Permeable Pavement Systems
Clean Water Faster and for Less Money

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P4 INFRASTRUCTURE

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April 2, 2021

Introduction

This paper outlines a process that incorporates measured product-level and system-level performance metrics into continuous simulation modeling of permeable pavement systems. It is intended to serve as an example for engineers to follow when designing and analyzing permeable pavement systems in the State of Wisconsin. The goal of this paper is to help get the State of Wisconsin clean water, faster and for less money.

Background

An articulating concrete block (ACB) system was constructed in Spring 2019 at the Van Norman Alley located in Cudahy, Wisconsin. The permeable surface was treated like a piece of storm sewer installed to reduce stormwater runoff downstream. The plan area of the permeable surface was selected as a practical matter considering the potential for heavy and repeated garbage truck traffic traversing the alley on a weekly basis. To minimize potential for rutting, the permeable strip width was limited to 4.1' and centered within the middle of the alley. The 4.1' dimension is four full blocks of an ACB system (PaveDrain™) and fits completely between the garbage truck wheel paths allowing garbage trucks to straddle the permeable surface and apply wheel loads directly to adjacent concrete pavement. Figure 1 shows the alley and the approximate limits of the permeable surface. Figure 2 shows a typical cross-section through the ACB system installed at this site.

Figure 1. Van Norman Alley permeable pavement installation with monitoring system locations.

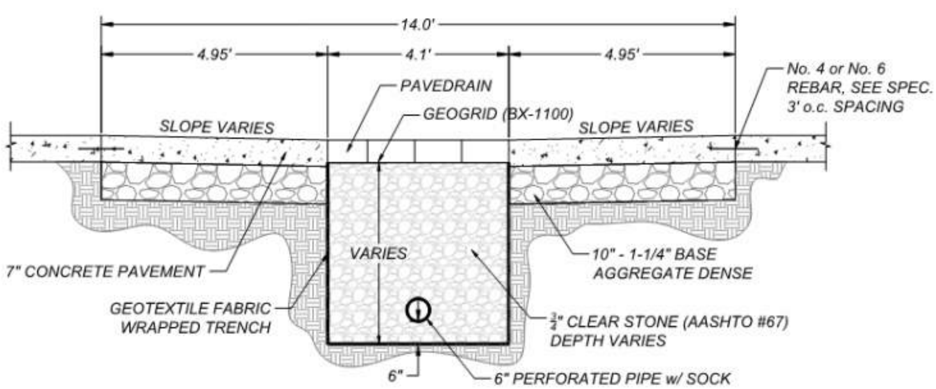


Figure 2. Van Norman Alley permeable pavement cross-section.

Rainfall and water-level monitoring systems were installed at this site in January 2020 and two other locations in the City of Cudahy. A rainfall monitoring system (P4 Rain-mX^{TM}) was installed on the roof of City Hall located on S. Lake Drive (0.7 miles away from Van Norman Alley) and a water-level monitoring system (P4 INFIL-Tracker^{TM}) was installed within the cross-section of the ACB system at the western-most (or low) end of the ACB pavement, near S. Swift Avenue.

The monitoring systems were installed to measure and document the ACB system's performance and response to measured rain events. A control valve and overflow pipe (P4 Flow-RTC^{TM}) were retrofitted onto the underdrain outlet inside the catch basin at S. Swift Avenue in July 2020. It should be noted that Flow-RTC^{TM} has been left closed since its installation and all water entering the ACB system has infiltrated into the ground within the drawdown period of 72 hours after the end of all rain events since July 2020. Figure 3 shows the Rain-mX^{TM}, INFIL-Tracker^{TM} and Flow-RTC^{TM} systems installed at/near this site.

Rain-mX INFIL-Tracker Flow-RTC

Figure 3. Systems for rainfall monitoring, water-level monitoring, and valve control with overflow.

Measured Data

Water levels measured during rainfall events suggest a run-on ratio larger than 5:1 for this site. The INFIL-Tracker^{TM} system allows infiltration rates into the subgrade to be measured and defined for modeling. Figure 4 shows measured rainfall and water-level time histories from January 2020 through March 2021. Figure 5 provides three measured rain events and the corresponding response measured under the pavement.

Measured subgrade infiltration rates can be computed event-by-event in the manner shown in Figure 5. The measured infiltration rate was calculated by computing the slope of a line connecting points located at the maximum water level measured and the point where one inch of water is measured. An average infiltration rate can be computed using several rain events. In this case, the average subgrade infiltration rate computed using the three measured events shown in Figure 5 is 1.34 in/hr.

Run-On Drainage Area

Hydrology for the Van Norman site is driven by its surrounding topography. Figure 6 provides aerial views of the alley, with and without contours, showing the alley and adjacent residential lots draining to the alley. Figure 6 highlights the difference between guidance document-recommended run-on vs. actual, topography-driven run-on drainage areas.

