Permeable Pavement Maintenance: A Review of Literature to Assess Clogging, Predict Maintenance Frequency, and Compare Maintenance Techniques

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Southern California Coastal Water Research Project
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ACRONYM LIST

BMP	best management practice
LID	low impact development
PA	porous asphalt
PICP	pervious interlocking concrete pavers
PC	pervious concrete
SIR	surface infiltration rate
SIT	simple infiltration test

1. INTRODUCTION

Impervious cover is the dominant factor in urban watersheds which leads to a substantial modification of the runoff hydrograph (Schueler et al. 2009), resulting in downstream impacts collectively referred to as the “urban stream syndrome” (Walsh et al. 2005). Permeable pavements are one option in a suite of low impact development (LID) type stormwater best management practices (BMPs) that may be utilized to reduce stormwater runoff from urban watersheds (Dietz 2007). They allow rainwater to infiltrate the pavement surface, where the water may subsequently be stored in an open-graded aggregate reservoir which also supports the pavement structurally (Figure 1). The design may include an underdrain when the underlying soils have substantial clay and silt content and thus poor infiltration rates, or where the influx of water to the subsurface might compromise other infrastructure or contaminated soils. When underlying soils are sandy, often the underdrain is omitted. The depth of the aggregate supporting the pavement is generally related to (1) ensuring structural integrity of the pavement based upon expected traffic loads and (2) meeting hydrologic and/or water quality goals specific to the city or region of implementation (American Society of Civil Engineers 2015). The most common types of permeable pavements installed in the United States are permeable interlocking concrete pavements (PICP), pervious concrete (PC), and porous asphalt (PA), though other types including concrete grid pavers and grass-covered plastic grid pavers are also utilized. Depending on the type of permeable pavement, the bedding, base, and subbase layers may be made up of AASHTO No. 8 or 9 aggregate, AASHTO No. 57 aggregate, and AASHTO No. 2 or 4 aggregate, respectively.

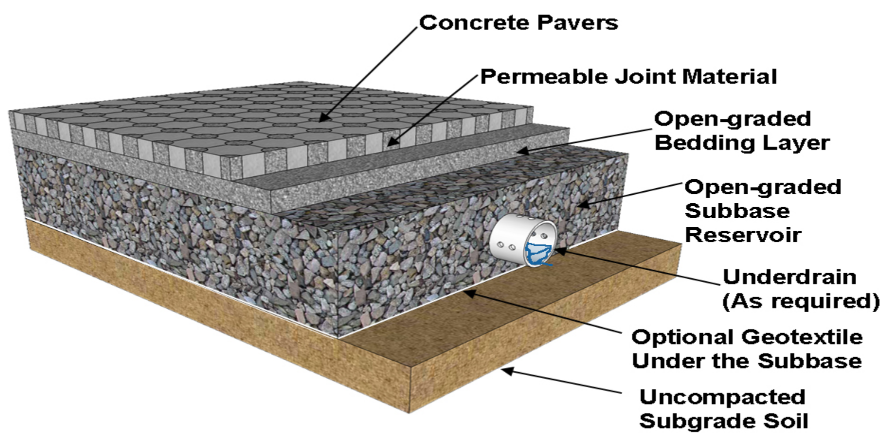

Figure 1. Typical cross-section of a permeable pavement stormwater control measure. Courtesy: Matthew Jones (formerly NC State University).

Permeable pavements provide substantial runoff reduction when located over sandy soils, as exfiltration to the native soil dominates the water balance (Brattebo and Booth 2003; Bean et al. 2007a). Research has shown that evaporation from these systems is a relatively minor contributor to runoff reduction (Brown and Borst 2015). Collins et al. (2008) showed that the type of permeable pavement was not a major factor to runoff reduction, but that aggregate depth, underlying soil type, and internal water storage in the subgrade were substantial contributors. Even when located over clay soils, permeable pavements treating direct rainfall can result in substantial runoff reduction relative to traditional impermeable asphalt or concrete (Fassman and Blackbourn 2010; Drake et al. 2014; Winston et al. 2018). Permeable pavement has been included in large-scale efforts to reduce runoff at the city block and small urban watershed scales (e.g., Page et al. 2015; Boening-Ulman et al. 2022). Within the last decade, engineering design has pushed the envelope to include systems which treat run-on or stormwater runoff, which is conveyed from impermeable pavements (or rooftops) onto the permeable pavement. Depending on the state or jurisdiction, ratios of 1:1, 2:1, or 5:1 are allowed to be built, and greater ratios have been studied in research projects (Selbig and Buer 2018; Tirpak et al. 2021).

Permeable pavements provide a water quality benefit as pollutants are treated as water passes through the pavement and is stored in the underlying aggregate. Sediment is removed via filtration at the pavement surface and sedimentation in the aggregate subbase (Weiss et al. 2019). Concurrent reductions in heavy metals and sediment-bound nutrients are frequently observed (Fassman and Blackbourn 2011; Roseen et al. 2012; Braswell et al. 2018; Tirpak et al. 2020). However, removal of dissolved pollutants, such as nitrate, chlorides, or orthophosphate is often not achieved (Bean et al. 2007b; Roseen et al. 2012). Water quality performance of permeable pavements may vary seasonally with changes in weather patterns and seasonal use of fertilizers elsewhere in the catchment (Tirpak et al. 2021).

The biggest challenge with permeable pavements after construction is their long-term maintenance. Without maintenance, all BMPs lose their intended function and may become aesthetically unpleasing (Blecken et al. 2017). For permeable pavements, this loss of function occurs as sediment and debris accumulate in the pore spaces (particularly near the pavement surface), causing a loss in surface infiltration rate (SIR), i.e., how quickly water percolates through the permeable pavement surface (Bean et al. 2007a; Drake and Bradford 2013; Al-Rubaei et al. 2013; Winston et al. 2016a; Razzaghmanesh and Beecham 2018; Simpson et al. 2021; Nguyen et al. 2022). Fine sediment particularly exacerbates the rate of clogging (Haselbach 2010) as it then traps larger particles. This clogging ultimately results in a greater fraction of (untreated) surface runoff; that is, as clogging worsens, the pavement begins to function more and more like an impermeable pavement (Winston et al. 2018). Thus, maintenance must be planned and undertaken to ensure that these systems retain the capacity to infiltrate runoff and thus provide an adequate level of service.

This report documents maintenance implications of permeable pavement, based on an installation's design and operation. Topics include the processes by which permeable pavements clog and its causes, methods to measure the SIR, and guidance on the types and frequency of maintenance to support long-term management of stormwater runoff. A literature review is coupled with professional experience of the authors and industry best practice to support the recommendations herein.

2. Routine and Restorative Maintenance

Maintenance practices for permeable pavement run the gamut from simple techniques to remove loose debris to full restoration aimed at removing deeply entrained clogging layers. Routine maintenance practices are designed to remove larger sediment and debris that accumulate near the pavement surface before it decomposes into smaller, more restrictive particles. Examples of routine maintenance include good housekeeping practices, mechanical street sweepers, regenerative air street sweepers, and pressure washing. Routine maintenance should be conducted more frequently to extend the intervals between restorative maintenance.

Restorative maintenance practices are meant to remove a substantial clogging layer that has formed near the surface of the pavement, substantially inhibiting the SIR. As larger particles build up at the pavement surface, smaller particles are also filtered out, resulting in substantial slowing of SIR. Restorative maintenance is typically aimed at removing a clogging layer up to 1 inch deep. Restorative maintenance techniques include milling, vacuum street sweepers, and industry-specific equipment that apply a combination of vacuuming and pressure washing. Details describing specific maintenance techniques are discussed in Section 4.0.

