Journal of Environmental Management 294 (2021) 112990

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Assessing maintenance techniques and in-situ pavement conditions to restore hydraulic function of permeable interlocking concrete pavements

Ian M. Simpson [a,*], Ryan J. Winston [a,b], R. Andrew Tirpak [a]

[a] Department of Food, Agricultural, and Biological Engineering, The Ohio State University, 590 Woody Hayes Dr., Columbus, OH, 43210, USA
[b] Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, 2070 Neil Ave., Columbus, OH, 43210, USA

ARTICLE INFO

Keywords:
Permeable pavement
Porous pavement
Maintenance
Clogging
Surface infiltration rate
Restoration

ABSTRACT

Permeable pavements are increasingly implemented to mitigate the negative hydrologic outcomes associated with impervious surfaces. However, the hydraulic function of permeable pavements is hindered by clogging in their joint openings, and systematic maintenance is needed to ensure hydraulic functionality throughout the design lifespan of these systems. To quantify the effectiveness of various maintenance measures, surface infiltration rates (SIRs) were measured before and after five different maintenance techniques were applied to five permeable interlocking concrete pavements (PICPs) in central Ohio, USA. Three maintenance techniques, the Municipal Cleaning Vehicle (MCV), the Rejuvenater, and a pressure washer and the Rejuvenater performed in series, significantly improved median SIRs from 16 to 26, 5 to 106, and 11 to 37 mm/min, respectively. However, pressure washing alone resulted in no significant difference to PICP SIR (median SIRs increased from 8 to 20 mm/min). Regenerative air street sweeping significantly worsened SIRs when performed during wet weather (median SIRs decreased from 19 to 4 mm/min) but had no significant impact on SIRs during dry weather (median SIRs decreased from 21 to 18 mm/min). This work captured the maintenance effectiveness of two techniques for the first or second time, namely the Rejuvenater and MCV, to investigate their use as a suitable maintenance technique. Further, the maintenance techniques were tested on multiple PICPs, thus the effect of *in-situ* pavement conditions had on hydraulic improvement via maintenance could be addressed. Differences in general upkeep, traffic, and runoff routed to a PICP affected the depth of clogging below the pavement surface, which forestalled hydraulic improvement. Though shown to improve the SIR of PICP systems, results indicate that the maintenance techniques were not capable of restoring pavement hydraulics to initial conditions. These results demonstrate the need for regular, routine maintenance and topping up of joint aggregate before clogging migrates deeper into the pavement profile.

1. Introduction

Human activity has altered approximately 50% of earth's land surface (National Research Council, 2005), with much of the world's population migrating to urban centers (FirminoCosta da Silva et al., 2017; Kojo and Paschal, 2018). Urbanization results in impervious cover which increases runoff, causing negative impacts to stream health (Dietz and Clausen, 2008). Parking lots and roads are substantial contributors to imperviousness in urban areas.

Permeable pavements are an alternative paving material that, in contrast to traditional asphalt and concrete, allow rainfall to infiltrate the pavement. Pollutant removal through sedimentation and filtration occurs near the surface of the pavement. Stormwater then passes through the underlying open graded aggregate layers before exiting the practice as exfiltration to the surrounding soil or discharge via an underdrain. Permeable pavements are often recommended as a stormwater control measure (SCM) (Collins et al., 2008; Vogel et al., 2015; Zahmatkesh et al., 2015) since they reduce runoff volume and peak flow rates (Bean et al., 2007; Hunt et al., 2002) and improve runoff quality (Bratteboand Booth, 2003; Brown and Borst, 2015; Fassman and Blackbourn, 2011; Myers et al., 2011; Sansalone and Buchberger, 1995; Drake et al., 2014; Wardynski et al., 2013; Tirpak et al., 2020). Common types of permeable pavement include permeable interlocking concrete pavement (PICP), porous asphalt, and pervious concrete.

PICP systems are comprised of interlocking bricks with open joints typically filled with ASTM No. 8, 89, or 9 aggregate (Liu and Armitage,

* Corresponding author. 590 Woody Hayes Dr. Room 250. Columbus, OH, 43210, USA.
E-mail address: simpson.725@osu.edu (I.M. Simpson).

https://doi.org/10.1016/j.jenvman.2021.112990
Received 27 January 2021; Received in revised form 12 May 2021; Accepted 1 June 2021
Available online 17 June 2021
0301-4797/

2020). These systems are increasingly utilized due to their ease of installation, greater hydraulic capacity, and less intensive maintenance requirements compared to other permeable pavements (Luckeand Beecham, 2011). Further, PICP systems have been shown to respond more positively to maintenance than other types of permeable pavement (Danzet al., 2020; Drake and Bradford, 2013). Surface infiltration rates (SIRs) of PICP systems significantly improve when the upper 20 mm of joint material (i.e., aggregate and accumulated debris) is removed (Dierkeset al., 2002; Gerrits and James, 2002; Borgwardt, 2006; Lucke and Beecham, 2011). Following maintenance, displaced or removed PICP joint material should be replaced with washed aggregate (Smith, 2006).

Permeable pavements are prone to clogging over time (Razzaghmaneshand Beecham, 2018), which is driven by local rainfall patterns, run-on ratio (defined as the ratio of impervious drainage area to the permeable pavement surface area), air quality, sediment and pollutant accumulation, and traffic patterns. Several studies observed clogging to occur in the upper few centimeters of the permeable pavement cross section (Baladeset al., 1995; Haselbach, 2010; Vancura et al., 2012). Though systematic surface cleaning (i.e., maintenance) has been observed to improve permeable pavement SIRs (Haselbach, 2010), studies have shown that it cannot restore SIRs to those of newly installed systems (Winston et al., 2016a). Newly constructed permeable pavements typically have initial SIRs greater than 200 mm/min; however, initial hydraulic performance is often substantially reduced within a few years of construction (Razzaghmaneshand Beecham, 2018). Sections of permeable pavement are considered clogged when SIRs are less than the infiltration rates of the existing subbase since runoff reduction through exfiltration is desirable (Weiss et al., 2019).

Permeable pavement maintenance practices have varying effects on recovering hydraulic function. Winston et al. (2016a) found that the effectiveness of regenerative air street sweeping was dependent on pre-maintenance SIRs of PICP systems in Durham, North Carolina USA. The authors observed that three to five passes of a regenerative air street sweeper had a significant effect on highly clogged systems (i.e., pre-maintenance SIRs below 2.5 mm/min), with SIRs increasing between 14 and 86 fold following maintenance activities. Conversely, no significant differences were observed after performing similar maintenance on a section of PICP with a pre-maintenance median SIR of 231 mm/min. It was concluded that regenerative air street sweeping was more effective in improving PICP SIRs than other maintenance techniques, including mechanical street sweepers or hand removal of the upper 20 mm clogging material (Winston et al., 2016a).

Drake and Bradford (2013) investigated the effects of small-scale (i.e., hand sweeping, low/high suction vacuum, and pressure washing), and large-scale (i.e., vacuum truck and regenerative air street sweeping) maintenance on PICP SIRs in Canadian parking lots. The authors observed wide-ranging results, as hand sweeping, low suction vacuums, high suction vacuums, and pressuring washing increased SIRs by −50 to 550%, 300 to 11,650%, 0 to 6625%, and ≥1325%, respectively. Drake and Bradford (2013) also performed the same small-scale maintenance on other types of permeable pavement (i.e., porous asphalt, pervious concrete), though greater improvements were reported for PICP systems after maintenance was performed. Large-scale maintenance, which significantly improved SIRs for PICP and porous concrete, was only effective on mild to moderately clogged sections of PICP; when clogging extended several centimeters into the joints or entire sections of joint lengths were crusted over, vacuum sweeping and regenerative air sweeping did not provide enough suction to dislodge the clogging material (Drake and Bradford, 2013).

Results from these studies indicate that pressure washing and regenerative air street sweeping may be effective in partially recovering hydraulic capacity of PICP systems; however, both have limitations to their implementation at the field-scale. Pressure washing is time consuming and may not be ideal in PICP streets, alleys, or larger parking lots due to traffic and time constraints. Conversely, research suggests that regenerative air street sweeping may not be able to restore the initial SIRs of PICP systems and may only work in mild to moderately clogged systems. The Interlocking Concrete Pavement Institute (ICPI) advises that PICP systems should provide 20–25 years of service when carefully constructed and maintained (Smith, 2006). Thus, a more robust understanding of practical, cost-effective management and maintenance techniques is needed to promote the intended functions of PICP throughout their operational lifespan.

The purpose of this research was to investigate the effects of different maintenance techniques on SIRs of PICP systems. Findings from this research expand the current knowledge and applicability of two maintenance techniques, pressure washing and regenerative air street sweeping. Further, two newer maintenance technologies which combine these techniques into a single apparatus were explored: the Rejuvenater and a Municipal Cleaning Vehicle (MCV). Finally, we expound on operational factors (speed of maintenance, number of maintenance passes) and *in-situ* pavement conditions (depth of clogging), which explain variability in maintenance effectiveness.

