher ($\alpha = 0.01$) in the west location in comparison to the central locations. Each of the three locations experienced differing volumes of tire traffic, with the central locations corresponding to the primary pathway between parking stalls, and therefore experiencing the highest volume of traffic. The west locations correspond to parking stalls farthest from the building and were observed to receive the least amount of usage. The east locations house the parking stalls that are closest to the adjacent office building and were therefore used more frequently than the parking stalls in the west locations. This usage pattern of the pavement was clearly reflected in the infiltration data, with low infiltration rates associated with locations of high usage.

Intensive Infiltration Transects on Porous Asphalt

To further investigate the spatial structure and extent of the clogging, the authors performed a series of spatially intensive infiltration tests along several transects on the PA in spring 2016. The infiltration tests were carried out in each PA cell along a transect from west to east in 1.8 m increments (Fig. 4). Results of these intensive infiltration tests showed that cells that received street dirt

Table 2. *P*-Values from Porous Asphalt Statistical Analysis

Year	Maintained > unmaintained	Control > maintained	Control > unmaintained	East > central	East = west	Central < west
2011	0.96	N/A	N/A	0.02[a]	0.02[a]	<0.01[b]
2012	0.67	0.80	0.31	0.03[a]	0.22	<0.01[b]
2013	0.82	0.55	0.69	<0.01[b]	0.11	<0.01[b]
2014	0.98	0.34	1.00	<0.01[b]	0.67	<0.01[b]
2015	0.93	0.48	0.48	<0.01[b]	<0.01[b]	<0.01[b]
2016	0.97	0.27	0.50	<0.01[b]	0.03[a]	<0.01[b]

[a]Significant at $\alpha = 0.01$.
[b]Significant at $\alpha = 0.05$.

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Fig. 4. Infiltration rates for the porous asphalt test along transects from west to east; error bars represent the standard error of the mean ($n = 6$)
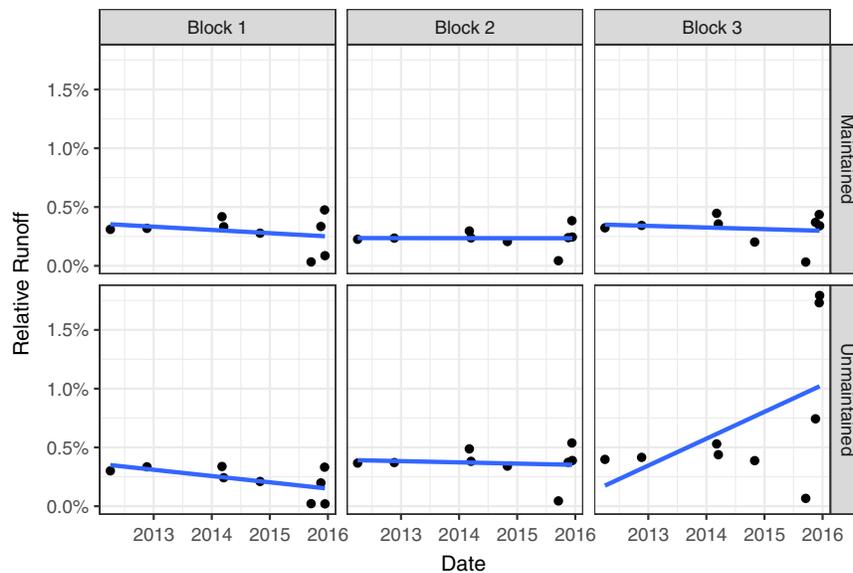
Fig. 5. Relative runoff from the six porous asphalt cells as a percentage of the precipitation depth of the corresponding storm

applications all had a clogged section of about 6 m in the middle (central locations) of the PA cell. The central locations in the control cells were not clogged but infiltration rates were reduced (Fig. 4). This result was contrary to the results from the Mann-Whitney U test, which indicated that street dirt applications did not decrease the infiltration rates.