3. Clogging Stimuli, Measurement of Surface Infiltration Rate, and Planning for Maintenance

3.1. Clogging stimuli

Permeable pavements can be installed in a variety of settings, from parking lots to roads to ultra-urban, downtown locations. Each of these settings induce different stimuli for clogging that affect maintenance frequency and difficulty. These stimuli are important to consider during the planning and design phase to estimate the total life cycle cost, particularly with respect to the implications for frequency of routine and restorative maintenance. Research has found that factors which affect permeable pavement SIR include: pavement type, slope, surface use (driveway, road, parking lot, etc.), age, vegetation overhang, proximity to unstable catchments or exposed soils (Fassman and Blackbourn 2010), and saturation during extended rainfall (Boogard et al. 2014; Nguyen et al. 2022).

In order to test for the effects of clogging stimuli on SIR, data were collected by the Winston research group on four permeable pavements in Northeast Ohio (Figure 2). Five to seven locations at each permeable pavement were selected based on potential clogging stimuli for repeat testing of SIR. Measurement of SIR was made in duplicate at these locations at an initial time point ("init") and a final time point three months later. Control locations were permeable pavements without clogging stimuli present, while the locations with stimuli tested were the permeable / impermeable interface (PII; Figure 3), locations beneath trees, locations receiving concentrated flow, locations draining pervious areas, and entries into parking lots (Figure 4). Over the three-month period, the SIRs of the control locations did not significantly decline; conversely, significant loss in SIR was noted for locations near the PII, under trees, receiving concentrated flow, and with nearby pervious areas. These data suggest that clogging is spatially varied within a permeable pavement application and that maintenance needs are not homogenous from application to application. The findings concur with Drake and Bradford (2013), that post-maintenance SIRs vary spatially due to localized conditions within a given permeable pavement.

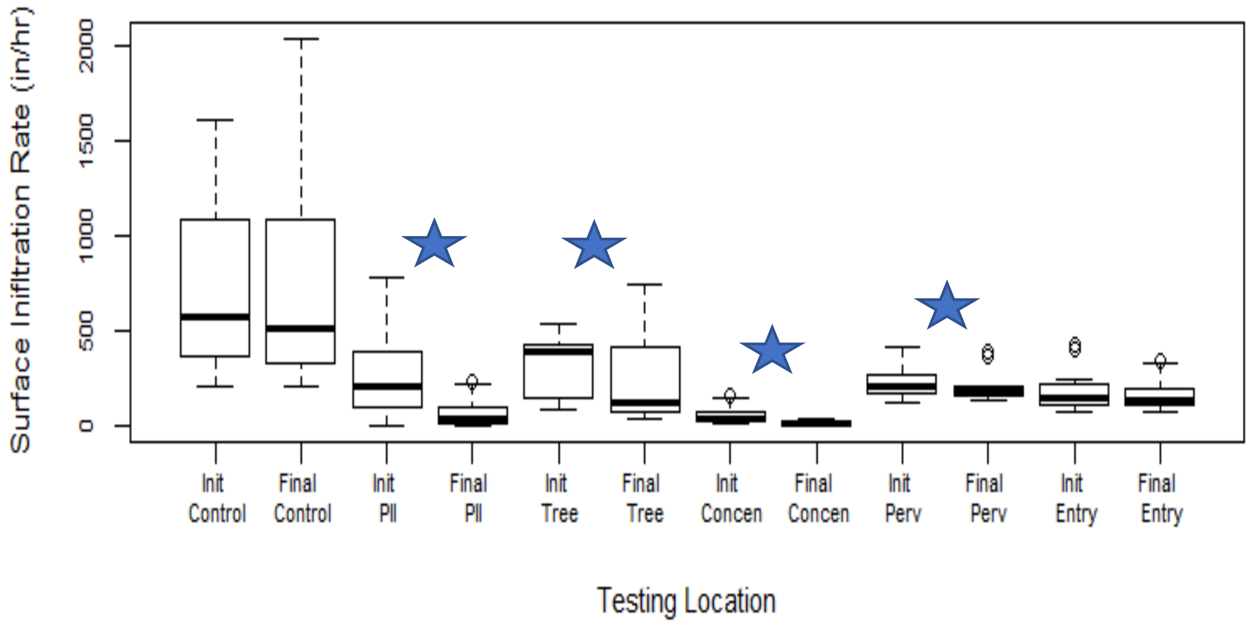

Figure 2. Surface infiltration rate as a function of clogging stimuli (Winston, unpublished data). Initial data were collected 3 months prior to final data. Control locations are those without clogging stimuli, PII is the permeable / impermeable interface, concen is concentrated flow, perv is pervious areas draining to the pavement, and entry is an entryway into a parking lot. Stars show statistically significant loss of surface infiltration rate. Dark horizontal lines within each boxplot indicate the median value.

Figure 3. The permeable / impermeable interface (PII) with several photos of clogging at these locations.

Figure 4. Clogging stimuli tested at permeable pavement sites in Ohio.

Unstable catchments describe areas with exposed soils which may exacerbate airborne deposition and run-on particulate concentrations, accelerating clogging in permeable pavements. The effects of an unstable catchment are reflected in the SIR at a PICP installation at the North Shore Events Centre parking lot in Auckland, New Zealand (Figure 5) (Fassman and Blackbourn 2010). The SIR measured in the end of the parking lot nearest to a builder's yard with exposed stockpiles of building materials was 21 in/hr, compared to measurements of 106-303 in/hr elsewhere. Construction areas pose substantial risk of sediment tracking and deposition. A qualitative example from Seattle, WA is presented in Figure 6, where pervious concrete sidewalks were installed in an early stage of constructing a residential neighborhood. Poorly covered stockpiles and poorly maintained erosion and sediment controls failed to protect the pervious pavement from exposure (Figure 6a), despite attempts at a dual-layer of protection (Figure 6b). If permeable pavement is installed as part of a larger construction project, it should be installed during the final phase of the construction to minimize the potential for clogging before the system comes online.

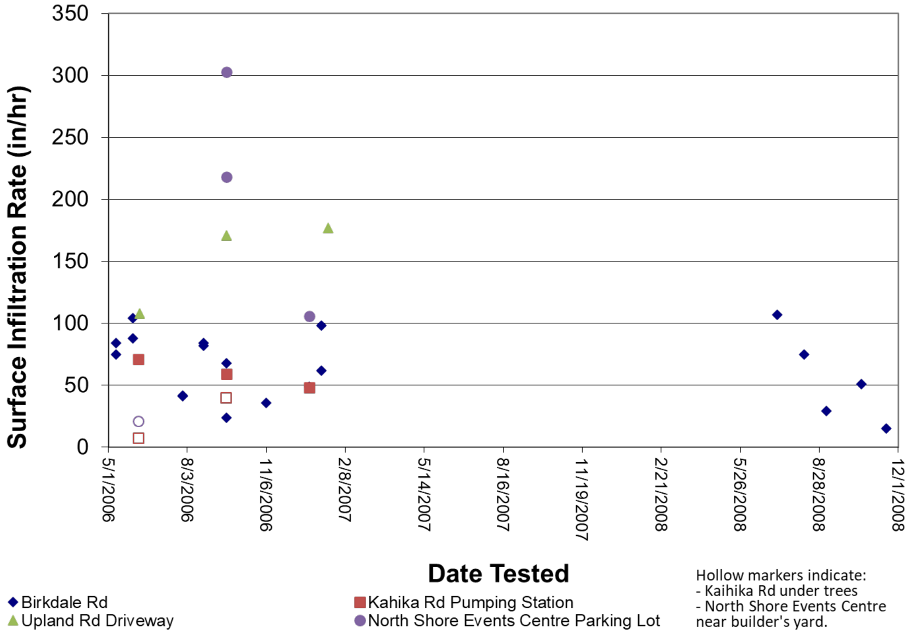

Figure 5. SIR measured at 4 PICP installations in Auckland, New Zealand. The Birkdale Rd. PICP surface was removed and relaid in early 2008. Source: Adapted from Fassman and Blackbourn 2010.