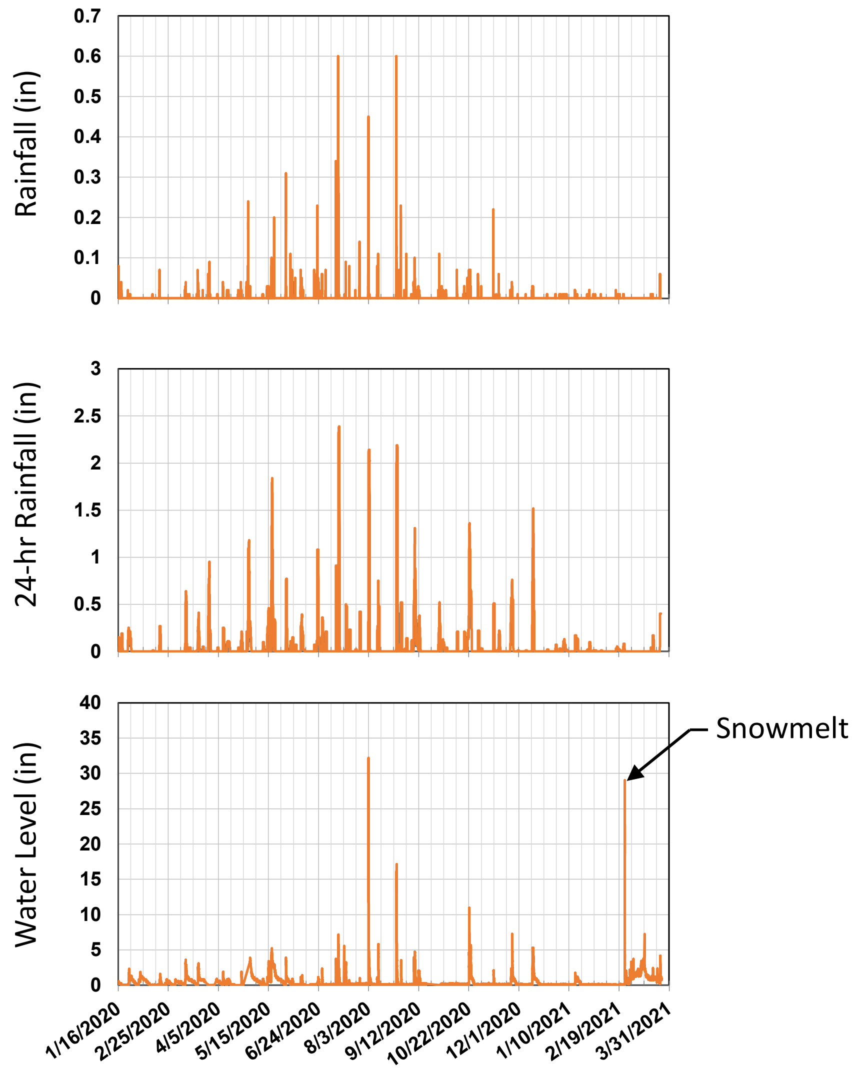


Figure 4. Measured time histories for rainfall and water level under pavement.

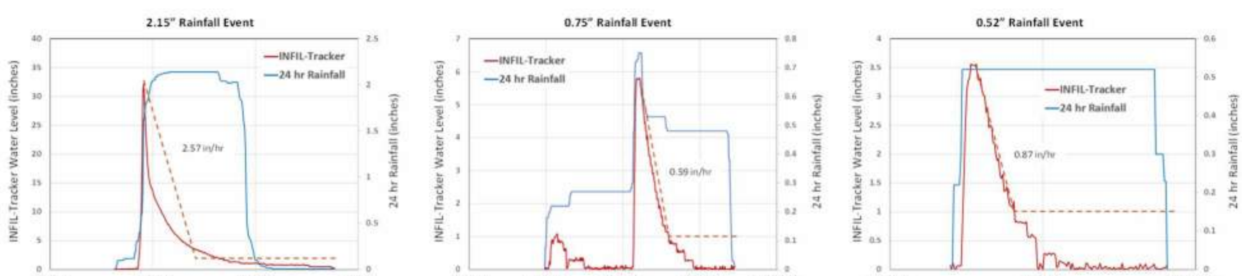


Figure 5. Measured rainfall and water level with corresponding subgrade infiltration rates.

Figure 6. Van Norman Alley and run-on drainage areas.

The tributary drainage area for the Van Norman Alley ACB system is approximately 33 times its permeable surface area, or 33:1 run-on. This is obviously larger than the 5:1 run-on limit established in the current permeable pavement guidance document.

There are a number of interesting observations gleaned from Figures 4-6. The first is that even with very high run-on, the ACB system performs exceedingly well, infiltrating all stormwater runoff being sent its way. The second is that Van Norman's site conditions would have precluded permeable pavement from consideration as a best management practice (BMP) for addressing stormwater runoff in this case. The reason is because the topography-defined drainage width, transverse to the alley, is approximately 135 ft. At 5:1 run-on, this drainage area would require a 27 ft wide permeable surface, assuming the drainage area and permeable area lengths are equal. The alley is only 14 ft wide.

Source Load and Management Modeling – One Year Simulations

Three separate models were built to evaluate the effects of using larger run-on ratios, measured subgrade infiltration rate and valve control with overflow. All three models were built following the current technical guidance, where applicable, and included the following input parameters:

- **Model 1** analyzes the BMP assuming 5:1 run-on ratio, 0.04 in/hr subgrade infiltration rate and a 6" dia. underdrain open and at the bottom of the gallery.
    - Note: 0.04 in/hr subgrade infiltration rate was used because clay subgrade was discovered during the preliminary site evaluation.
- **Model 2** is Model 1 with a 33:1 run-on ratio.
- **Model 3** analyzes the BMP assuming a 33:1 run-on ratio, 1.34 in/hr subgrade infiltration rate and a 6" dia. underdrain at the top of the gallery to simulate Flow-RTC™ valve control and overflow.