The central locations experienced greater tire traffic than the areas on the edges of the PA cells, which suggests two possible conditions: (1) more debris from tires and vehicles to these central locations potentially increases debris deposition and clogging of pores and (2) increased stress forces on the pavement from high tire traffic caused the applied street dirt to be driven deeper into the pores of the PA, thereby further increasing clogging of the

porous structure of the PA. Expectedly, these clogged areas did not participate in infiltration of stormwater.

Rainfall-Runoff Relationships

Runoff was collected from the six PA cells during nine qualifying storm events. As infiltration rates decreased and clogging occurred in the central locations (Fig. 3), the authors wanted to determine if surface runoff from these cells also increased over time. Fig. 5 shows relative runoff from nine qualifying storms, where relative runoff is the volume of surface runoff expressed as a fraction of rainfall volume. Rainfall volume is the product of rainfall depth and the area of a PA cell. In general, relative runoff values were

below 0.5% and no increase was observed over time, with one exception. That exception was an unmaintained PA cell in Block 3 (PA9) that exhibited increased clogging in 2015 and an increase of relative runoff up to 1.8% over the last three storms in the study (Fig. 5).

Although some areas of the PA cells were clogged, the areas that remained permeable allowed infiltration for almost all of the incident stormwater. Relative runoff or the proportion of rainfall measured as surface runoff was below 0.5% for all maintained cells and below 1.0% for all unmaintained cells (Fig. 5). Even several years after installation these values are still less than the 7–50% runoff reported by Ahiablame et al. (2012) but slightly higher than the 0.1% found by Collins et al. (2008). However, it raises the questions of how long these cells infiltrate stormwater without a significant increase in surface runoff and whether clogging can be reversed.

Effects of Alternative Cleaning Methodology of Permeable Pavement

The effects of the alternative permeable pavement cleaning were assessed by completing another infiltration test after the 2016 cleaning with a single pass of a water-based vacuum cleaner. Table 1 shows the mean values and the standard errors for the 2016 infiltration data after cleaning. Additionally, infiltration was also tested along the transects described above (Fig. 4).

For the porous asphalt, the average infiltration rate was 68 ± 13 and 54 ± 10 mm/min in 2015 and 2016, respectively (error terms represent standard error of the mean for $n = 27$). Although the porous asphalt was cleaned in 2016, the average infiltration rate continued to decline with time. The paired Wilcoxon signed rank test (p-value 0.98) suggests that the infiltration rate did not increase after cleaning. However, given that the 2015 and 2016 measurements were about a year apart, there is a strong likelihood that debris and street dirt accumulation between measurements may have obscured the effect of the single-pass wet-vacuum cleaning in 2016.

However, the intensive transect infiltration measurements conducted prior to and after the 2016 wet-vacuum cleaning occurred only 2 months apart and were considered a better indicator of the wet-vacuum cleaning effort. For the porous asphalt transects, the average infiltration rate was 43 ± 4 and 37 ± 4 mm/min before and after the water-based wet-vacuum cleaning in 2016, respectively (error terms represent standard error of the mean for $n = 144$). The average infiltration rates of the transects were lower than the annual infiltration tests because the transects sampled a lot more locations with low or no infiltration. The paired Wilcoxon signed rank test resulted in a p-value of 0.73, meaning the intensive transect infiltration rates did not improve with the single-pass wet-vacuum cleaning in 2016.

Annual maintenance with a regenerative air street sweeper, as well as the one-time cleaning with a water-based vacuum system, did not improve or maintain infiltration rates of porous asphalt. Rather, the data indicate that the average infiltration rates were lower after cleaning with a water-based vacuum system and on the annually maintained plots. However, the infiltration of clogged areas was improved by the cleaning process (Fig. 4). Transect infiltration was measured at 144 locations, of which 52 were clogged and did not infiltrate any water. After cleaning, 21 locations were still clogged but 31 locations were unclogged with infiltration rates of 10 ± 1 mm/min. These values are still low, but the results of the single-pass wet-vacuum cleaning may further improve with more passes. Additionally, the wet cleaning was the only method that removed a surficial layer of moss with visibly dramatic results were apparent after a single pass. Further evaluation of this technology by increasing the frequency of cleaning events is necessary, potentially in combination with pressure washing as demonstrated by Al-Rubaei et al. (2013).