(a)  (b) 

Figure 6. Pervious concrete sidewalks in Seattle in 2008; (a) at high risk of clogging due to adjacent sediment stockpile and poor erosion and sediment controls; (b) attempts to protect pervious concrete during construction by wrapping in HDPE and geotextile secured with sand bags.

The run-on ratio (i.e., ratio of impermeable pavement surface area draining to permeable pavement surface area) is a critically important factor to discerning how fast a permeable pavement will clog. The run-on ratio should be minimized in the design phase. Run-on to permeable pavements will have total suspended solids (TSS) concentrations of 50-250 mg/L (i.e., typical of urban runoff), and this sediment will clog the pore spaces. Many states restrict the maximum run-on ratio to 2:1 (North Carolina, Ohio) or 5:1 (Wisconsin) to reduce clogging potential (OEPA 2014; WDNR 2021). When only treating direct rainfall, permeable pavements can sustain high enough SIR to infiltrate most of the water on an annual basis (Figure 7). At a very high run-on ratio (e.g., 27:1; Figure 7 at right), surface runoff becomes significant as clogging occurs in the permeable pavement quickly (Tirpak et al. 2021). In this study, the permeable pavement was not hydrologically different from an impermeable asphalt due to the quick clogging of the pavement surface and lack of maintenance causing surface runoff to dominate the water balance. The run-on ratio is the best predictor of permeable pavement maintenance interval as it is directly related to sediment contribution and therefore to clogging.

The run-on ratio dictates the rate of SIR decline. SIR decline has been shown to occur exponentially with time (Figure 7, note log scales on y-axes). These results have been corroborated across a range of permeable pavement types by Razzaghmanesh and Beecham (2018) Nguyen et al. (2022).

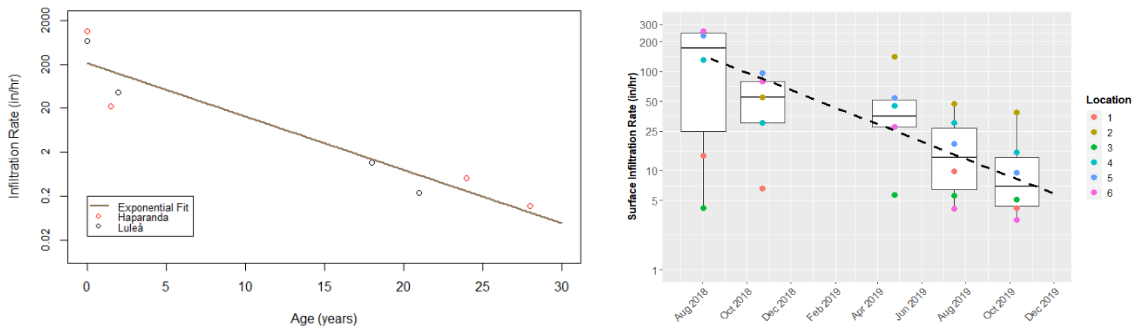

Figure 7. Decay in surface infiltration rate for permeable pavements without any maintenance treating only direct rainfall in northern Sweden (at left; Winston et al. 2016b) and with a 27:1 run-on ratio in Reynoldsburg, Ohio (at right; Tirpak et al. 2021).

Recently, the Winston research group has been testing the SIR of permeable pavements located in residential streets. Two permeable pavement roads in Columbus, Ohio, were compared against data from parking lots in Columbus and Cleveland. The roads are (1) a secondary residential road and (2) a residential cul-de-sac. Permeable pavement roads appeared to clog more quickly than those located in parking lots, perhaps due to greater average daily traffic and greater traffic speed. Higher vehicular speed is thought to cause greater vibration of the pavement, causing sediment to migrate deeper into the pavement cross-section than in parking lot applications (Simpson et al. 2021). These data again demonstrate that SIR, and maintenance need, is spatially varied.

Catchment indicators provide practical considerations for developing maintenance regimes. The proportion of the total permeable pavement area that is impacted by each clogging stimuli described above and perhaps other novel, local stimuli should be considered in addition to SIR when determining maintenance frequency. If the entire permeable pavement area is under large deciduous trees, for instance, then maintenance will need to be more frequent than a site treating only direct rainfall with no stimuli for clogging. There may be “sacrificial” areas within a permeable pavement application that clog very quickly but act as a buffer for the rest of the system. SIR may be difficult to completely restore in these areas, but the hydraulic function of the whole permeable pavement may be supported. A rule of thumb is that 90% of the permeable pavement should have acceptable infiltration rates following maintenance.

3.2. Measurement of surface infiltration rate (SIR)

Visiting a permeable pavement during a rain event is one of the simplest ways to determine if restorative maintenance is needed. Surface ponding visible over a substantial portion of the permeable pavement during or after a rain event indicates substantial clogging and that restorative maintenance is needed. Another simple "bucket test" begins with dumping a 5-gallon bucket of water onto the permeable pavement surface. Restorative maintenance is needed if the water runs downslope creating a surface plume (Figure 8, right), rather than percolating through the pavement (Figure 8, left).

Figure 8. Examples of a successful (left; note infiltration at point of water application) and a failed bucket test (right; note runoff plume).

Two typical methods are employed to quantify SIR. ASTM C1701/C1781, which is a single ring, constant head infiltration test (Figure 9; ASTM 2017; ASTM 2021), involves pouring 40 lbs of water through a 12-inch diameter ring affixed to the pavement surface with plumber's putty. A constant head of 0.4-0.6 inches must be ensured. The time for water to infiltrate is measured and converted to an SIR. Some drawbacks of ASTM C1701/C1781 include: (1) 12-inch ring is not easily obtained, (2) the constant head is difficult to achieve in very high infiltration rate conditions, (3) the ring encircles a relatively small surface area, and (4) this test can take > 30 minutes to perform in heavily clogged locations.

The Simple Infiltration Test (SIT) employs a wooden two-by-four cut into four equal lengths and screwed together to make a square infiltrometer (Figure 9; Winston et al. 2016a). The infiltrometer is affixed to the pavement surface using plumber's putty. Five gallons of water are quickly poured into the square to perform a falling head infiltration test. The time for the water to infiltrate is recorded and SIR is calculated. This square infiltrometer has a > 3 times larger surface area than the ASTM C1701/1781 methodology, providing an SIR representative of a larger area and a much quicker test duration (generally < 10 minutes). If the SIT test takes < 1 minute to run, the pavement is performing as intended and routine maintenance should be continued. At > 1 minute duration, restorative maintenance should be scheduled.

Figure 9. ASTM C1701 standard (left) and Simple Infiltration Test (right) SIR measurement methodologies.

SIR should be measured at multiple locations on a contiguous permeable pavement to develop an average condition for the facility. It is important that these measurement locations represent the various stimuli for clogging on a site while also capturing locations without clogging stimuli (if applicable). At minimum, 3 tests should be run for a < 1/4-acre site, with additional tests for larger facilities. This value can then be compared against thresholds for restorative maintenance discussed in the following section.