2. Materials and methods

2.1. Site descriptions

A variety of maintenance techniques were performed on five PICP systems in Franklin County, Ohio, USA; four were located in the Clintonville neighborhood of Columbus, while one was located in a commercial store parking lot in Reynoldsburg, Ohio (Fig. 1a). The Clintonville PICP systems, hereafter referred to as Bishop, Cooke, Dixon, and Dominion, had nearly identical engineering designs and were maintained semiannually with a regenerative air street sweeper. Joint aggregate was not topped up after this routine maintenance at the Clintonville PICP systems. The Reynoldsburg PICP system, referred to hereafter as Commercial, received no routine maintenance. All five PICP systems were built in accordance with stormwater guidance in the state of Ohio, *Rainwater and Land Development* (OEPA, 2018).

In addition to direct rainfall, the Bishop and Commercial PICP systems treated run-on from adjacent catchments (Fig. 1b and c). The run-on ratios of these systems were 3.4:1 and 26.3:1, respectively. The Dixon, Dominion and Cooke systems treated primarily direct rainfall and negligible run-on from adjacent houses/buildings and driveways (Fig. 1b). Characteristics and design features of the PICP systems are presented in Table 1.

2.2. Description of maintenance techniques

The ability of five maintenance techniques to improve the hydraulic function of PICP systems were evaluated. These techniques included regenerative air street sweepers, a pressure washer, a walk-behind pressure washer and vacuum combination (Rejuvenater), the MCV, and a pressure washer and the Rejuvenater in series (Fig. 2). A Craftsman hand-held pressure washer powered by a 163 cc Briggs and Stratton engine was used to perform maintenance at the Commercial PICP system. The pressure washer applied 19.3 MPa of pressure and a 15° nozzle was equipped to the sprayer. The pressure washer nozzle was held approximately 30 cm above the ground and was used to apply water to the pavement joints at approximately a 45° angle (Fig. 2a). Pavement joints were pressure washed until the water deflecting out of the joints was clear.

The Rejuvenater is a street cleaning apparatus developed by Contract Sweepers and Equipment in Columbus, Ohio. It utilizes a walk behind 0.6-m-wide deck equipped with a rotating nozzle pressure washer to dislodge sediment and debris. The nozzle sprays water (from an external water source) at 22 MPa. The deck is attached to a 15-cm diameter vacuum hose which was connected to a Model 210® Tymco regenerative air street sweeper (Fig. 2b). Suction provided by the street sweeper was used to deposit the dirty water and recovered debris into the hopper. The

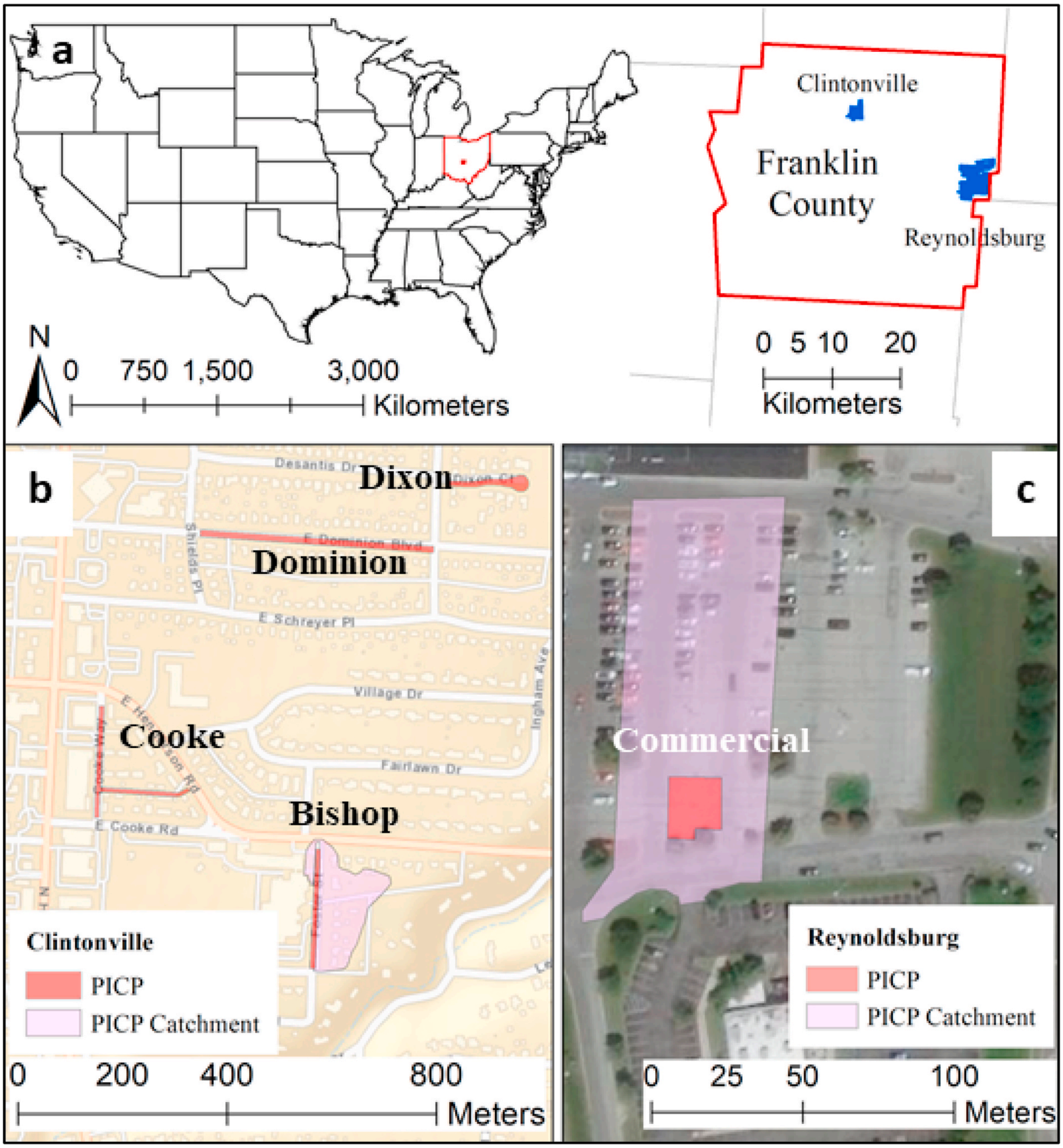

Fig. 1. Location of Franklin County in central Ohio (a). Dixon, Dominion, Cooke, and Bishop PICP systems and their contributing catchment areas (b). Commercial PICP system and its contributing catchment area (c).

Rejuvenater made two passes on the Commercial PICP.

Hand-held pressuring washing followed by maintenance using the Rejuvenater was performed at the Commercial PICP. Measurements of SIRs were performed for pre- and post-pressure washing, pre- and post-Rejuvenater, and pre- and post-pressure washing and Rejuvenater in series. These three maintenance techniques were performed on June 11, 2020 during dry weather conditions. Three locations on the PICP were tested for each of these three maintenance techniques (Fig. 3).

A regenerative air street sweeper performed maintenance on the entirety of all five PICP systems with varying number of passes. The numbers of passes at each PICP was determined by operators visually inspecting debris removal from the PICP joint spaces. Regenerative air systems use a blower to create a high velocity blast of air onto the PICP, dislodging debris, sediment, and dust. The dislodged particles are sucked into a hopper where they are screened such that the same air stream can be filtered and reused as the sweeper truck moves. A Model 435® Tymco Regenerative air street sweeper (Fig. 2c) was used at the Commercial PICP on April 25, 2019 during a small, low intensity (2.5 mm depth, 0.37 mm/h average intensity) rainfall event. During the event, the sweeper passed over the entirety of the 200 m^2 PICP system ten times. The street sweeper operated at less than 5 kph and stopped over heavily clogged areas (identified visually) for 5–10 s, representative of very intensive maintenance with the regenerative air street sweeper. SIRs utilizing this maintenance technique were measured pre- and post-maintenance at six locations at the Commercial PICP (Fig. 3).

A Model 500x® Tymco regenerative air street sweeper was used to maintain the four PICP systems in Clintonville on June 2, 2020 during dry weather. Varying numbers of passes of the sweeper were applied to these systems: Dominion (six), Dixon (six), Cooke (three), and Bishop (two). The Model 500x® Tymco was operated between 5 and 8 kph on

Table 1
Catchment and PICP design characteristics.

	Bishop	Commercial	Cooke	Dominion	Dixon
Surface Area (ha)	0.10	0.02	0.16	0.3	0.13
Catchment Area (ha)	1.88	0.42	0	0	0
Run-on Ratio■	3.4	26.3	0	0	0
Construction Completed	Sept. 2018	Nov. 2017	Dec. 2017	Sept. 2018	Dec. 2017
Speed Limit (kph)	–	–	40*	40	40*
Joint Aggregate Size	No. 89	No. 9	Nos. 8, 89	No. 89	No. 89
Brick Thickness (cm)	8	8	8	8	8
Maintenance Techniques	R	R, PW, RJ, PW+RJ	R, MCV	R, MCV	R, MCV
SIR Testing Locations	2	15	8	8	8
PICP Location	Parking stalls	Parking stalls	Curb to curb in alley	Curb to curb in road	Curb to curb in cul-de-sac
Adjacent Land Use	Asphalt road, residential	Parking Lot	Commercial, residential	Residential	Residential

R = Regenerative air, PW=Pressure washer, RJ = Rejuvenater, MCV = Municipal Cleaning Vehicle.
* Denotes traffic was typically traveling < 40 kph by visual inspection.
■Run-on ratio defined as the ratio of impervious area in catchment to PICP surface area.