The results from one-year simulations using the Milwaukee 1969 rain file are shown in Figure 7. Results from models 2 and 3 highlight the importance of including measured data and the Flow-RTC system when building continuous simulation models in WinSLAMM. 67% more pollutant is removed when the infiltration rate increases from an assumed value of 0.04 in/hr to the INFIL-Tracker measured value of 1.34 in/hr AND the Flow-RTC control system is used.

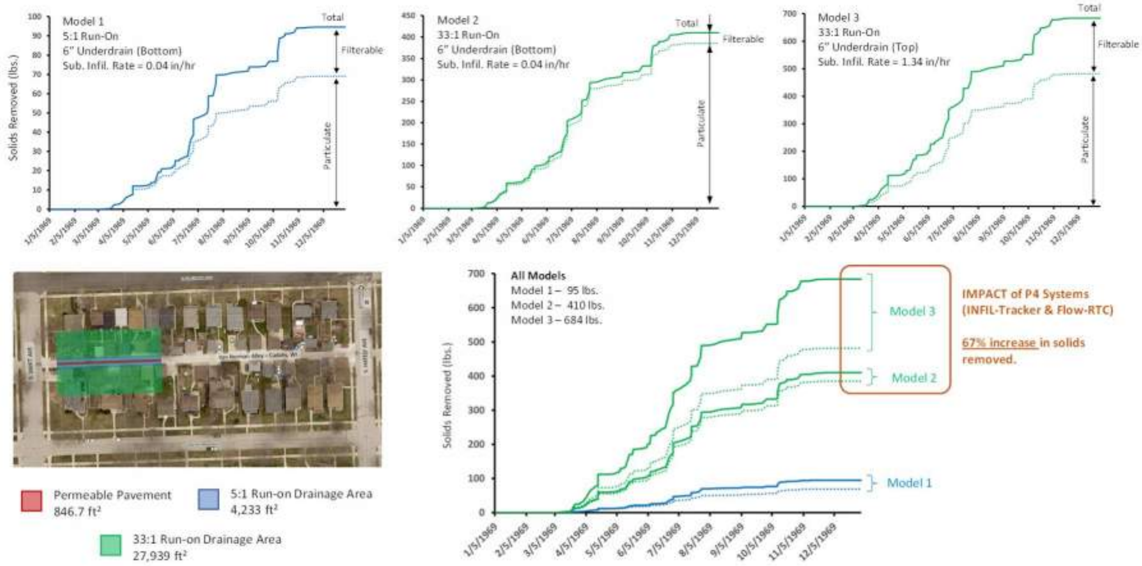


Figure 7. One-Year solids pollutant capture in Van Norman Alley.

After completing the simulations for Models 1-3, three new models were built by simply scaling the drainage and permeable surface areas to reflect a 4.1' wide strip extending the full length of the alley. The drainage and permeable surface areas defined in Models 4, 5 and 6 are effectively 3x larger than those defined in Models 1, 2 and 3, respectively. All other input parameters remained the same. The goal was to estimate the pollutant capturing ability of a typical, repeatable, city block.

Figure 8 provides the pollutant capture results for Models 4-6. The results shown here confirm that the pollutant captured is proportional to the increased run-on and permeable surface areas.

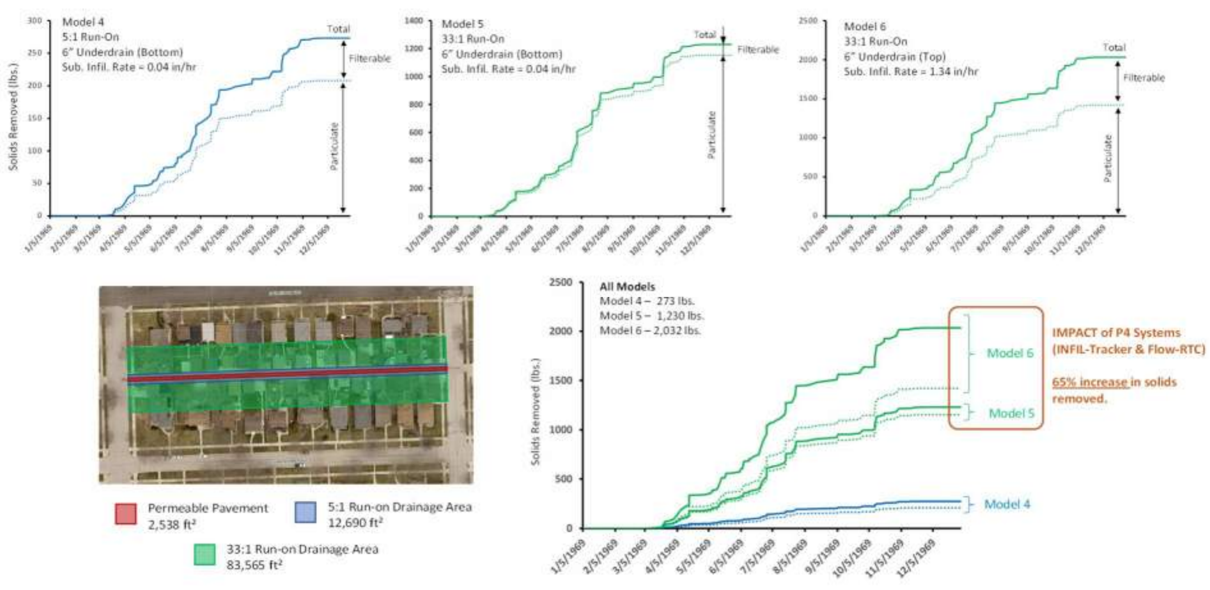


Figure 8. One-Year solids pollutant capture for a typical, repeatable, city block.