3.3. Estimating frequency of routine maintenance

Routine maintenance should be performed to remove accumulated debris from the upper inch of the permeable pavement section (Gerrits and James 2002; Bean et al. 2007a). Maintenance frequency can be established by considering the stimuli for clogging for a particular permeable pavement. For permeable pavement parking lots treating run-on, routine maintenance is recommended at the intervals in Figure 10. The recommendations are based on collection of SIR data from more than a dozen permeable pavements with a variety of run-on ratios; note that maintenance frequency increases non-linearly with run-on ratio. For sites with overhanging trees or for permeable roads, routine maintenance frequency may need to be twice that in Figure 10. For sites without run-on, routine maintenance frequency may be 2-5 times less than that in Figure 10. For each permeable pavement, measurement of SIR in the first year following construction can help to determine the rate of decline in SIR, thereby allowing for a better determination of routine maintenance frequency needs.

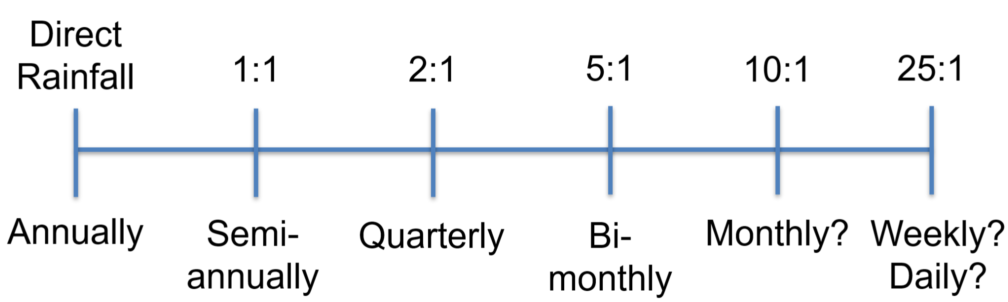

Figure 10. Recommended routine maintenance intervals as a function of run-on ratio.

3.4. Guidance on minimum acceptable surface infiltration rate

Initial permeable pavement SIR should be very high immediately following construction, such as at least 200 in/hr, but studies have reported > 1,000 in/hr (Al-Rubaei et al. 2013). If the initial SIR is too low, the thresholds for maintenance provided below will be frustratingly difficult to achieve. Post-construction SIR testing should be performed before project sign-off and minimum post-construction SIRs enforced. Neither routine nor restorative maintenance can correct construction defects inhibiting SIR.

Threshold SIR should be established to ensure proper routine and restorative maintenance of permeable pavements. Once the average SIR has been determined from multiple locations representing where clogging stimuli are and are not present, this value should be compared against thresholds for (1) permeable pavements with run-on and (2) permeable pavements without run-on. For the former case, and assuming the run-on occurs as dispersed sheet flow, a minimum recommended SIR of 100 in/hr should be targeted since these pavements clog more quickly, and run-on has velocity, meaning that it takes more contact time for it to infiltrate compared to permeable pavements managing only direct rainfall. For sites treating only direct rainfall, a minimum SIR of 10 in/hr typically provides for infiltration of all but unusually extreme rainfall intensities. Restorative maintenance is needed if > 80% of the SIRs measured are less than the recommended thresholds.

4. MAINTENANCE TECHNIQUES

4.1. Good Housekeeping

Simple post-construction good housekeeping techniques within the watershed that drains to a permeable pavement can help extend its life and reduce maintenance intervals. For catchments with tree cover, blowing off or sweeping leaves, litter and acorns, particularly in autumn, and grass clippings following mowing reduces organic debris accumulation in the pore spaces. The frequency of vegetation removal depends on the type of vegetative cover. For example, catchments with evergreen versus deciduous trees may require seasonally-different routine maintenance schedules. Street sweeping near outparcels, unstable catchments, and in nearby construction zones to reduce transport of sediment to the permeable pavement is also crucial (see Section 3.1, Figure 5). Keeping parking lot islands well-vegetated, reducing pervious surface run-on, and reducing the presence of "dirty" vehicles (e.g., dump trucks) near permeable pavements will help to slow clogging rates. Educating landscapers working near permeable pavement to keep topsoil and mulch off of the pavement and covering stockpiles during construction (and ensuring the on-going integrity of the covering [Figure 6]) or landscape activities will also help to reduce the maintenance burden. These good housekeeping practices should be employed as part of routine permeable pavement maintenance.

4.2. Street sweepers

Three general categories of street sweepers exist: (1) mechanical, (2) regenerative air, and (3) vacuum truck (Figure 11). Mechanical sweepers utilize the friction from bristles to mobilize debris and sediment into an internal hopper. Regenerative air street sweepers utilize a blower system that blows air down on one side of the truck to lift debris and sediment off the pavement and a suction system on the other side to convey it into the hopper. These two street sweepers are generally used for routine maintenance. The vacuum truck is a large vacuum-only sweeper (often with a boom on the back for catch basin cleanout) that can be used to apply large suction forces to the pavement surface.

Figure 11. Photographs of routine and restorative maintenance techniques for permeable pavements. Cyclone photograph courtesy Bill Selbig (WI USGS). BIRD photograph courtesy: Count of Ventura Public Works.

A heavily clogged permeable pavement in Durham, NC, was maintained using a bristle street sweeper (Figure 12). Following 5 passes over the PICP by the street sweeper, the SIR effectively doubled to 5.7 in/hr from 2.5 in/hr pre-maintenance. As this post-maintenance SIR did not meet the locally established threshold for restorative maintenance (100 in/hr), a regenerative air street sweeper was brought to the site the following day. The regenerative air sweeper made 3 passes over the PICP, resulting in post-maintenance median SIRs of 33.3 in/hr, a roughly 6-fold increase. Since post-maintenance SIRs were still below desirable restorative maintenance levels (100 in/hr), the regenerative air street sweepers are considered only effective as a routine maintenance technology for PICP. Jayakaran et al. (2019) concluded that regenerative air street sweepers provided an excellent preventative maintenance measure.

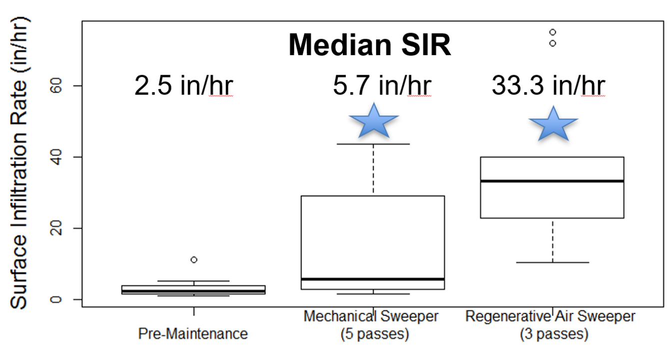

Figure 12. Improvement in surface infiltration rate on a heavily clogged PICP in Durham, NC after mechanical street sweeping and subsequent regenerative air street sweeping.

A vacuum truck was tested for maintenance effectiveness on a PICP in Northeast Ohio; pre-maintenance SIR testing suggested that the pavement needed maintenance after the first year of operation (Figure 13). One pass with a vacuum truck resulted in removal of the upper 1 inch of joint stone and clogging material from the PICP. Following replacement with clean joint stone, median SIRs of approximately 500 in/hr were measured, which were in the range of like-new conditions. One year later, the pavement had again clogged to the point of needing restorative maintenance (Figure 13). Following three passes with the vacuum truck, the pavement again had like new SIRs, suggesting that the vacuum technique can provide reliable restoration of SIR for PICP.