Rainfall Outflow Lag Analysis

The co- and quad-spectra were calculated for each storm group and PA cell—impervious and porous (Table 3). Fig. 6 exemplifies the temporal data analysis by showing the co- and the quad-spectra for Storm Group IV and Block 1 (Fig. 1). PA1 and PA2 have distinct maxima in the cospectra [Figs. 6(a and b)]. The quad-spectrum has a local minimum in PA1 [Fig. 6(a)] and an absolute minimum in PA2 at a frequency of $f = 1$ [Fig. 6(b)]. A distinct minimum indicates a phase lag in the two time series as can be observed for PA2 [Fig. 6(b)]. However, the quad-spectrum for the impermeable PA cell PA1 has only a local minimum at a frequency of $f = 1$. The reason for this could be that there is no or only a small phase lag between the two time series. This makes sense when considering that this is an impermeable PA cell and that rainfall runs off with little delay. Another explanation is that the time increments of the tipping bucket measurements, which are 5 min, are larger than the temporal delay; therefore the temporal model does not reflect this. A higher temporal resolution, for example each minute, could result in a more distinct minimum at a frequency of $f = 1$.

Table 3. Results from the Time-Series Analysis: Cospectra, Quad-Spectra, and Lag Time for the Five Synthetic Time Series and Three Pavement Treatments

| Treatment | Block | Synthetic time series | | | | |
		I	II	III	IV	V
		Cospectrum				
MIA	1	4,987	3,705	3,660	7,569	8,021
	2	920	1,632	2,409	5,473	5,059
	3	5,694	2,322	1,986	5,454	3,748
MPA	1	4,603	3,002	1,658	2,661	1,937
	2	3,352	1,834	1,404	2,582	2,128
	3	3,933	2,389	1,457	2,754	2,952
UPA	1	551	149	548	369	124
	2	8,897	8,764	5,463	8,031	9,142
	3	10,242	8,615	5,172	8,209	9,298
		Quad-spectrum				
MIA	1	72	−80	−196	−152	−265
	2	77	58	−207	−316	−225
	3	38	−39	−335	−418	−273
MPA	1	−560	−548	−669	−316	−271
	2	−371	−395	−618	−270	−334
	3	−591	−630	−770	−396	−713
UPA	1	−33	−75	−217	12	5
	2	−727	−1,138	−649	−818	−1,346
	3	−1,497	−1,187	−709	−761	−1,276
		Lag time (min)				
MIA	1	N/A	−20	−49	−18	−30
	2	N/A	N/A	−78	−53	−41
	3	N/A	−15	−153	−70	−67
MPA	1	−111	−166	−352	−108	−127
	2	−101	−194	−380	−96	−143
	3	−137	−236	−445	−131	−217
UPA	1	−54	−427	−346	N/A	N/A
	2	−75	−118	−108	−93	−134
	3	−133	−125	−125	−85	−125

Note: MIA = maintained impervious asphalt; MPA = maintained porous asphalt; UPA = unmaintained porous asphalt.