It is important to note that Model 4 is what the current technical guidance allows for pollutant capture. ***Incorporating topography-defined run-on area, INFIL-Tracker™ measured subgrade infiltration rate, and the Flow-RTC™ control system with overflow is how engineers can improve an alley like Van Norman Alley from Model 4 to Model 6 performance.***

Source Load and Management Modeling – Twenty Year Simulations

Permeable pavements are typically intended to have 20 or more years of useful service life. Twenty years of service comes with twenty years of clogging potential at the surface and twenty years of sediment accumulation in the gallery. This section looks at the permeable pavement surface infiltration rate, clogging capacities, surface infiltration replenishment after cleaning and sediment accumulation assumed in WinSLAMM.

Surface Clogging

The first year of a twenty-year simulation and the impact of careless clogging capacity definition are shown in Figure 9. In the first six-month interval before maintenance intervention, surface clogging capacity for both systems of 0.06 lbs/sf results in the porous pavement system losing 17.2 in/hr of surface infiltration rate. The ACB system loses 343.4 in/hr of infiltration rate in that same six-month interval. More interestingly is that after maintenance, the next sixth month interval has the porous pavement losing 58 in/hr of surface infiltration rate while the ACB system loses 1,160 in/hr of surface infiltration rate. The reason for this behavior is that the clogging capacity and the initial surface infiltration rate set the stage for surface infiltration loss between maintenance intervals.

The results shown in Figure 9 illustrate that improper definition of surface clogging capacity can result in one system losing infiltration rate at the surface 20 times faster than the other system. ***An ACB system does not lose infiltration rate at the surface 20 times faster than a porous pavement system.*** Its clogging capacity is significantly greater and its replenishment through vacuuming is significantly greater compared to porous pavements. Figure 9 illustrates that the two systems have significantly different infiltration rate losses in the first year if clogging capacity is not consistently defined and this is contrary to physical performance. Source Load and Management Modeling can and must account for these differences to reflect actual system performance while in service. Engineers must be given guidance on the relationship between clogging capacity and initial surface infiltration rate when SLAMM is implemented.

If one were to assume that the infiltration rate lost in between maintenance interventions in SLAMM is the same for both systems, clogging capacities for the systems must, therefore, be different. Figure 10 shows results from an analysis where the ACB system is assumed to have a clogging capacity 20 times greater than a porous pavement system. It is interesting to note that the infiltration rate at the surface lost in each 6-month interval between maintenance is now the same in each six-month interval.

Defining the clogging capacity more accurately for ACB systems is very important because the actual infiltration loss rate has, to this point, not been measured in the field. ***However, in-service performance of ACB systems suggests that it is unreasonable to assume that an ACB system will lose surface infiltration rate 20 times faster than a porous pavement system.*** One could argue that keeping surface infiltration loss rates the same for all porous pavement systems in SLAMM is a conservative approach.

Figure 10 illustrates the impact of increasing clogging capacity such that both systems clog at the same rate. Surface infiltration rate loss in each interval between maintenance interventions is now equal. This is done by changing the surface clogging capacity to 1.2 lbs/sf for the ACB system. Physically, this means that it will take 1.2 lbs of material to clog one square foot of ACB surface at the same time 0.06 lbs of material will clog one square foot of porous pavement surface. This modeling assumption is consistent with the significant size difference in joint vs. surface porosity AND resulting initial surface infiltration rate.