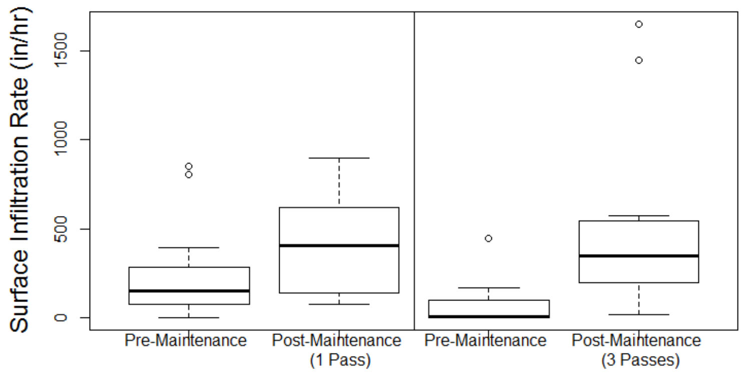

Figure 13. Resulting pre- vs post-maintenance SIRs for a vacuum truck on a PICP parking lot in Ohio. Data collected on the right side of the vertical line were ~1 year after those on the left.

A vacuum truck was tested for side-by-side cleaning of clogged PA, PC, and PICP in Madison, WI (Danz et al. 2020). Differences were observed in restoration of SIR, as average SIR increased by 535% for PICP, decreased by 32% for PC, and increased by 16% for PA. The researchers surmise that pore spaces in PA and PC are fixed in place, and thus extracting clogging particles from these pavements may be more difficult due to the tortuous path they must travel. For PICP, removal of the chip stone in the joints concurrently removes the clogging material, so the authors suggest that restorative maintenance may be easier for these pavements. PICP and PA average post-maintenance SIRs were well above the 100 in/hr threshold, but PC SIR was 58 in/hr. This suggests that a vacuum truck alone on PC may not work for restorative maintenance.

Recent research has shown that street sweeping during or immediately following a rain event reduces the effectiveness of maintenance, presumably due to consolidation of detritus in the pore spaces and the added weight of the water, making it more difficult to remove particulates (Simpson et al. 2021). This finding corroborates that of Baladès et al. (1995) who found that moistening prior to street sweeping often caused reductions rather than improvements in SIR. It is also critical to add chip stone to the joints of PICP following restorative maintenance as future maintenance efforts will be less effective as clogging will occur deeper in the pavement section (e.g., regenerative air at Bishop, Dixon, and Dominion in Figure 17).

Recent research has shown that pre-treatment with a power brush or pressure washer loosens the clogging material, making it easier to remove debris from the pavement using follow on regenerative air or vacuum street sweepers (Sehgal et al. 2018). However, this would require more equipment and staff time than the use of a street sweeper alone.

4.3. Vacuuming

Vacuuming of two heavily clogged PA roads was performed for 1 minute using a dustcontrol DC-50 handheld industrial vacuum (Figure 11). In both cases, significant improvements in surface infiltration rate were observed post-maintenance (Figure 14). However, post-maintenance SIR remained quite low (e.g., less than 5 in/hr for both roads). Thus, post-maintenance SIRs suggest that handheld vacuuming (with a shopvac or similar) can be useful to remove large debris (e.g., mulch particles that were accidentally stored on the permeable pavement) but not to dislodge debris from a clogged permeable pavement in need of restorative maintenance.

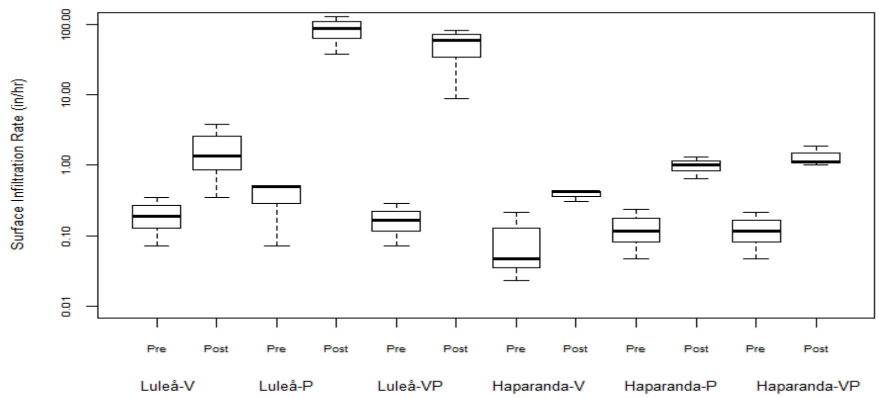

Figure 14. The effects of vacuuming (V), pressure washing (P), and vacuuming plus pressure washing (VP) on surface infiltration rate of PA pavements in Sweden (Winston et al. 2016b).

4.4. Pressure washing

Handheld pressure washing has been tested on PA, PC, and PICP (Figure 11). Hu et al. (2020) note that pressure washing works to rejuvenate PC SIR, but that the ability to fully restore the SIR with this maintenance technique declined over time. Two heavily clogged PA roads in northern Sweden (Figure 14) along with a heavily clogged PICP in Reynoldsburg, Ohio (Figure 17) were used to test pressure washing as a maintenance measure. Significant improvements in average SIR were observed for the PA roads, but post-maintenance SIRs were highly varied between individual testing locations (i.e., ~1 and ~100 in/hr). Pressure washing also resulted in a substantial increase in median surface infiltration rate for PICP (~50 in/hr post-maintenance), but none of these trials produced post-maintenance SIRs greater than the 100 in/hr restorative maintenance threshold. Thus, handheld pressure washing can be used for spot routine maintenance (for instance in the case of mulch or soil being accidentally stored on a permeable pavement), but is not appropriate as a sole technique.

Pressure washing and handheld vacuuming were also tested as a combined treatment on PA roads (Figure 14). The combined effect of these treatments was no better than pressure washing alone, suggesting that pressure washing was providing much of the improvement in SIR. It should be noted that the vacuum was a handheld industrial vacuum (Dustcontrol DC-50), which is substantially less powerful than the truck-mounted vacuums discussed elsewhere in this document.

4.5. Milling

Surface infiltration rate data were collected on a nearly 30-year-old PA pavement in northern Sweden (Winston et al. 2016b). The PA had received no maintenance and was regularly sanded during the winter for traction control. Pre-maintenance SIRs were < 0.5 in/hr. Three depths of milling were applied to the pavement: (1) 0.2 in, (2) 0.6 in, and (3) 1 in (Figure 15). Results showed that milling to a 0.2-in depth resulted in restoration of SIR to 168 in/hr, suggesting that most of the clogging material had accumulated in the upper pore space. Milling to a 1-inch depth resulted in an SIR of 574 in/hr, which was within the range of the initial surface infiltration rate of 685 in/hr measured nearly 30 years earlier. These data support the idea that the majority of the clogging material accumulates in the upper 1 in of the permeable pavement section.

One practical challenge with milling PA or PC as a long-term maintenance solution is that it causes the final grade of the pavement to decrease. A new course of PA or PC would need to be applied to the existing pavement to bring the final pavement grade in line with gutters, manhole covers, and other structures. Thus, this maintenance technique is likely expensive to perform at scale.

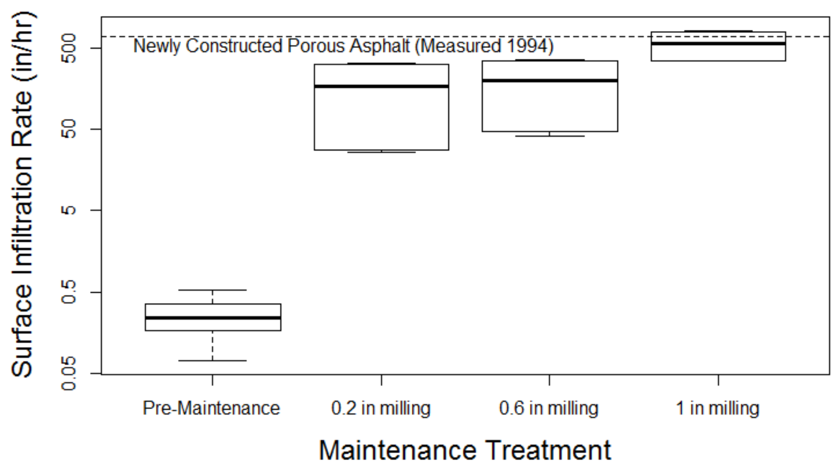

Figure 15. Surface infiltration rate as a function of milling depth for PA pavements.