Fig. 2. Pressure washer (a), Rejuvenater (b), Regenerative air street sweeper (c), Municipal Cleaning Vehicle (d).

the four Clintonville PICP systems without stopping at heavily clogged locations, following the standard operating procedure used by the City of Columbus for routine permeable pavement maintenance. SIRs were measured pre- and post-maintenance at two locations at each of the four PICP systems in Clintonville (Fig. 3).

The MCV (Triverus Cleaning and Environmental Solutions) was trialed on Dominion, Dixon, and Cooke. The MCV was operated by the manufacturer on October 29, 2019 during dry weather. The cleaning apparatus was affixed to a Bobcat® Toolcat 5600 (Fig. 2d) and consisted of a rotating pressure washer cleaning and recovery system, spraying at a maximum of 31 MPa, with typical operation at 20.7–24 MPa. The Bobcat® was operated at speeds below 13 kph during maintenance. The MCV incorporates a 28 m^3/min vacuum system to recover the water and debris as slurry that is delivered to on-board storage for later hygienic disposal. At each of the MCV testing locations (two locations at Cooke, Dixon, and Dominion) three adjacent SIR tests (separated by 1 m) were performed, for a total of six testing locations on each PICP system. The number of maintenance passes of the MCV varied (i.e., one, two, and three passes) at each SIR testing location to document the effect of increasing maintenance effort on SIR. One, three, and five passes were performed in this fashion at the west-most testing location at the Cooke PICP system because the pre-maintenance SIRs were exceptionally low (i.e., median SIR of <2 mm/min) at this location (Fig. 3).

2.3. Surface infiltration rate measurements

SIR tests were performed at several locations on each PICP system following procedures outlined in ASTM C1781 (ASTM, 2013). Briefly, this involves affixing a 30-cm diameter single ring infiltrometer to the PICP surface with plumber's putty, after which a constant head of 1–1.5 cm of water was applied to the pavement. Tests were performed in duplicate at each location for all PICP systems; the first test involved applying 3.6 L of water into the infiltrometer. If all the water infiltrated the pavement within 30 s, 18.1 L of water was used for the second test. If the initial volume did not drain within 30 s, 3.6 L of water was used again for the subsequent test. The SIR (mm/min) was calculated as the quotient of total depth of water poured through the single ring infiltrometer over the time required for the water to infiltrate the PICP surface. SIRs from both measurements at each location were used in the analysis that follows.

Initial SIRs at the Dominion PICP were measured at seven locations prior to the installation of all of the bricks. Initial SIRs were measured at five locations at Bishop within two weeks of the completion of construction (Fig. 3). These data were used as a baseline to determine the effectiveness of maintenance techniques at restoring initial hydraulic conditions. The maintenance techniques studied herein were tested at minimum 14 months following the completion of construction of the

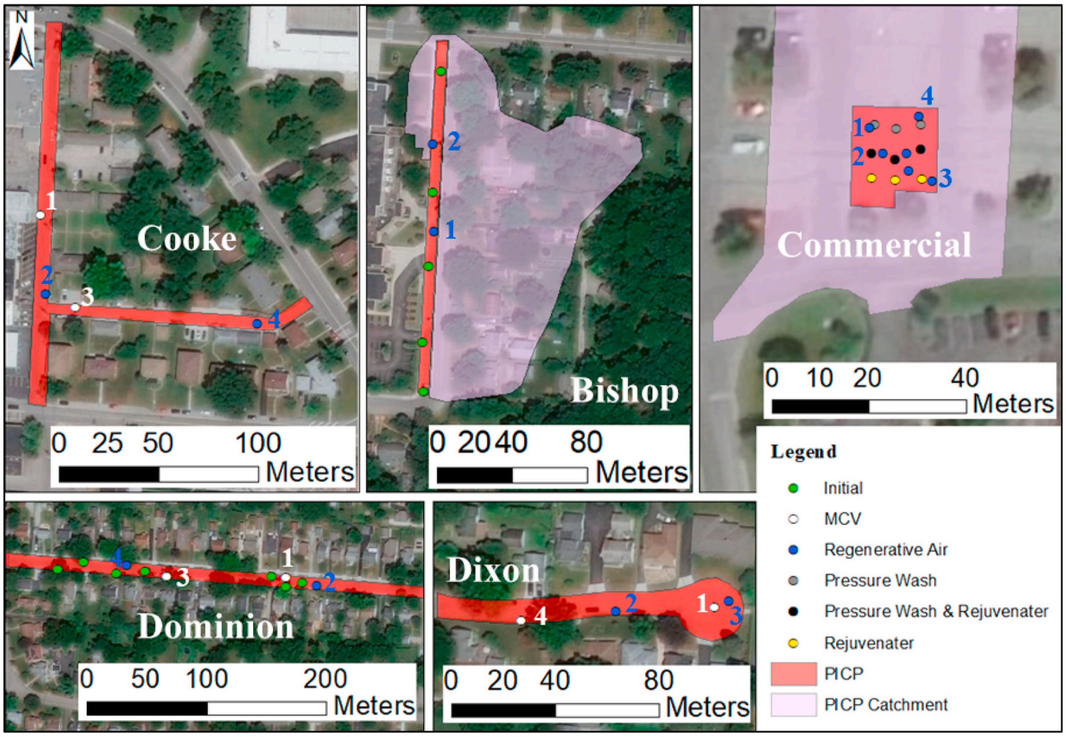

Fig. 3. Surface infiltration rate (SIR) testing locations on the five PICPs. Numbered points correspond to locations where infiltration rates were measured at varying depths (i.e., SIR, 2 cm, 4 cm, and 8 cm) of removed joint aggregate.

PICP systems. Initial SIRs were not measured at the Commercial, Cooke, or Dixon PICPs.

SIR tests were conducted within a 24-h period before and after maintenance was performed. The tests were conducted at the same locations to allow for direct comparison of pre- and post-maintenance SIRs. All SIR testing and maintenance was conducted at least 24 h after the most recent storm event, with the aforementioned exception of regenerative air street sweeping at the Commercial site, where maintenance was performed during a small, low intensity rain event. In this case, pre- and post-maintenance SIR testing was conducted before the start of rainfall and approximately 24 h after the cessation of rainfall.

Infiltration rate tests were performed to investigate joint clogging with respect to depth at four testing locations at the Commercial, Cooke, Dixon, and Dominion PICP systems and two testing locations at the Bishop PICP system (Fig. 3). The infiltration tests were performed as previously described (i.e., SIRs) and after 2, 4, and 8 cm of interstitial joint material (i.e., joint aggregate and any accumulated debris and sediment, measured downward from the PICP surface) was removed. The tests were performed at the Commercial site on July 21, 2020, over one year following maintenance using a regenerative air street sweeper. The infiltration tests at the PICP systems in Clintonville were performed between the 14th and July 21, 2020, approximately nine months after the MCV and 1.5 months after the regenerative air street sweeper were used to perform maintenance. Debris and clogging material were visually observed at all testing locations.

Infiltration tests were designed to elucidate variability in infiltration rate as a function of removal of layers of clogging material; to do so, all material was removed from the joints within the bounds of the single ring infiltrometer using a flat head screwdriver and a putty knife to the specified depth. The screwdriver and putty knife were inserted into the joints at an approximate angle of 30° (or less) to avoid compaction of joint material. Since the pavers were 8 cm thick, the measurement of infiltration rate at this depth required the removal of pavers, after which all joint material was removed, and the paver was replaced prior to testing. Plumber's putty was inserted within the joints to the depth of removed material and sealed to the pavers using a putty knife to prevent lateral leakage. To avoid saturation, tests at the same location were separated by approximately 2 h, duplicate tests were not performed at each depth, and all tests were performed with 3.6 L of water. Otherwise, infiltration testing followed the previously described methodology. In some instances, joint aggregate/material did not completely fill the joints due to loss from tire suction or from previous maintenance efforts wherein joint stone was not topped up; at these locations, infiltration tests began at the next interval of depth where joint aggregate/material was present.

2.4. Data analysis

The percent change (C) from pre-to post-maintenance was calculated using equation (1):

$$C = \left(\left| SIR_i - SIR_f \right| \right) / SIR_i \times 100 \tag{1}$$

where SIR_i and SIR_f are the surface infiltration rates pre- and post-maintenance, respectively. Summary statistics were tabulated for pre- and post-maintenance SIRs and further investigated using boxplots. Normality of the data was tested using the Shapiro-Wilk test. Since pre- and post-maintenance SIRs were taken at the same location and all data were non-normally distributed, paired Wilcoxon signed rank tests were used to identify significant differences between pre- and post-maintenance SIRs for each maintenance technique. SIR testing was not duplicated at the central location at the Commercial PICP before pressure washing and Rejuvenater maintenance (Fig. 3) due to time constraints. Since paired statistical tests require an equal number of observations between testing groups, the second pre-maintenance value was assumed to have the same SIR (0.46 mm/min) as the first test.