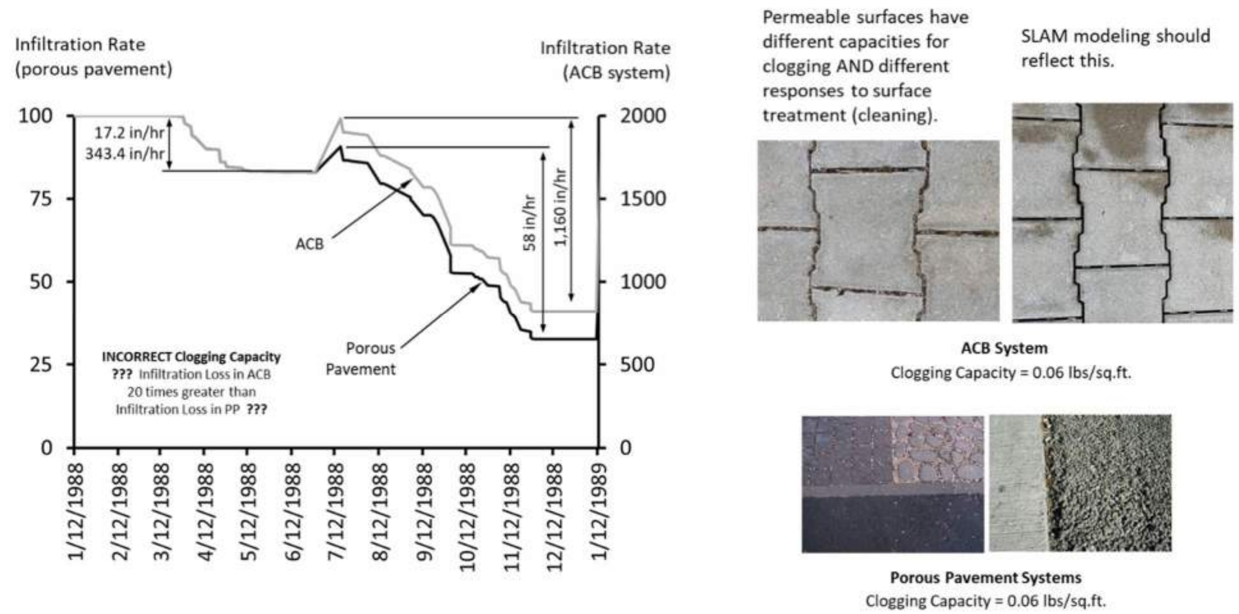


Figure 9. Surface infiltration loss and clogging capacity – impact of careless definition.

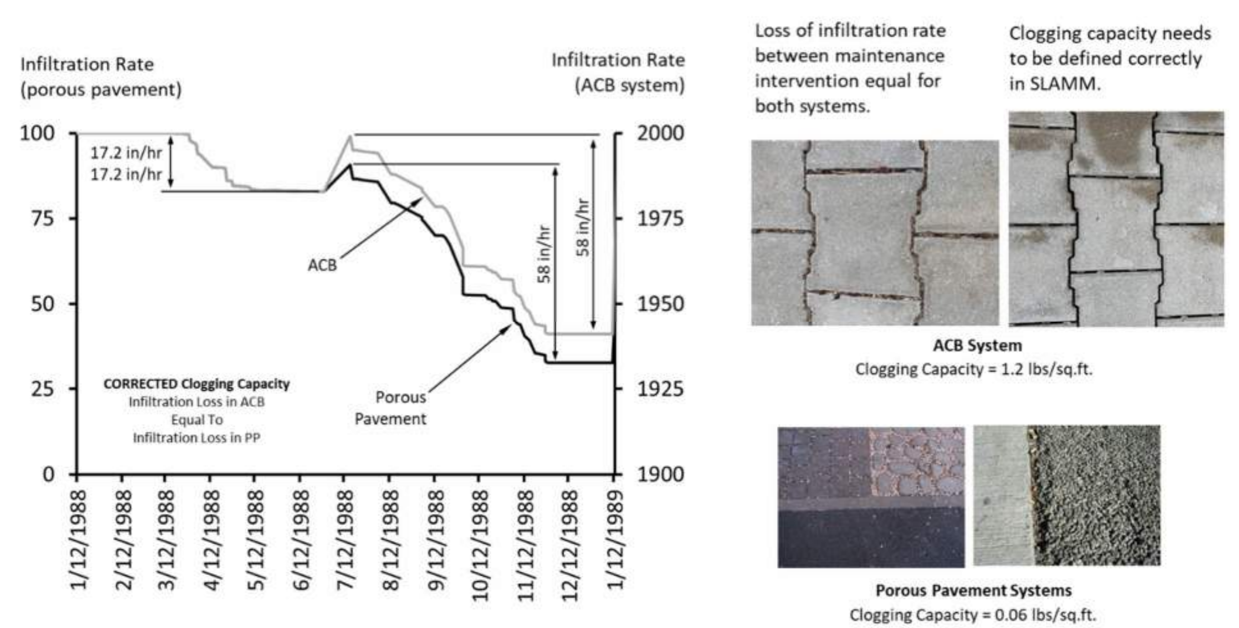


Figure 10. Surface infiltration loss and clogging capacity – impact of consistent definition.

WinSLAMM simulations include surface infiltration rates that are modeled over time using an expression found in Figure 11 (top right corner). The degradation model is predicated on the initial surface infiltration rate and this rate declines with time as the surface clogging mass accumulates. When the cumulative clogging mass at the surface reaches the surface clogging capacity, the surface infiltration rate becomes zero.

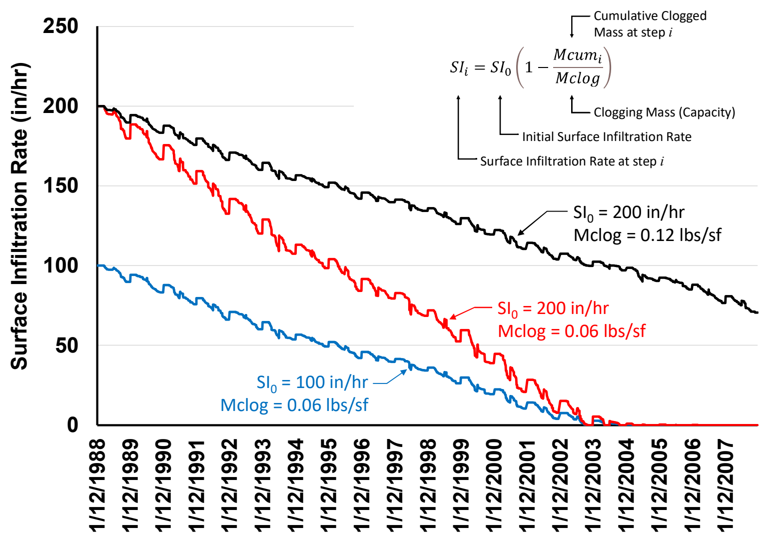


Figure 11. Surface infiltration loss over time and impact of clogging capacity.