4.6. Industry-specific equipment

4.6.1. The BIRD

The Bunyan Infiltration Restoration Device (BIRD) is a specialized attachment for a vactor truck that can be used for restorative maintenance of permeable pavements. It combines the suction provided by the vactor truck with 15 rotating, high pressure water nozzles. The vacuum hood is a walk-behind unit with spray nozzles in it, which can maintain a 42-inch wide swath of permeable pavement. This is the typical maintenance practice currently contracted by the County of Ventura for restorative maintenance of their PC pavements at the County Government Center (CGC) and a residential section of the El Rio neighborhood.

Data provided by the County of Ventura were used to compare pre- and post-maintenance SIR of pervious concrete (Figure 16). During most seasons at CGC and all seasons at El Rio, pre-maintenance SIRs were below the restorative maintenance threshold of 100 in/hr. All maintenance trials of the BIRD were successful in improving median infiltration rate, with median SIRs at or exceeding the 100 in/hr threshold. The smallest incremental improvement (i.e., CGC in the fall) was for pavements that were already functioning above the threshold for restorative maintenance. Overall, the BIRD technology appears to successfully improve the hydraulic function of the PCs.

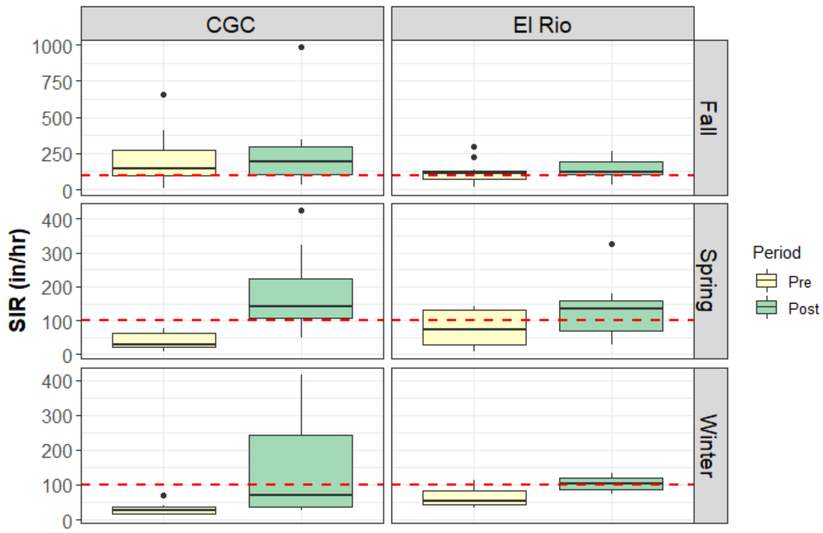

Figure 16. Pre- and post-maintenance surface infiltration rate for the BIRD maintenance device by season and across two sets of permeable pavement applications in Ventura, CA. Red dashed lines represent the threshold for restorative maintenance for permeable pavements with run-on (100 in/hr).

4.6.2. Machine Cleaning Vehicle

The Machine Cleaning Vehicle (MCV) is a purpose-built permeable pavement maintenance system constructed on a Bobcat Toolcat 5600, resulting in a self-contained vehicle (Figure 11). It has a cleaning apparatus on the front that includes rotating high-pressure nozzles (3200 psi) along with a vacuum component to remove the resulting slurry from the pavement surface (Simpson et al. 2021). The MCV was operated on three PICP installations in the same neighborhood of Columbus, Ohio, at a speed of 8 mph (Figure 17). At all three permeable pavements, SIR significantly improved following maintenance, but two of three cases did not result in post-maintenance SIRs greater than the 100 in/hr restorative maintenance threshold. The three PICP systems had not been maintained regularly; coupled with loss of joint chip over time, it is likely that clogging was deep in the pavement joints, limiting the potential for full SIR restoration. Regenerative air street sweepers were also tested at these three permeable pavements. The MCV clearly performed better in all three cases, supporting the case for the use of combined pressure washing and suction for permeable pavement maintenance.

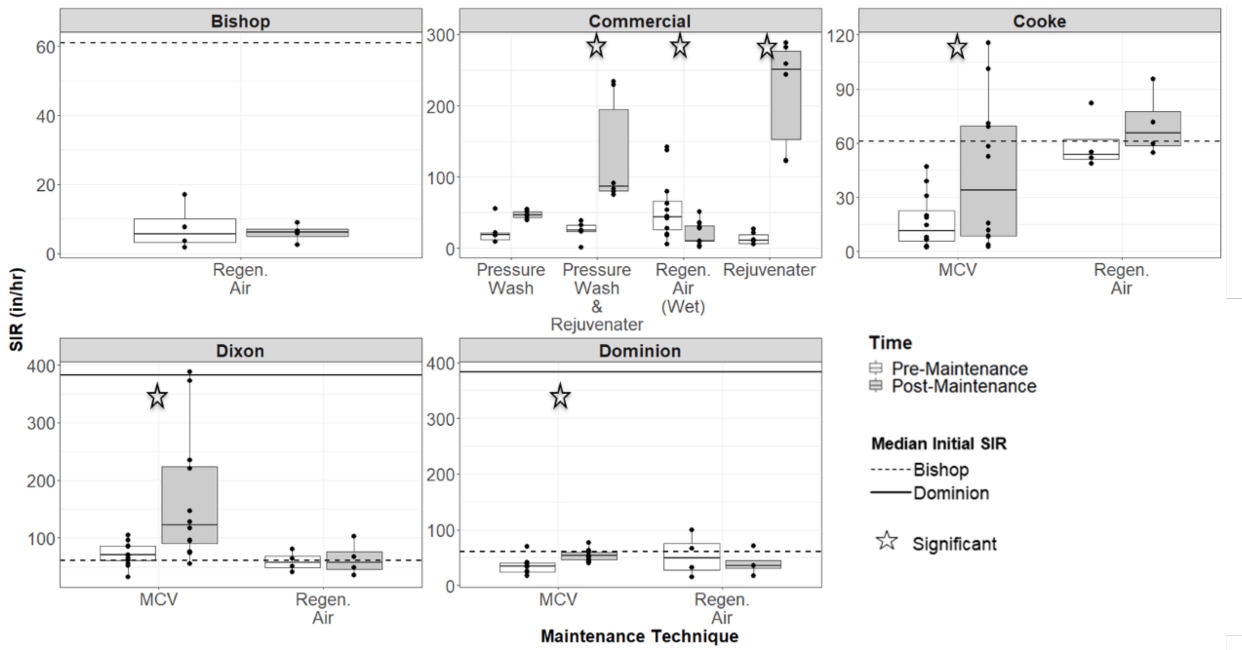

Figure 17. Evaluation of various maintenance techniques for PICP maintenance (Simpson et al. 2021). Starred values are significant differences between pre- and post-maintenance.