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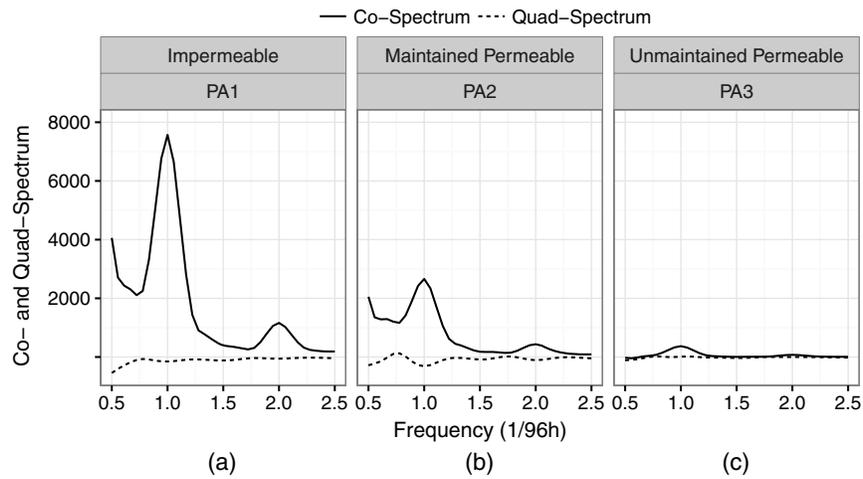
Fig. 6. Co- and quad-spectrum of Storm Group IV and Block 1, in which the co-spectrum has distinct maxima at a frequency of $f = 1$ in the PA cells, the minimum of the quad-spectrum in PA cell PA2 indicates a delay in both time series, and the co- and quad-spectrum in PA3 have a maximum and minimum, respectively; in comparison to the other PA cells, these extreme values are relatively small so that a temporal relationship is very weak: (a) PA1; (b) PA2; (c) PA3

The critical points in the co- and quad-spectra for PA3 [Fig. 6(c)] are very low in comparison to those of PA1 and PA2. Outflow times and volume of PA3 have shown unreliable performance over the whole project period as outflow volumes did not reflect the precipitation depth. Several qualifying storms did not result in any outflow at all, while at other times PA3 had outflow despite the lack of a rainfall event. The authors assume that the impermeable cell liner was damaged at the time of construction and believe that spring-fed subsurface flows are entering the PA cell. These reasons may explain why there is no strong correlation
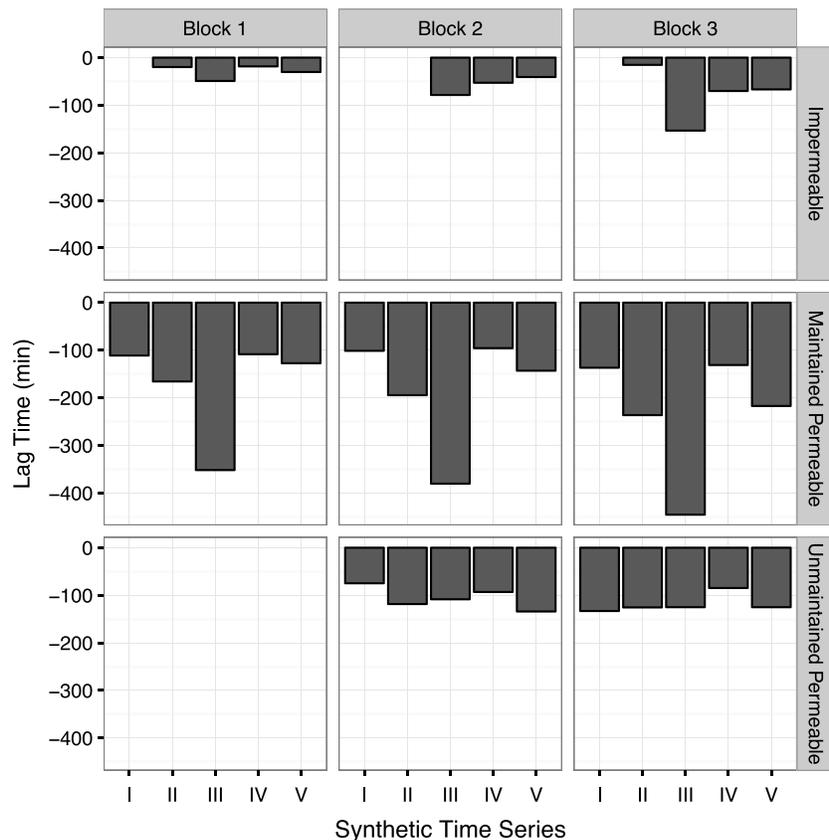
Fig. 7. Lag time result from time-series analysis; data are only plotted if the time-series analysis resulted in meaningful data; lag times were lower for impervious asphalt with average lag times of N/A, −18, −94, −47, and 46 min; porous asphalt had distinct longer lag times with 116, 199, 393, 112, and 162 min for unmaintained and 101, 122, 117, 89, and 130 min for maintained porous asphalt, respectively; numbers reflect the synthetic Time Series I–V in that order

of the time series at $f = 1$ as there is for PA2 [Fig. 6(b)]. If outflow occurs randomly, a temporal relationship cannot be expected and the reason that co- and quad-spectrum signals are low [Fig. 6(c)] for that cell.