The Kruskal-Wallis test, a non-parametric analysis of variance (ANOVA), was used to test for significance between the number of maintenance passes by a specific maintenance technique, which varied over 3 or more levels, and the percent change in SIR. Further, the Kruskal-Wallis test was also used to assess differences in the effectiveness of regenerative air street sweeping during wet and dry weather conditions. Because all other maintenance techniques utilized the same number of passes within a single PICP system, only the MCV data were used to assess improvements in SIR with varying number of passes. Statistical analysis of infiltration rates at varying depths of removed joint material were not conducted due to low sample size. Trends in the data and summary statistics were reported in the text and tabulated, respectively.

Data analysis was performed using R statistical software (R Core Team, 2019). A 95% confidence interval ($\alpha = 0.05$) was used to evaluate statistical significance.

3. Results and discussion

3.1. Initial SIRs

The median initial SIR at the Dominion and Bishop PICP systems were 162 mm/min (range: 32–279 mm/min) and 26 mm/min (range: 8–87 mm/min), respectively. Median initial SIRs for both systems were generally lower than other permeable pavements in the literature. In a laboratory study, Liu and Armitage (2020) reported mean SIRs from 165 to 293 mm/min for 10 PICP systems with varied designs. Hu et al. (2020) reported a mean initial SIR for a pervious concrete system in Jinan, China of 583 mm/min (range: 231–1000 mm/min). Winston et al. (2016a) reported an initial SIR of 470 and 290 mm/min for two porous asphalt systems in northern Sweden. Values herein were most similar to Danz et al. (2020), who reported mean SIRs of 135 and 162 mm/min for a PICP and pervious concrete system, respectively, one month after their construction in Madison, Wisconsin, USA.

Three storm events, totaling 166 mm of rainfall (measured <0.5 km from Bishop and Dominion PICP systems), were observed between the construction end date (September 1, 2018) and the initial SIR tests at the Bishop system (September 13, 2018). Each storm event, which were 68 mm (September 1, 2018), 15 mm (September 6, 2018), and 83 mm (September 7, 2018), would have contributed to the transport and deposition of sediment from the 1.88 ha catchment (approximately 0.15 ha of which was directly connected impervious area) to the joint spaces of the Bishop PICP system. The system was also the only pavement in Clintonville with a surface slope, which ranged between 1.2 and 3.4%. Leipard and Kevern (2015) reported that horizontal sheet flow from a catchment area and the cross slope of a PICP system were inversely correlated with SIRs. It is likely that the combination of run-on from three large storms and pavement slope led to lower initial SIRs at Bishop than Dominion. Additionally, smaller aggregate in the joint space has been shown to decrease initial SIRs of PICP systems (Kim et al., 2013); thus, the lower initial SIR observed at the Dominion system relative to other PICP studies may be attributable to the No. 89 aggregate used in the joint spaces.

3.2. Evaluation of maintenance techniques

The improvements in SIR provided by each PICP maintenance technique were highly varied (Table 2). The median percent changes in SIR were −28, 67, 149, 505, and 1075% for the regenerative air street sweeper, MCV, pressure washer, pressure washer and Rejuvenater in series, and Rejuvenater, respectively. Techniques involving a high-power pressure washer and suction were typically the most effective because they were able to dislodge joint material and immediately remove it from the system. The Rejuvenater may have been the most effective because of the slow (walking speed) operational speed, which allowed more time over the joints.

The regenerative air street sweeping at the Commercial PICP was hampered by rainfall that occurred during maintenance; a significant difference ($p < 0.01$) was observed in the percent change in SIR when this maintenance was performed during dry and wet weather conditions. During dry conditions, the regenerative air street sweeper improved SIRs in Clintonville by a median of 11 percent (Table 2). However, maintenance using the regenerative air street sweeper during wet weather caused consolidation of clogging material, and post-maintenance SIRs decreased by a median of 59 percent (Table 2).

The median initial SIR of the Dominion PICP was obtained only once by post-maintenance SIRs, when MCV maintenance of the Dixon system increased the pre-maintenance SIR from 41 to 164 mm/min (Fig. 4). This was the second highest pre-maintenance SIR from any testing location among all PICP systems, supporting findings from previous studies which observed greater improvements in SIR when PICPs were mildly to moderately clogged (Danz et al., 2020; Drake and Bradford, 2013). Low pre-maintenance SIRs result from clogging in the joints, which generally does not exceed the upper few centimeters of a permeable pavement system (Balades et al., 1995; Haselbach, 2010; Vancura et al., 2012), though Weiss et al. (2019) argued clogging in PICP can penetrate the bedding layer due to the larger joint spaces compared to other types of permeable pavement. The maintenance techniques studied herein may have improved additional testing locations to initial conditions if the pre-maintenance hydraulic conditions were less severe (e.g., the median 13.5 mm/min pre-maintenance SIRs; Table 2). Excluding tests that had pre-maintenance SIRs greater than the median initial SIR at Bishop (26 mm/min), 32% of the tests restored SIRs above this threshold.

3.2.1. Regenerative air street sweeping

Maintenance using the regenerative air street sweeper on the Clintonville PICP systems during dry weather conditions did not significantly improve SIRs ($p = 0.67$). Though the median percent change in SIR increased by 11%, the median SIR decreased from 21.1 mm/min to 17.7 mm/min (Table 2), suggesting this maintenance technique was unsuccessful and impacted each PICP system differently. Pre- and post-maintenance median SIRs changed from 2.4 to 2.6, 22.7 to 27.8, 24.2 to 24.4, and 20.9 to 15 mm/min, respectively, for the Bishop, Cooke, Dixon, and Dominion PICP systems (Fig. 4).

Table 2
Summary statistics of pre-vs post-maintenance surface infiltration rates (SIRs) (mm/min) for various maintenance techniques.

	n	Pre-Median	Post- Median	Pre- Mean	Post- Mean	Pre- Std. Deviation	Post- Std. Deviation	Median % Change in SIR
MCV	36	15.6	25.5	17.3	37.2	12.1	37.5	67
PW	6	8.1	20	9.5	20	7.3	2.5	149
PW + RJ	6[a]	10.6	37	10.2	56	6	33	505
RJ	6	4.7	106	5.8	93	3.8	32	1075
R (total)	28	19.8	13.7	20.9	14.4	15.5	12.1	−28
R (dry)	16	21.1	17.7	19	19	12.7	13.5	11
R (wet)	12	18.5	4.4	23.4	8.4	19	6.6	−59
All Combined	82[a]	13.5	23	16.7	33.6	13.1	35.1	50

MCV = Municipal Cleaning Vehicle, PW=Pressure washer, R = Regenerative air, RJ = Rejuvenater.
[a] One pre-maintenance SIR was assumed due to time constraints.

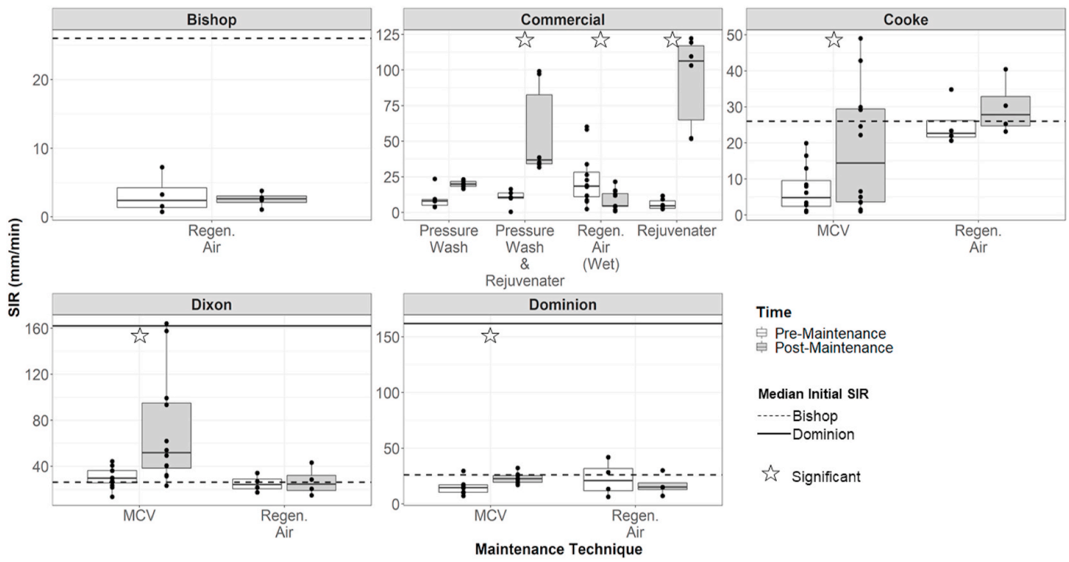

Fig. 4. Boxplots of pre- and post-maintenance surface infiltration rates (SIRs) for various maintenance techniques (e.g., pressure washing, regenerative air sweeping performed during dry weather ["Regen. Air"] and wet weather ["Regen Air (Wet)"], Municipal Cleaning Vehicle [MCV], and the Rejuvenater). Horizontal lines correspond to median initial SIRs at the Bishop and Dominion PICPs.