4.6.3. Rejuvenator

The Rejuvenator is a walk-behind street cleaning apparatus that was tested on a heavily clogged PICP system with a 27:1 run-on ratio in Reynoldsburg, Ohio (Figure 11). It consists of a 2 ft wide deck with rotating nozzles (3200 psi) and a 6-inch diameter suction hose affixed to a Tymco regenerative air street sweeper. This device was tested alone and in conjunction with preceding hand-held pressure washing. Both techniques produced significant improvement in PICP SIR and resulted in median SIRs at or substantially above the 100 in/hr restorative maintenance threshold (Figure 17). These treatments produced substantially better post-maintenance SIRs than pressure washing alone, which resulted in a median SIR of approximately 50 in/hr. These results again support the use of combined high pressure washing with vacuuming as the best currently available combination of restorative maintenance tools for permeable pavements (Chopra et al. 2010; Kazemi et al. 2017).

4.6.4. Cyclone

Cyclone machines apply high pressure water to the pavement surface and simultaneously recover water and debris into a hopper. These machines were originally developed to take rubber off of airport runways, and so they also heat the water to 160°F before applying it to the pavement surface (Danz et al. 2020). The heated water is applied to the pavement surface with rotating nozzles at 4,300 psi. The technique was evaluated at a test site in Wisconsin and increased the SIR of PICP and PC by 172% and 92%, respectively (Danz et al. 2020).

4.6.5. TYPHOON and PAVEVAC

Side-by-side PA, PC, and PICP systems were maintained with two technologies: (1) the TYPHOON and (2) the PAVEVAC (Danz et al. 2020). The TYPHOON was intended to excavate clogging material from the pavements using compressed air. The PAVEVAC is a high lift vacuum which removes the debris from the pavement. The combination of these technologies resulted in 1,703% increase in average SIR for PICP, 169% increase for PC, and 40% increase for PA. All average post-maintenance SIRs exceeded the target of 100 in/hr.

4.7. Post-Maintenance Recommendations

It is critical to refill PICP chip stone in the joints between the pavers following restorative maintenance. Restorative maintenance practice typically removes the upper inch of the join chip stone. If not replaced, an air gap at the surface of the pavement is created, allowing the clogging material to accumulate deeply within the pavement surface, compromising the effectiveness of future restorative maintenance efforts (Simpson et al. 2021). Loss of joint chip stone may also cause pavers to shift, compromising the structural integrity of the permeable pavement (Fassman and Blackbourn 2010). In small permeable pavement applications, joint stone can be added manually using a push broom. A skid steer with a broom attachment may be used to sweep new stone into the PICP joints for larger applications.

Post-maintenance SIR testing should be conducted in many locations across a site to quickly ascertain whether restorative maintenance was successful. At minimum, three tests should be run for a < 1/4-acre site, with additional tests for larger facilities, noting that several studies reported significant spatial heterogeneity (see section 3.2). If SIR testing shows that restorative maintenance was not successful, supplemental passes are recommended with increased vacuum strength.

A schedule for routine maintenance should be implemented immediately following restorative maintenance, to prolong the interval before the more resource-intensive restorative activities are necessary.

5. Summary Recommendations

Permeable pavement is a type of stormwater best management practice (BMP) that functions by enabling rainfall and runoff to percolate through a pavement surface to minimize or eliminate stormwater runoff. Permeable pavement offers runoff water quality and quantity management benefit and does not occupy additional valuable urban land space as it serves a dual function for parking, driving, and pedestrian activities. Maintenance is needed periodically to remove sediment and debris carried in stormwater runoff, and organic materials deposited from landscape elements that otherwise reduce the permeable pavement surface infiltration rate (SIR), compromising its ability to manage stormwater. This report summarizes research and best practices to support siting and design considerations for permeable pavements to minimize future maintenance needs, explains how catchment conditions influence maintenance regimes, how to measure and track where maintenance is needed, and how to perform routine and restorative maintenance. This guidance is widely applicable across Southern California and beyond, although it does not consider snow- and freeze-thaw-related considerations.

Research demonstrates that the primary factors influencing the maintenance requirements include (Section 3.0): run-on ratio, pavement type, slope, surface use (driveway, road, parking lot, etc.), age, vegetation overhang, and proximity to unstable catchments or exposed soils. Elements such as the run-on ratio, pavement type, slope, and surface use may be controlled or considered in the siting and design phase. Several studies conclude that increasing the run-on ratio (the ratio of supplemental impervious surface area creating run-on to permeable pavement surface area) has the most deleterious impact on a permeable pavement's SIR. The largest best practice recommended run-on ratio currently in jurisdictional design manuals in the USA is 5:1 (WDNR 2021). Run-on from supplemental drainage areas should be designed to sheet flow over large pervious pavement areas, e.g., curb-to-curb installations, or entire rows of parking spaces. Even where localized clogging occurs, dispersed sheet flow supports the ability for run-on to find alternative open pores or pathways to the subsurface. Conversely, the horizontal velocity and depth of concentrated flows may overwhelm the surface infiltration capacity of even well-functioning and maintained permeable pavements.

Planning for the type and frequency of maintenance required to sustain the SIR includes consideration of conditions across the catchment. More frequent local or spot maintenance is typically required at the interface of impervious and pervious pavements (i.e., where the run-on area meets the edge of permeable pavement), under areas with overhanging vegetation (which may also be avoided in the design phase in some circumstances), near landscaped areas, and if/when unstable catchments or exposed soils are in proximity to the permeable pavement (aerial deposition can be significant). If or when a permeable pavement prematurely clogs, inspection of conditions outside the immediate vicinity of the installation is warranted to determine the cause and identify remedial or protective action. For example, construction activity or exposed soils anywhere in the catchment warrants supplemental protection for the permeable pavement.

Post-installation SIR testing should be performed on newly installed permeable pavements to ensure that acceptable ranges of SIR are met (Section 3.2). ASTM C1701 provides a standard method for testing SIR, while an alternative Simple Infiltration Test (SIT) can provide a measurement using less time or water (Section 3.2). At a minimum, three tests should be run for a < 1/4-acre site, with additional tests for larger permeable pavements. If the target SIR is not met, newly installed products should be rejected, and the contractor should be encouraged to meet the SIR specification to ensure a more maintainable final product. Neither routine nor restorative maintenance can correct construction defects in SIR.

Once constructed, maintenance practices for permeable pavement run the gamut from simple techniques to remove loose debris to full restoration aimed at removing deeply entrained clogging layers. Routine maintenance practices are designed to remove larger sediment and debris that accumulate near the pavement surface before it decomposes into smaller, more restrictive particles. Examples of routine maintenance (Section 4.0) include good housekeeping practices, mechanical street sweepers, regenerative air street sweepers, and pressure washing. Routine maintenance should be conducted more frequently to extend the intervals between restorative maintenance.

Restorative maintenance practices are meant to remove a thick clogging layer that has formed near the surface of the pavement, substantially inhibiting the SIR. As larger particles build up at the pavement surface, smaller and smaller particles are also filtered out, resulting in substantial slowing of SIR. Restorative maintenance is typically aimed at removing a clogging layer up to 1-inch deep. Restorative maintenance techniques include milling, vacuum street sweepers, and industry specific equipment that apply a combination of vacuuming and pressure washing. Different equipment types may be more or less successful for maintaining different types or conditions of permeable pavements (Section 4.6).

6. References

Al-Rubaei, A.M., Stenglein, A.L., Viklander, M., and Blecken, G.T. 2013. Long-term hydraulic performance of porous asphalt pavements in northern Sweden. J. Irrig. Drain. Eng. 139, 499-505.

American Society of Civil Engineers. 2015. Permeable Pavements. Eds. Eisenberg, B., Lindow, K.C., and Smith, D.R. Reston, VA.

American Society for Testing and Materials (ASTM). 2017. "Standard test method for infiltration rate of in place pervious concrete." ASTM C1701, West Conshohocken, PA.