The resulting lag times for each group, block, and treatment are shown in Fig. 7 and Table 3. Negative values indicate that the outflow was delayed after the rainfall, which is logical. Outflow can only occur if there was rainfall. Lag times were not computed for time series whose critical points did not meet the above-mentioned criteria, i.e., where the quad-spectrum did not have a minimum. The differences between impermeable and porous asphalt were very distinct. On average, stormwater was delayed 54 min on the MIA, 196 min on the MPA, and 112 min on the UPA. Interestingly, the lag time for the MPA was higher than for the UPA. These results fit well to the above reported infiltration rates that were also higher for the UPA. Maintenance with the regenerative air street sweeper seemed to increase lag time and decrease infiltration rates, contrary to the initial hypothesis. The authors hypothesize that street sweeping with a regenerative street sweeper might result in street dirt moving deeper into the pavement matrix, therefore promoting clogging and increasing lag between the onsets of rainfall and outflow. This could explain the differences between the infiltration results measured between the maintained and unmaintained porous asphalt cells.

The storm group that represents different amounts of applied street dirt did not affect the lag time in the UPA cells. However, there were differences between storm groups in the MPA cells. For example, the MPA cell in Block 2 showed initially increasing lag times that then decreased. The MIA had average lag times of 18, 94, 47, 46, and 45 min for Storm Groups I–V, respectively. The MPA had average lag times of 116, 199, 393, 112, and 162 min and the UPA had average lag times of 104, 122, 117, 89, and 130 min for Storm Groups I–V, respectively. In summary, there was no common pattern among the MPA and UPA that would indicate a systematic increase in lag time with the continued addition of street dirt.

Conclusions

A study to determine functional performance of porous asphalt pavements over a period of 5 years showed that clogging did occur and was manifested as decreasing infiltration rates over the period of study. However, it was shown that annual maintenance using a regenerative air sweeper did not yield a significant improvement of pavement performance when compared to those sections of pavement that were not maintained at all. The authors showed that an annual cleaning schedule was not frequent enough to maintain infiltration rates with all pavements showing a gradual decrease in infiltration. More research is necessary to develop a greater understanding of appropriate cleaning schedules for permeable pavement systems. It was shown that the location had a significant effect on pavement infiltration rates. The authors hypothesized that location was a proxy variable for traffic patterns with zones that connected pavement sections experiencing the most traffic coinciding with regions of the lowest infiltration rates. This disproportional vehicular use was a greater influence on clogging than annual pavement cleaning. A one-time single-pass cleaning of all pavements using a novel wet vacuum process did not yield any significant improvement of infiltration rates.

From a design and maintenance perspective, this study implies that the hydrologic benefit of permeable pavement is sustained even though zones of pavement might become impervious by experiencing high traffic volumes, as long as the surrounding zones remain permeable. While certain sections of the porous asphalt cells were clogged, the overall hydrologic performance of each cell as measured by the proportion of rainfall that was converted to surface runoff did not decrease over time. From a design perspective, this study implies that for stormwater management it is not necessary for the entire pavement to be porous, as long as the zones surrounding high-traffic pavement remain permeable. The zones with permeable pavements would then have to be maintained more frequently because they would receive run-on from impervious zones. In terms of stormwater peak-flow mitigation, there was more than an average sixfold increase in lag times for porous asphalt cells compared with traditional impervious asphalt. While these results suggest that permeable pavements are well suited for the management of stormwater, finding the most appropriate type and frequency of maintenance to ensure that these systems are economically viable is a topic of future work.

Acknowledgments

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