Previous research on the effects of regenerative air street sweeping has typically observed positive impacts to PICP SIRs. Winston et al. (2016a) studied the effect of this maintenance technique at two parking lots retrofitted with PICP in Durham, North Carolina, USA. In one lot (NCCU), the authors noted a significant ($p < 0.01$) increase in median SIR (from 1 to 14.1 mm/min) after three passes of the regenerative air street sweeper. In the other lot (Piney Wood), the authors found a significant ($p = 0.02$) increase in median SIR (from 1.8 to 154 mm/min) after five passes were performed. However, the authors noted an insignificant ($p = 0.1$) decrease in SIR at testing locations in the same lot where little clogging was observed. The median SIR at these locations decreased from 231 to 143 mm/min after one maintenance pass. Drake and Bradford (2013) also noted increases in SIR following the use of regenerative air street sweepers on PICP systems, though their margins were more difficult to summarize since most of their pre-maintenance SIRs were quantified as below the severe level of clogging (pre--maintenance SIR of 0.83 mm/min). The varying effectiveness of the regenerative air street sweeper on PICP systems studied herein suggests that SIR improvement may also be a function of *in-situ* pavement conditions (see section 3.3).

Maintenance at the Commercial PICP site using the regenerative air street sweeper was performed during a rain event and resulted in a significant reduction of 59% (from 18 mm/min to 4 mm/min) in pre-vs. post-maintenance median SIRs ($p < 0.01$) (Table 2, Fig. 4). In dry conditions, regenerative air street sweepers can improve SIRs by dislodging and removing clogging material (Drake and Bradford, 2013; Winston

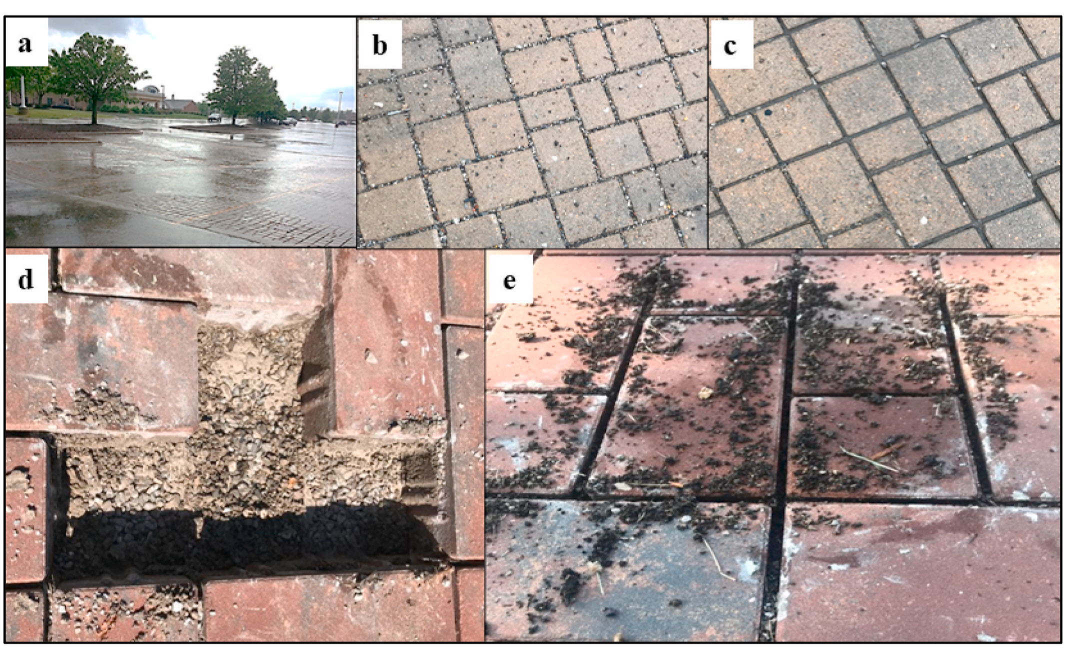

Fig. 5. Run-on via sheet flow (a), loose aggregate, sediment, and debris deposited on the PICP before maintenance (b), and the crusted seal formed after maintenance (c) at the Commercial PICP. Clogging material reaching the pavement bedding layer at the Dominion PICP (d) and clogging material removed from pavement joints at the Cooke PICP (e).

et al., 2016a); however, the large run-on ratio (26.3, Fig. 1c) of this PICP system allowed for sediment and debris to accumulate on the PICP surface and in the joint spaces via sheet flow during this small (2.5 mm) storm event (Fig. 5a). Loose aggregate dislodged from the paver joints was successfully collected by the regenerative air street sweeper during maintenance (Fig. 5b); however, the significant loss of SIR was accredited to a crusted seal that formed within the joints after ten maintenance passes with the regenerative air street sweeper were performed. The accumulated debris and sediment in the PICP joints was saturated by the rainfall, causing it to become sticky and heavy, preventing its removal from the PICP system. The downward force applied by the regenerative air street sweeper's blower may have served to compact the clogging material, forming the observed crusted seal (Fig. 5c). This crusted seal was found across the entire PICP surface, thus reducing SIRs substantially (Table 2, Fig. 4). The vacuum on the regenerative air street sweeper was not powerful enough to free the joints of the crusted seal, resulting in a reduced hydraulic function compared to pre-maintenance conditions. Balades et al. (1995) also noted that wetting prior to sweeping maintenance negatively impacted SIR improvement.

3.2.2. Pressure washing, Rejuvenater, and pressure washing and Rejuvenater in series

Though not statistically significant ($p = 0.06$), the median percent improvement in SIR following maintenance using the pressure washer was 149% (median SIRs improved from 8.1 to 20 mm/min from pre-to post-maintenance, respectively [Table 2]). This result may be attributed to the relatively low number of paired SIR tests ($n = 6$) in which the pressure washer was evaluated. Winston et al. (2016a) documented significant increases in SIR at two porous asphalt streets in Luleå and Haparanda, Sweden, though fewer testing locations were investigated ($n = 3$ for both streets). SIRs increased drastically; medians increased from 0.08 to 37.4 and 0.05 to 0.43 mm/min at Luleå and Haparanda, respectively. Danz et al. (2020) also noted a significant increase in SIR on a section of pervious concrete in Madison, Wisconsin, USA after pressure washing and vacuuming, though SIRs were increased by only 5% on average. These results suggest effectiveness of pressure washing is dependent on permeable pavement type. Amalgamating the results from Danz et al. (2020), Winston et al. (2016a), and from this study may indicate that improving SIR using a pressure washer on PICP systems may be more difficult than on porous asphalt and pervious concrete systems, which would contradict the findings from Drake and Bradford (2013). This might be due to the PICP geometry wherein joints represent a small percentage of the pavement surface, whereas diffuse porosity exists in porous asphalt and pervious concrete systems.

Maintenance using the Rejuvenater ($p = 0.03$) and pressure washer and Rejuvenater in series ($p = 0.03$) resulted in significantly improved SIRs at the Commercial PICP system. While the Rejuvenater was the most successful maintenance technique for improving SIRs (Fig. 4, Table 2), neither the Rejuvenater nor the pressure washer and Rejuvenater in series were able to restore SIRs to the median initial SIR of the Dominion PICP (162 mm/min). The largest post-maintenance SIR observed from any test following these maintenance techniques was 122 mm/min (Fig. 4), also considerably less than initial SIRs for PICPs reported in literature. The largest median percent changes in SIR was observed for the pressure washer, pressure washer and Rejuvenater in series, and Rejuvenater in part because the pre-maintenance SIRs were the lowest for these tests. The hydraulic function of the same Commercial PICP system (Fig. 1c) was studied by Tirpak et al. (2021), who concluded that the substantial run-on ratio of 26.3 caused quick clogging of the PICP; thus, no significant runoff reduction was observed for the catchment after the PICP was retrofitted into the parking lot.

Median pre-maintenance SIRs were 8, 11, and 5 mm/min before the pressure washer, pressure washer and Rejuvenater in series, and Rejuvenater maintenance techniques were conducted at the Commercial PICP, respectively, while the median SIRs before the MCV and regenerative air street sweeper were operated in Clintonville were 16 and 21 mm/min, respectively. The greatest median SIR (106 mm/min) was observed after maintenance by the Rejuvenater at the Commercial PICP system (Table 2). This SIR was 3–8 fold higher than the median post-maintenance SIR for the other maintenance techniques. Sehgal et al. (2018) performed pressure washing on four different PICPs in Canada, two of which were pressure washed followed by either vacuum or regenerative air street sweeping. Though these street sweepers were not comparable to the Rejuvenater, results herein as well as Sehgal et al. (2018) suggest that adding maintenance techniques in series with pressure washing will not necessarily yield additional hydraulic improvement. This result may occur because pressure washing may dislodge substantial clogging material in the upper few centimeters of the joint but can compact clogging material deeper in the cross section without vacuuming simultaneously. Further, wetting the pavement before the use of suction or a blower system, would saturate clogging material; this adds weight and cohesiveness to the clogging material, which may forestall its removal with a blower and/or vacuum system, a similar phenomenon which occurred in section 3.2.1 during wet weather conditions. This finding reinforces the theory that wetting of a pavement surface (even if the wetting is part of a maintenance technique) prior to (additional) maintenance negatively impacts maintenance of a permeable pavement (Balades et al., 1995).