American Society for Testing and Materials (ASTM). 2021. "Standard test method for surface infiltration rate of permeable unit pavement systems." ASTM C1781, West Conshohocken, PA.

Baladès, J.D., Legret, M., and Madiec, H. 1995. Permeable pavements: Pollution management tools. *Water Science a*nd Technology. 32, 49–56.

Bean, E.Z., Hunt, W.F., and Bidelspach, D.A. 2007a. Field survey of permeable pavement surface infiltration rates. *Journal of Irrigation and Drainage Engineering*, *133*(3), 249-255.

Bean, E.Z., Hunt, W.F., and Bidelspach, D.A. 2007b. Evaluation of four permeable pavement sites in eastern North Carolina for runoff reduction and water quality impacts. Journal of Irrigation and Drainage Engineering, 133(6), 583-592.

Blecken, G.T., Hunt, W.F., Al-Rubaei, A.M., Viklander, M., and Lord, W.G. 2017. Stormwater control measure (SCM) maintenance considerations to ensure designed functionality. *Urban Water Journal*. 14(3), 278-290.

Boening-Ulman, K.M., Winston, R.J., Wituszynski, D.M., Smith, J.S., Tirpak, R.A., and Martin, J.F. 2022. Hydrologic Impacts of Sewershed-Scale Green Infrastructure Retrofits: Outcomes of a Four-Year Paired Watershed Monitoring Study. *Journal of Hydrology*, 128014.

Boogaard, F., Lucke, T., and Beecham, S. 2014. Effect of age of permeable pavements on their infiltration function. CLEAN–Soil Air Water. 42, 146-152.

Braswell, A.S., Winston, R.J., and Hunt, W.F. 2018. Hydrologic and water quality performance of permeable pavement with internal water storage over a clay soil in Durham, North Carolina. *Journal of Environmental Management*, *224*, 277-287.

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

Brown, R. A., and Borst, M. 2015. Quantifying evaporation in a permeable pavement system. *Hydrological Processes*, 29(9), 2100-2111.

Chopra, M., Kakuturu, S., Ballock, C., Spence, J., and Wanielista, M. 2010. Effect of rejuvenation methods on the infiltration rates of pervious concrete pavements. *Journal of Hydrologic Engineering*. 15(6), 426-433.

Collins, K.A., Hunt, W.F., and Hathaway, J.M. 2008. Hydrologic comparison of four types of permeable pavement and standard asphalt in eastern North Carolina. *Journal of Hydrologic Engineering.* 13, 1146-1157.

Danz, M.E., Selbig, W.R., and Buer, N H. 2020. Assessment of restorative maintenance practices on the infiltration capacity of permeable pavement. *Water*, 12(6), 1563.

Dietz, M.E. 2007. Low impact development practices: A review of current research and recommendations for future directions. *Water Air and Soil Pollution*. 186, 351-363.

Drake, J., and Bradford, A. 2013. Assessing the potential for restoration of surface permeability for permeable pavements through maintenance. *Water Science and Technology*. 68, 1950-1958.

Drake, J., Bradford, A., and Van Seters, T. 2014. Hydrologic performance of three partial-infiltration permeable pavements in a cold climate over low permeability soil. *Journal of Hydrologic Engineering*. 19, 04014016.

Fassman, E.A. and Blackbourn, S. 2011. Runoff Water Quality Mitigation by Permeable Pavement. *Journal of Irrigation and Drainage* 137(11):720-729.

Fassman, E.A. and Blackbourn, S. 2010. Urban runoff mitigation by a permeable pavement system over impermeable soils. *Journal of Hydrologic Engineering*. 15, 475-485.

Gerrits, C., and James, W. 2002. *Restoration of infiltration capacity of permeable pavers*. In: Proc. 9th Int. Conf. Urban Drain. ASCE, Portland, Ore.

Haselbach, L.M. 2010. Potential for clay clogging of pervious concrete under extreme conditions. *Journal of Hydrologic Engineering*. 15, 67-69.

Hu, N., Zhang, J., Xia, S., Han, R., Dai, Z., She, R., Cui, X., and Meng, B. 2020. A field performance evaluation of the periodic maintenance for pervious concrete pavement. *Journal of Cleaner Production*, 263, 121463.

Jayakaran, A. D., Knappenberger, T., Stark, J. D., and Hinman, C. 2019. Remediation of stormwater pollutants by porous asphalt pavement. *Water*, 11(3), 520.

Kazemi, H., Rockaway, T. D., Rivard, J., and Abdollahian, S. 2017. Assessment of surface infiltration performance and maintenance of two permeable pavement systems in Louisville, Kentucky. *Journal of Sustainable Water in the Built Environment*, *3*(4), 04017009.

Nguyen, N., Sultana, A., Areerachakul, N., and Kandasamy, J. 2022. Evaluating the Field Performance of Permeable Concrete Pavers. *Water*, 14(14), 2143.

Ohio Environmental Protection Agency (OEPA), Division of Soil and Water Conservation. 2014. *Rainwater and land development: Ohio's standards for stormwater management, land development, and urban stream protection*. 3rd edition, revised Nov. 6, 2014. Ed: John Mathews.

Page, J.L., Winston, R.J., Mayes, D.B., Perrin, C., and Hunt, W.F. 2015. Hydrologic mitigation of impervious cover in the municipal right-of-way through innovative stormwater control measures. *Journal of Hydrology*. 527, 923-932.

Razzaghmanesh, M., and Beecham, S. 2018. A review of permeable pavement clogging investigations and recommended maintenance regimes. *Water*, 10(3), 337.

Roseen, R.M., Ballestero, T.P., Houle, J.J., Briggs, J.F., and Houle, K.M. 2012. Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. *Journal of Environmental Engineering* 138, 81-89.

Schueler, T.R., Fraley-McNeal, L., and Cappiella, K. 2009. Is impervious cover still important? Review of recent research. *Journal of Hydrologic Engineering*.14, 309-315.

Sehgal, K., Drake, J., Seters, T.V., and Vander Linden, W.K. 2018. Improving restorative maintenance practices for mature permeable interlocking concrete pavements. *Water*, 10(11), 1588.

Selbig, W.R., and Buer, N. 2018. Hydraulic, water-quality, and temperature performance of three types of permeable pavement under high sediment loading conditions (No. 2018-5037). US Geological Survey.

Simpson, I.M., Winston, R.J., and Tirpak, R.A. 2021. Assessing maintenance techniques and in-situ pavement conditions to restore hydraulic function of permeable interlocking concrete pavements. *Journal of Environmental Management*, *294*, 112990.

Tirpak, A., Winston, R.J., Feliciano, M., and Dorsey, J.D. 2020. Stormwater quality performance of permeable interlocking concrete pavement receiving run-on from an asphalt traffic lane in a cold climate. *Environmental Science and Pollution Research*, 27(17), 21716-21732.

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

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., and Morgan, R.P. 2005. The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society*, *24*(3), 706-723.

Weiss, P.T., Kayhanian, M., Gulliver, J.S., and Khazanovich, L. 2019. Permeable pavement in northern North American urban areas: research review and knowledge gaps. *International Journal of Pavement Engineering*, 20(2), 143-162.

Winston, R.J., Al-Rubaei, A.M., Blecken, G.-T., and Hunt, W F. 2016a. A simple infiltration test for determination of permeable pavement maintenance needs. *Journal of Environmental Engineering*. 142(10), 06016005.

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

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

Wisconsin Department of Natural Resources (WDNR). 2021. *Storm water post-construction technical standards: Permeable pavement*. Retrieved from https://dnr.wisconsin.gov/topic/Stormwater/standards/postconst_standards.html