It is interesting to note that the rate at which the surface infiltration rate degrades is scaled by the initial surface infiltration rate. This means that doubling the initial surface infiltration rate will double the rate at which the surface clogs when the surface clogging capacity is constant. The results of two 20-year SLAMM simulations are shown: (a) initial surface infiltration rate equal to 100 in/hr and a surface clogging capacity of 0.06 lbs/sf; (b) initial surface infiltration rate equal to 200 in/hr and surface clogging capacity of 0.06 lbs/sf. Comparison of these simulations (blue and red lines) illustrates the scaling effect. The model with 200 in/hr initial surface infiltration rate loses surface infiltration at 2x the rate of the 100 in/hr simulation if the surface clogging capacity is kept constant.

If the surface clogging capacity is doubled along with doubling the initial surface infiltration rate (200 in/hr with 0.12 lbs/sf versus 100 in/hr with 0.06 lbs/sf), the rate at which the surface infiltration rate degrades will be the same. This is shown through comparison of the blue versus black lines in Figure 11.

What this means is that **the engineer MUST be cognizant of the fact that the SLAMM simulation has a built-in model for surface infiltration rate loss and this model MUST reflect expected in-service performance of the permeable pavement surface.**

The simulation results shown in Figure 11 illustrate that a system with initial surface infiltration rate equal to 100 in/hr and a surface clogging capacity of 0.06 lbs/sf will have the same rate of surface infiltration rate loss as a system with 200 in/hr initial surface infiltration rate and a clogging capacity of 0.12 lbs/sf. If the surface clogging capacity is not correctly coupled to the initial surface infiltration rate, the SLAMM simulations will NOT show any benefits to increasing the surface infiltration rate. In other words, there will be no point in seeking surfaces with greater infiltration capacity, because the modeling will illustrate that a system clogs twice as fast because the surface clogging capacity has not changed.

Figure 12 provides side-by-side images of surface condition and system response to a rain event and to snowmelt.

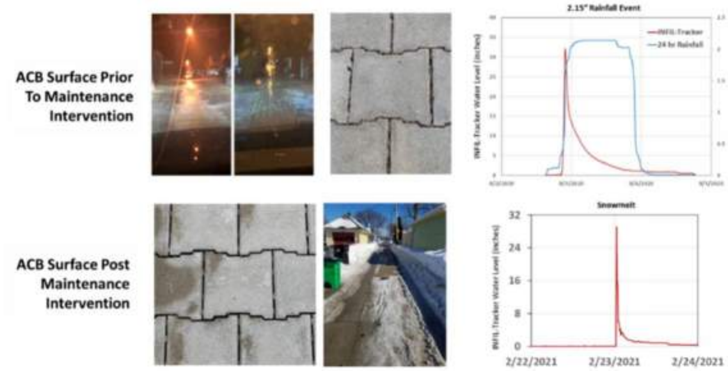


Figure 12. Articulating concrete block pavement surface condition and infiltration comparison.

While the surface appears clogged in the top photos of Figure 12, INFIL-Tracker data indicates the system was infiltrating a significant amount of water through the surface. The pavement was cleaned after two years of service in Fall 2020 and the post-cleaning images are shown in the bottom photos of Figure 12. The post-maintenance runoff event due to snowmelt looks very similar to the response of the system that appears to be clogged.

The surface infiltration rate over twenty years is plotted for the two SLAMM models in Figure 13. The left reflects results from an analysis using DNR 1008 guidance – as currently written. The right graph shows the results of a simulation that uses measured data and updated permeable pavement parameters reflective of actual site conditions and system capability.

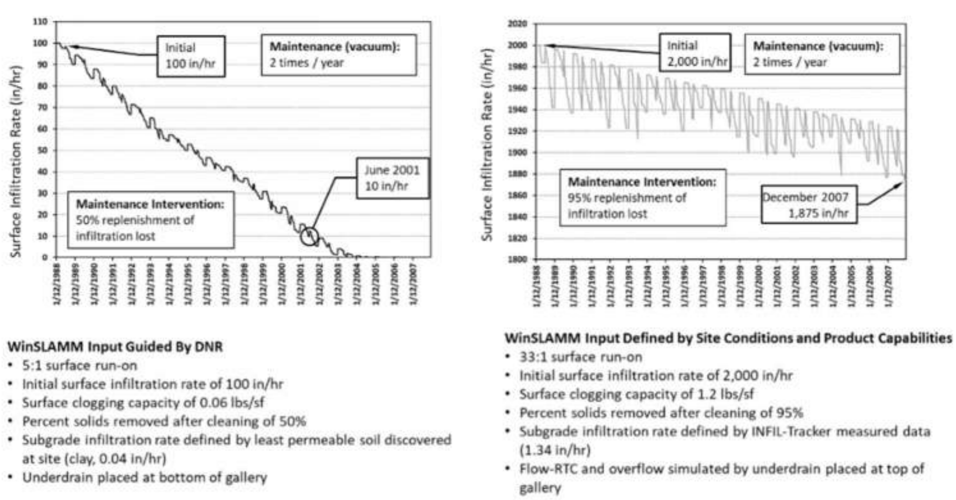


Figure 13. 20-Year surface infiltration rate comparison.

The model in the left graph does not last the full 20 years. It fails around year 17 due to surface clogging. The model in the right graph easily lasts 20 years with residual capacity that exceeds the starting infiltration rate recommended by the current DNR 1008 guidance documents.