3.2.3. Municipal Cleaning Vehicle

The median percent improvement in SIR following maintenance with the MCV was 67% (median SIRs increased from 15.6 to 25.5 mm/min) for the Cooke, Dixon, and Dominion PICP systems, which included all data regardless of the number passes (Table 2). Though these improvements were significant ($p < 0.01$), effectiveness of this maintenance technique was dependent on the PICP system. Following maintenance with the MCV, median SIRs increased from 4.8 to 14.4, 29.7 to 51.7, and 14.5 to 22.6 mm/min at Cooke, Dixon, and Dominion, respectively (Fig. 4). UNHSC (2019) reported that mean SIRs increased from 1.3 to 39.8 and 1.3 to 35.6 mm/min for two porous asphalt parking lots in Durham, New Hampshire, USA after maintenance with the MCV, substantially greater improvements than those observed herein. Continued SIR recovery was observed with increasing passes of the MCV at the Clintonville PICP systems (see section 3.4); SIR increases were 244, 319, and 72% for the Cooke, Dixon, and Dominion PICP after three passes of the MCV. The varying effectiveness of the MCV on different permeable pavement systems (PICP and porous asphalt) further supports that SIR improvement may also be a function of *in-situ* pavement conditions.

3.3. Infiltration rate and joint material removal depth

Compared to other studies (Drake and Bradford, 2013; UNHSC, 2019; Winston et al., 2016a), the MCV and regenerative air street sweeper underperformed with respect to improvements in SIRs at the Clintonville PICP systems. Because of this, it was surmised that clogging in the Clintonville PICP systems had occurred at greater depths than typically reported in the literature due to the lack of refilling joint aggregate following systematic maintenance (or after substantial loss following wheel suction applied by car tires [Fassman and Blackbourn, 2010]). It was speculated that this would reduce the effectiveness of the two maintenance techniques since it might be more difficult to remove clogging from deeper in the joint section.

A series of infiltration tests with depth were conducted on the PICP systems 1.5 months after regenerative air street sweeping; this was justified because the maintenance did not significantly affect pre- and post-maintenance SIRs (Fig. 4). All other maintenance techniques were performed at least nine months before these series of tests. Though SIRs often vary spatially within a permeable pavement system (Drake et al., 2013; Winston et al., 2016b), the removal of joint media to specified depths typically resulted in similar infiltration rates from different test locations within the same PICP system (Table 3). This suggests that failing to top up joint aggregate after surface maintenance (or loss of joint aggregate from wheel suction), paired with anthropogenic and natural activity within the catchment, causes subsurface clogging in a relatively uniform fashion.

The Bishop and Commercial PICP systems had median SIRs (depth of 0 cm) of 15.5 and 10.3 mm/min, respectively (Table 3). The median SIRs of these systems, which were the lowest of the five systems, were likely affected by their run-on ratios (3.4 and 26.3 for the Bishop and Commercial systems, respectively), which contribute greater sediment loads than direct rainfall during storm events. However, these systems also exhibited the greatest percent improvement in infiltration rate after 2 cm of joint material was removed (median percent improvement of 379 and 60% for the Bishop and Commercial PICP systems, respectively). Notably, infiltration rates at both testing locations at the Bishop PICP were greater than the median initial SIR (26 mm/min) after 2 cm of media was removed. The large increases in infiltration rate after removing 2 and 4 cm of media suggests that a substantial amount of clogging occurred in the 0–4 cm depth from the Bishop and Commercial PICP systems.

Conversely, infiltration rates at Dominion and Dixon decreased as joint material was removed (Table 3). Near the pavement surface, joint material consisted of organic material (e.g., grass clippings, soil, small leaves, straw) as opposed to crusted sediment or aggregate which was observed at the Bishop and Commercial systems. The median SIR at the Dominion PICP was 18.5 mm/min, with infiltration rates falling to median values of 7.8 and 3.7 mm/min after 2 and 4 cm of joint material were removed, respectively. Similarly, the median SIR at the Dixon PICP was 41.6 mm/min, with median infiltration rates decreasing to 27.1 and 37.5 mm/min after 2 and 4 cm of joint material were removed, respectively. Infiltration rates may have decreased with the removal of joint material due to unintended compaction with the putty knife or joint material was partially saturated despite the 2-h wait time between tests. Infiltration rates did not improve compared to SIRs at either system until the bricks were removed, cleaned entirely of joint material, and replaced into the system. The median infiltration rate after the bricks were replaced atop the Dominion PICP bedding layer was 161 mm/min, about a 1% decrease from the median initial SIR at this pavement. After removal of all joint obstructions and replacement of the pavers, the infiltration rates should be representative of the pavement bedding course, which would allow water to pass at extremely high rates. These results indicate that clogging occurred more than 4 cm below the surface of the Dominion PICP and clogging material was beginning to penetrate the bedding course (Fig. 5d), supporting conclusions by Weiss et al. (2019). Infiltration rates over 300 mm/min were observed after complete removal of joint material and replacement of bricks at Dixon (Table 3), indicating clogging below the surface, but not into the pavement bedding layer.

Table 3
Infiltration rates (mm/min) as a function of joint material removal depth. Location of tests correspond with Fig. 3.

PICP	Location	Depth below pavement surface			
		SIR (0 cm)	2 cm	4 cm	8 cm
Bishop	1	8.7	64.1	78.5	>300
Bishop	2	22.3	49.2	73.9	–
Commercial	1	10.3	17.2	17.7	–
Commercial	2	10.6	27.9	43.0	–
Commercial	3	6.4	14.5	30.6	–
Commercial	4	10.3	9.9	23.0	–
Cooke	1	3.0	4.0	19.4	–
Cooke	2	33.2	49.8	137.5	–
Cooke	3	42.3	44.9	63.1	>300
Cooke	4	29.0	30.2	47.7	–
Dixon	1	48.4	28.7	18.4	–
Dixon	2	34.7	25.5	28.2	–
Dixon	3	21.1	20.0	46.7	>300
Dixon	4	65.9	65.9	69.8	>300
Dominion	1	–	9.6	2.7	–
Dominion	2	–	5.9	3.7	139.1
Dominion	3	10.7	3.9	3.7	–
Dominion	4	26.3	9.8	10.4	183.1
Overall median		21.7	22.8	29.4	

"-" denotes absence of joint material at the pavement surface (i.e., 0 cm depth, equivalent to surface infiltration rates) or that brick removal was not practical due to difficulty of removal, traffic, or time constraints. An infiltration rate was documented as >300 mm/min if water infiltrated too quickly to obtain an accurate measurement.

The median percent improvement after 2 cm of media was removed from the joints on the Cooke PICP system was approximately 20% (Table 3). The infiltration rates at Cooke improved by a median 189% after 4 cm of media was removed compared to SIRs; therefore, the most substantial hydraulic restriction in the Cooke PICP system occurred 2–4 cm below the surface. The median infiltration rate after 4 cm of media was removed was 55.4 mm/min, well below initial SIRs reported in literature and herein. Infiltrations rates of >300 mm/min were observed after 8 cm of joint material was removed. These results indicate some clogging reached depths greater than 4 cm below the surface, but not into the pavement bedding layer (Fig. 5e).

The clogging observed in the upper few centimeters of the Bishop and Commercial PICP systems may be attributable to the catchment land use. Both PICPs were retrofitted into parking lots in which speeds of vehicular traffic were too low to dislodge joint aggregate, meaning that clogging stimuli could not penetrate deeper in the joints. Even though semiannual maintenance was conducted at the Bishop PICP system without topping up aggregate, the surface was heavily clogged and the regenerative air street sweeper could not remove the clogged material (as evidenced by the moderate improvement in median SIR from 2.4 to 2.6 mm/min following maintenance). Clogging at the Dominion PICP likely occurred at greater depths relative to the other Clintonville PICP systems because it was more heavily traveled than Dixon or Cooke (Table 1, Fig. 3). Additionally, vehicular traffic contributes to deep clogging by removing joint aggregate due to wheel suction (Fassman and Blackbourn, 2010) and breaks down coarse debris into finer particles which become dispersed and embedded more permanently into the joints (Kresin, 1997; van Duin et al., 2008).

The deep clogging at the Cooke, Dixon, and Dominion PICP systems (and heavily clogged upper surface at the Bishop PICP) likely explains the lower effectiveness of MCV and regenerative air street sweeper maintenance compared to previous studies (UNHSC, 2019; Drake and Bradford, 2013; Winston et al., 2016a). When clogging occurs below the upper few centimeters and surface maintenance cannot significantly improve SIRs, excavation of the PICP bricks and replacement of the joint aggregate, as described by Emerson et al. (2008), may be the only option to restore the initial hydraulic capacity of PICP. Improved techniques for maintenance scheduling need to be developed for permeable pavements (i.e., as a function of design and clogging material) to avoid this worst-case scenario. After maintenance, SIRs do not need to be restored to initial conditions for a permeable pavement to be effective (Weiss et al., 2019) because SIRs are often far greater than rainfall intensities (Chai et al., 2012); pavements with slightly diminished hydraulic function compared to conditions immediately after installation will still provide effective management of runoff. Smith (2011) recommended PICP systems to have a minimum SIR of 25 cm/h (4.2 mm/min), however, a considerably greater SIR is critical when run-on is routed onto a permeable pavement so that runoff and direct rainfall can infiltrate the pavement surface (Winston et al., 2018).

3.4. Effect of number of maintenance passes on SIR recovery

The MCV produced median improvements of 38, 117, and 163% in SIR after one, two, and three passes, respectively, across all testing locations at Cooke, Dixon, and Dominion. Before any maintenance by the MCV was performed, the median SIR for all test locations was 16 mm/

min. The locations that received one, two, and three maintenance passes had a median pre-maintenance SIR of 20, 15, and 13 mm/min, which were significantly improved to 30, 25, and 25 mm/min post-maintenance, respectively ($p < 0.01$). These results suggest that increasing the number of maintenance passes by the MCV will continue to improve SIRs. However, at some point, diminishing improvements to SIRs likely occur wherein increasing the number of passes does not remove more joint material.

Though increasing the number of MCV passes continued to enhance SIR, improvements were dependent on the depth at which the PICP system had clogged. Increasing the number of passes at the Dominion system had little effect on improving SIRs, likely because the most substantial clogging was greater than 4 cm into the pavement profile. Median SIRs on Dominion improved from 16.6 to 24.2, 12.1 to 19.9, and 13.7 to 22.8 mm/min after one, two and three maintenance passes, respectively (Fig. 6). This result suggests that increasing the number of maintenance passes may not increase the *depth* to which joint material is removed. Larger improvements with increasing MCV maintenance passes were observed at Cooke (where the most substantial clogging was between 2 and 4 cm) and Dixon (where pre-maintenance clogging was less severe). Median SIRs improved from 4.5 to 11.8, 13.9 to 27.3, and 5.7 to 24.7 mm/min after one, two, and three MCV maintenance passes, respectively, at the Cooke PICP system, and 29.7 to 40.4, 24.5 to 96.3, and 38.4 to 161 mm/min, respectively, at the Dixon PICP system (Fig. 6).

Because substantial clogging occurred below the upper few centimeters at all three PICP systems where the MCV was implemented (Table 3), increased maintenance passes using the MCV may have been more effective on PICP systems with clogging patterns similar those documented in the literature (i.e., clogging only in the upper centimeters of below the pavement surface; Balades et al., 1995; Haselbach, 2010; Vancura et al., 2012). Though increasing maintenance passes may not increase the *depth* to which aggregate is removed, it may increase the *volume* of joint material removed to a particular depth. van Duin et al. (2008) concluded that increasing the volume of joint material removed enhanced SIR improvements. This was correlated to increasing the number of maintenance passes by a regenerative air street sweeper. Chopra et al. (2010) documented fully restored SIRs on PICP and pervious concrete systems after two passes of a vacuum truck but noted that increasing the number of vacuum truck passes hindered SIRs on a porous asphalt system. In the latter case, the authors hypothesized that joint material was compacted with several maintenance passes (e.g., via the breaking of coarse sediment into fine sediment, which would penetrate further into the pavement joints; Chopra et al., 2010). ***In-situ*** pavement conditions should be considered before increasing maintenance passes so that time and money are not wasted to minimally improve hydraulic function (similar to what was observed at Dominion). A simple, quick, and reliable test to determine the depth at which hydraulic restriction has occurred in PICP needs to be developed. Further, if no joint material has been removed from the pavement system after one maintenance pass, more powerful maintenance techniques should be applied to remove the clogging layer.

4. Conclusions

SIRs were measured at several locations on newly installed PICP and immediately before and after maintenance once the systems had aged. Maintenance techniques evaluated were regenerative air street sweeping, pressure washing, MCV, Rejuvenater, and pressure washing and Rejuvenater in series. Future research should establish a maintenance frequency or timeline for specific techniques which are shown to substantially improve pavement hydraulics. The degree to which maintenance intensity (i.e., the number of passes) and incremental removal of joint material with depth affected SIRs were also investigated. Results from this study support the following conclusions and management recommendations:

1. PICP systems which received run-on from a contributing catchment had the lowest overall SIRs. Additional maintenance requirements for such systems should be considered during the design phase to reduce the maintenance burden.
2. Maintenance using the MCV, the Rejuvenater, and pressure washing and Rejuvenater in series significantly improved SIRs compared to pre-maintenance conditions. Further research on the MCV and Rejuvenater should be conducted on PICP systems with low run-on ratios or treating direct rainfall only to benchmark their function across a range of PICP conditions.
3. Regenerative air street sweeping did not significantly improve SIRs on the PICP systems tested herein, a result which differs from previously published research. Results indicate that this maintenance

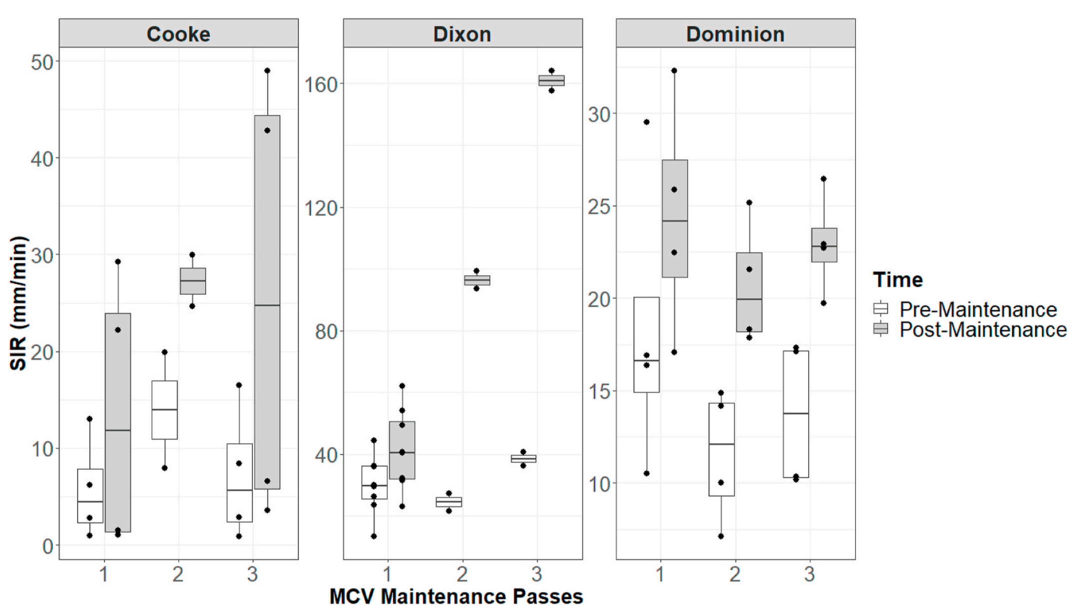

Fig. 6. Boxplots of surface infiltration rates (SIRs) before and after one, two, and three maintenance passes were performed with the Municipal Cleaning Vehicle (MCV).

technique should be avoided during wet weather as it hinders the removal of accumulated debris and sediment which clogs the pavement.

4. Topping up PICP joint aggregate after maintenance or after loss from vehicular wheel suction is vital to prevent deeper clogging in the PICP cross section. In systems where this critical activity was not performed, clogging was observed more than 4 cm below the pavement surface, substantially hindering maintenance efficacy compared to previously published work.
5. Maintenance techniques which combined a pressure washer and vacuum suction provided the most substantial improvements to SIRs. Suction while pressure washing is necessary to prevent clogging from being translocated within the PICP.
6. Increasing the number of maintenance passes by the MCV from one to three continued to improve PICP hydraulic function. We hypothesize that increasing the number of passes will continue to increase the volume of joint material removed up to a given depth, beyond which diminishing improvements to SIR can be expected.

Credit statement

Ian Simpson performed conceptualization, Writing – original draft, Formal analysis, Investigation, and visualization. Ryan Winston performed conceptualization, Resources, Writing – review & editing, Supervision, and funding acquisition. R. Andrew Tirpak performed investigation and writing – review and editing.

Funding

This research was partially funded by the City of Columbus, Meijer Corporation, and Ohio Environmental Protection Agency.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We acknowledge Steve Karlin with Triverus Cleaning and Environmental Solutions and Brook Haygood with Contract Sweepers and Equipment for providing technical specifications and demonstrating the Municipal Cleaning Vehicle and the Rejuvenater, respectively. We acknowledge Matt Repasky and Perrin Bushon with the City of Columbus for coordinating maintenance and allowing us to conduct research on the PICP systems in Clintonville. Meijer Corporation provided funding for construction and monitoring of the PICP system in Reynoldsburg and allowed us to conduct research on their property. Finally, we acknowledge Matthew Jones, formerly of North Carolina State University, for creating the permeable pavement cross-section in the graphical abstract.