Figure 14 illustrates the impact of changing cleaning frequency on surface infiltration rate using 20-year simulations. The results from these simulations using updated input parameters suggest ACB systems are capable of 20-year service lives without maintenance intervention. Surface infiltration rates after 20 years computed using SLAMM simulation are four times the initial DNR guidance value of 100 in/hr. ***The simulations and measured response suggest cleaning twice per year is unnecessary for ACB systems.*** In-service observations confirm this. While it is NOT recommended that maintenance be discontinued, maintenance interventions could be spaced out and defined using measured data specific to the site being considered.

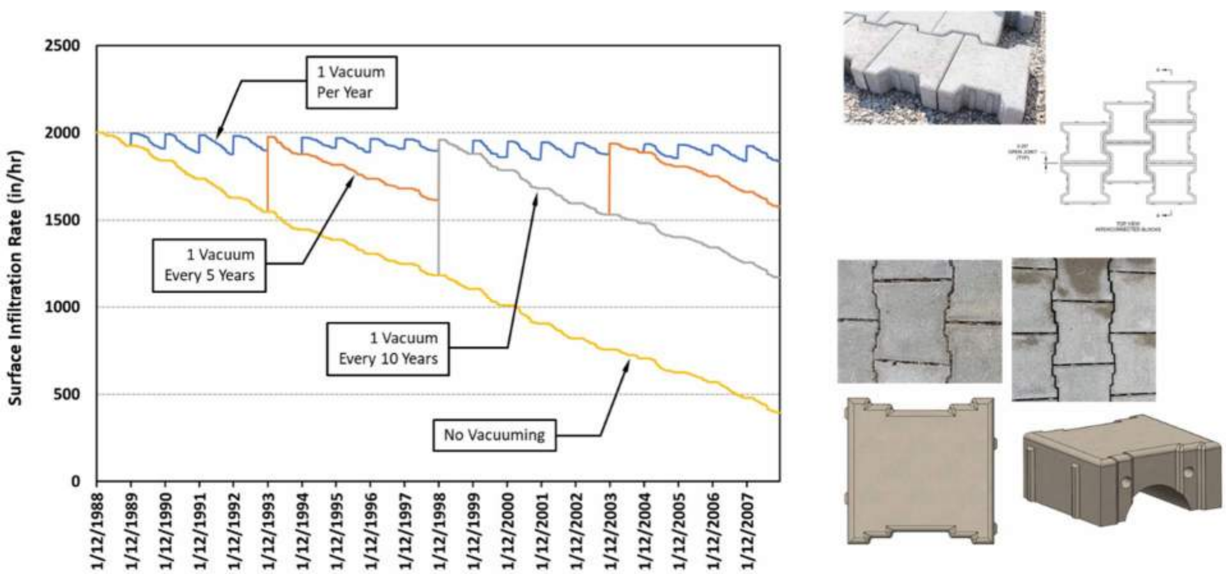


Figure 14. Impact of maintenance intervention (vacuuming) on surface infiltration rate.

<u>*Subgrade Clogging*</u>

SLAMM assumes a clogged subgrade when sediment accumulation reaches a height of 0.25 inches at the bottom of the gallery. The graph in Figure 15 shows solids removed over time for both run-on ratios considered. The solid lines represent total solids removed, including both particulate solids (the dotted lines) and filterable solids (the dashed lines). The 33:1 run-on ratio and 2,000 in/hr initial surface infiltration rate work together to introduce larger amounts of sediment into the BMP at a faster rate.

Figure 15 shows the 33:1 run-on accumulating 0.25" of sediment around year three. This means, beginning at year three, water is no longer allowed to infiltrate into the subgrade for this model. This causes filterable solids removal to plateau thereby reducing the total solids removed for the remaining years left in the simulation. ***If an ACB system with a Flow-RTC™ valve (maintained in a closed state) is being monitored by an INFIL-Tracker™ system and subgrade infiltration is documented after year three, additional filterable solids removed could (and should) be credited to the BMP.***

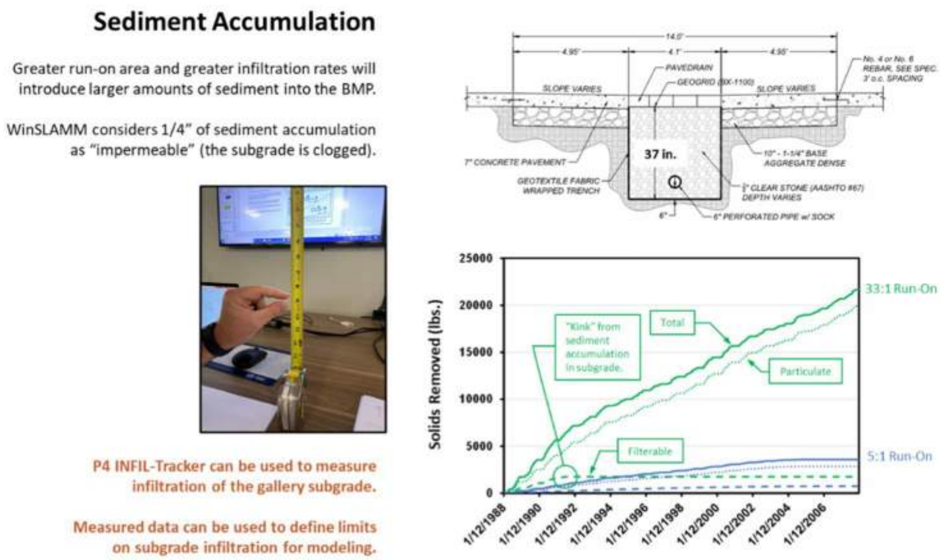


Figure 15. Subgrade sediment accumulation impact on pollutant removal.