References

ASTM, 2013. Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems. ASTM C1781, West Conshohocken, PA.
Balades, J.D., Legret, M., Madiec, H., 1995. Permeable pavements: pollution management tools. Water Sci. Technol. 32 (1), 49–56.
Bean, E.Z., Hunt, W.F., Bidelspach, D.A., 2007. Field survey of permeable pavement surface infiltration rates. J. Irrigat. Drain. Eng. 133 (3), 249–255.
Borgwardt, S., 2006. Long-term in-situ infiltration performance of permeable concrete block pavement. In: Proceedings of the 8th International Conference on Concrete Block Paving, San Francisco, CA, US.
Brattebo, B.O., Booth, D.B., 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. Water Res. 37 (18), 4369–4376.
Brown, R.A., Borst, M., 2015. Nutrient infiltrate concentrations from three permeable pavement types. J. Environ. Manag. 164, 74–85.
Chai, L., Kayhanian, M., Givens, B., Harvey, J.T., Jones, D., 2012. Hydraulic performance of fully permeable highway shoulder for storm water runoff management. J. Environ. Eng. 138 (7), 711–722.
Chopra, M.B., Stuart, E., Wanielista, M.P., 2010. Pervious pavement systems in Florida—research results. In: Low Impact Development 2010: Redefining Water in the City, pp. 193–206.
Collins, K.A., Hunt, W.F., Hathaway, J.M., 2008. Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina. J. Hydrol. Eng. 13 (12), 1146–1157.
Danz, M.E., Selbig, W.R., Buer, N.H., 2020. Assessment of restorative maintenance practices on the infiltration capacity of permeable pavement. Water 12 (6), 1563.
Dierkes, C., Angelis, G., Kandasamy, J., Kuhlmann, L., 2002. Pollution retention capability and maintenance of permeable pavements. In: Proceedings of the 9th International Conference on Urban Drainage. IWA, Portland, OR, US.
Dietz, M.E., Clausen, J.C., 2008. Stormwater runoff and export changes with development in a traditional and low impact subdivision. J. Environ. Manag. 87 (4), 560–566.
Drake, J., Bradford, A., 2013. Assessing the potential for restoration of surface permeability for permeable pavements through maintenance. Water Sci. Technol. 68 (9), 1950–1958.
Drake, J.A., Bradford, A., Marsalek, J., 2013. Review of environmental performance of permeable pavement systems: state of the knowledge. Water Qual. Res. J. Can. 48 (3), 203–222.
Drake, J., Bradford, A., Van Seters, T., 2014. Stormwater quality of spring–summer-fall effluent from three partial-infiltration permeable pavement systems and conventional asphalt pavement. J. Environ. Manag. 139, 69–79.
Emerson, C.H., Traver, R.G., 2008. Multiyear and seasonal variation of infiltration from storm-water best management practices. J. Irrigat. Drain. Eng. 134 (5), 598–605.
Fassman, E.A., Blackbourn, S.D., 2011. Road runoff water-quality mitigation by permeable modular concrete pavers. J. Irrigat. Drain. Eng. 137 (11), 720–729.
Fassman, E.A., Blackbourn, S., 2010. Urban runoff mitigation by a permeable pavement system over impermeable soils. J. Hydrol. Eng. 15 (6), 475–485.
Firmino Costa da Silva, D., Elhorst, J.P., Silveira Neto, R.D.M., 2017. Urban and rural population growth in a spatial panel of municipalities. Reg. Stud. 51 (6), 894–908.
Gerrits, C., James, W., 2002. Restoration of infiltration capacity of permeable pavers. In: Proceedings of the 9th International Conference on Urban Storm Drainage, Portland, OR, US.
Haselbach, L.M., 2010. Potential for clay clogging of pervious concrete under extreme conditions. J. Hydrol. Eng. 15 (1), 67–69.
Hu, N., Zhang, J., Xia, S., Han, R., Dai, Z., She, R., et al., 2020. A field performance evaluation of the periodic maintenance for pervious concrete pavement. J. Clean. Prod. 121463.
Hunt, B., Stevens, S., Mayes, D., 2002. Permeable pavement use and research at two sites in Eastern North Carolina. Global Solutions for Urban Drainage, pp. 1–10.
Kim, J.Y., Slater, C., Gil, G., Architectural, O., 2013. Investigation of Hydraulic Capacity and Water Quality Modification of Stormwater by Permeable Interlocking Concrete Pavement (PICP) System. Dept. of Environmental and Civil Engineering, Florida Gulf Coast University.
Kojo, R., Paschal, N., 2018. Urban population growth and environmental sustainability in Nigeria. J. Empir. Stud. 5 (1), 12–19.
Kresin, C., 1997. Long-term Stormwater Infiltration through Concrete Pavers.
Leipard, A.R., Kevern, J.T., Richardson, J.R., 2015. Hydraulic characterization and design of permeable interlocking concrete pavement. In: World Environmental and Water Resources Congress 2015, pp. 292–301.
Liu, B.K., Armitage, N.P., 2020. The link between permeable interlocking concrete pavement (PICP) design and nutrient removal. Water 12 (6), 1714.
Lucke, T., Beecham, S., 2011. Field investigation of clogging in a permeable pavement system. Build. Res. Inf. 39 (6), 603–615.
Myers, B., Beecham, S., van Leeuwen, J.A., 2011. July). Water quality with storage in permeable pavement basecourse. Proceedings of the Institution of Civil Engineers-Water Management 164 (No. 7), 361–372. Thomas Telford Ltd.
National Research Council, 2005. Population, Land Use, and Environment: Research Directions. National Academies Press.
Ohio Environmental Protection Agency (OEPA), 2018. Rainwater and Land Development. Division of Surface Water, Columbus, OH.
R Core Team, 2019. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Razzaghmanesh, M., Beecham, S., 2018. A review of permeable pavement clogging investigations and recommended maintenance regimes. Water 10 (3), 337.
Sansalone, J.J., Buchberger, S.G., 1995. An infiltration device as a best management practice for immobilizing heavy metals in urban highway runoff. Water Sci. Technol. 32 (1), 119–125.
Sehgal, K., Drake, J., Seters, T.V., Vander Linden, W.K., 2018. Improving restorative maintenance practices for mature permeable interlocking concrete pavements. Water 10 (11), 1588.
Smith, D.R., 2006. Permeable Interlocking Concrete Pavements. *Selection, Design, Construction, and Maintenance*. Interlocking Concrete Pavement Institute, Herndon, VA.
Smith, D.R., 2011. Permeable Interlocking Concrete Pavements. *Design, Specifications, Construction, Maintenance*, fourth ed. Interlocking Concrete Pavement Institute, Herndon, VA.
Tirpak, A., Winston, R.J., Feliciano, M., Dorsey, J.D., 2020. Stormwater quality performance of permeable interlocking concrete pavement receiving run-on from an asphalt traffic lane in a cold climate. Environ. Sci. Pollut. Control Ser. 1–17.

Tirpak, R.A., Winston, R.J., Simpson, I.M., Dorsey, J.D., Grimm, A.G., Pieschek, R.L., Petrovskis, E.A., Carpenter, D.D, 2021. Hydrologic impacts of retrofitted low impact development in a commercial parking lot. J. Hydrol. 592, 125773.

University of New Hampshire Stormwater Center (UNHSC), 2019. Triverus Cleaning Technology Report.

van Duin, B., Brown, C., Chu, A., Marsalek, J., Valeo, C., 2008. Characterization of long-term solids removal and clogging processes in two types of permeable pavement under cold climate conditions. In: Proceedings of the 11th International Conference on Urban Drainage, Edinburgh, UK, vol. 31.

Vancura, M.E., MacDonald, K., Khazanovich, L., 2012. Location and depth of pervious concrete clogging material before and after void maintenance with common municipal utility vehicles. J. Transport. Eng. 138 (3), 332–338.

Vogel, J.R., Moore, T.L., Coffman, R.R., Rodie, S.N., Hutchinson, S.L., McDonough, K.R., et al., 2015. Critical review of technical questions facing low impact development and green infrastructure: a perspective from the Great Plains. Water Environ. Res. 87 (9), 849–862.

Wardynski, B.J., Winston, R.J., Hunt, W.F., 2013. Internal water storage enhances exfiltration and thermal load reduction from permeable pavement in the North Carolina mountains. J. Environ. Eng. 139 (2), 187–195.

Weiss, P.T., Kayhanian, M., Gulliver, J.S., Khazanovich, L., 2019. Permeable pavement in northern North American urban areas: research review and knowledge gaps. Int. J. Pavement Eng. 20 (2), 143–162.

Winston, R.J., Al-Rubaei, A.M., Blecken, G.T., Hunt, W.F., 2016b. A simple infiltration test for determination of permeable pavement maintenance needs. J. Environ. Eng. 142 (10), 06016005.

Winston, R.J., Al-Rubaei, A.M., Blecken, G.T., Viklander, M., Hunt, W.F., 2016a. Maintenance measures for preservation and recovery of permeable pavement surface infiltration rate–The effects of street sweeping, vacuum cleaning, high pressure washing, and milling. J. Environ. Manag. 169, 132–144.

Winston, R.J., Dorsey, J.D., Smolek, A.P., Hunt, W.F., 2018. Hydrologic performance of four permeable pavement systems constructed over low-permeability soils in northeast Ohio. J. Hydrol. Eng. 23 (4), 04018007.

Zahmatkesh, Z., Burian, S.J., Karamouz, M., Tavakol-Davani, H., Goharian, E., 2015. Low-impact development practices to mitigate climate change effects on urban stormwater runoff: case study of New York City. J. Irrigat. Drain. Eng. 141 (1), 04014043.