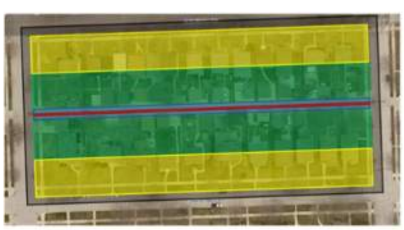
Economic Impact

The economic impact of using updated modeling parameters based upon measured performance metrics is summarized in Figure 16. The cost to build the Van Norman Alley, full length, is estimated to be $420,000. Assuming a 20-year service life and 3% interest rate, the annualized payment for this BMP would cost the City of Cudahy approximately $28,230 per year.

Van Norman CapEx: $ 420,000
20-year service life: n = 20
Interest Rate: i = 3%

Annualized Expense
$ 28,230/year

20-Year Service Life (and Simulation)



	TSS		TP	
20-Year Simulation	**Amount**		**Amount**	
Baseline Load	116,177 lbs.		507.5 lbs.	
TMDL Reduction Goal (75% TSS, 54% TP)	87,132 lbs.		274 lbs.	
Annualized Reduction Goal	4,357 lbs/yr		13.7 lbs/yr	
Pollutant Removals	**Annual Amount**	**Cost**	**Annual Amount**	**Cost**
WDNR Guidance	**282 lbs/yr**	**$100/lb**	1.2 lbs/yr	$23,525/lb
ACB Powered by P4	**2,047 lbs/yr**	**$14/lb**	8.9 lbs/yr	$3,172/lb
Annual Pollutant Removal Gaps				
WDNR Guidance	**4,075 lbs/yr**		12.5 lbs/yr	
ACB Powered by P4	**2,310 lbs/yr**		4.8 lbs/yr	
Cost to Close Gap				
WDNR Guidance	**$407,500 /yr**		$294,063 /yr	
ACB Powered by P4	**$32,340 /yr**		$15,226 /yr	

Figure 16. Economic impact of SLAMM enhancement and P4 systems.

Land area draining to the constructed permeable surface depends upon the method used to analyze the pavement. The aerial image in Figure 15 shows 5:1 run-on area in blue and 33:1 run-on area in green.

When considering this alley as a typical block, repeated throughout the city, there would be portions of land not able to drain to the alley because of topography. These areas are shown in yellow and black (essentially the perimeter).

Baseline total suspended solids (TSS) and total phosphorus (TP) loads for the repeatable block are shown in the table of Figure 15. If this repeatable block were located within a TMDL basin with 75% and 54% reduction goals for TSS and TP, respectively, it means that this block is aiming to remove 4,357 lbs of TSS per year and 13.7 lbs of TP per year.

The present discussion focuses on TSS. There are many instances when meeting targeted TSS removal will automatically satisfy the TP removal goal. Van Norman Alley TSS removals are shown for each method considered. If DNR guidance is followed, the alley would remove 282 lbs/yr resulting in a removal cost of $100 per lb and a gap of 4,075 lbs per year to reach 75% reduction from baseline. If monitoring systems like P4's are implemented and ACB systems can use their full potential in the SLAMM simulations, this alley would remove 2,047 lbs per year resulting in a removal cost of $14 per lb and a much smaller gap of 2,310 lbs per year to reach the 75% reduction goal.

It should be noted that not all land is draining to the alley and additional infrastructure is required to close the pollutant gaps in both cases. ***It will cost $407,500 per year to close the TSS gap using porous pavement following current DNR 1008 guidance for this land area. It will cost $32,340 per year to close the TSS gap using ACB systems powered by P4 systems.***

Pollutant removal costs required to close gaps can be reduced by a factor of 12 when modeling implements measured data and parameter definitions that reflect system capabilities. This is the net effect of communities implementing P4 systems approved by the Wisconsin DNR.

Recommendations

It is highly recommended that current DNR technical guidance (1008) be updated to allow measured parameters to be incorporated within existing modeling practices using SLAMM. Engineers should have the freedom to use site-specific measured data to enhance SLAMM simulations. Interactive monitoring systems capable of controlling and documenting BMP performance, should be allowed to provide measured modeling parameters for SLAMM simulations. If manufacturer data is available, engineers should be allowed to use such properties in their SLAMM simulations to accurately estimate stormwater runoff and pollutant capture provided monitoring systems can document performance with these enhanced parameters.

The following is a list of product-specific properties capable of being monitored at the system level: Hydrology-Driven Run-On Area; Surface Clogging Capacity; Surface Infiltration Rate; Subgrade Infiltration Rate; Maintenance Replenishment Effectiveness; and Subgrade Infiltration Clogging. If engineers are allowed to enhance these properties using system-level, measured performance data and/or product-specific, manufacturer-provided data when defining input parameters in SLAMM simulations, the Wisconsin DNR will effectively remove the handcuffs from stormwater utilities and drainage districts across the State and be on a path to attaining clean water faster and for less money.