Center for Environmentally Sustainable Transportation
in Cold Climates

Stormwater-Pavement Interface in Cold Climates

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13. ABSTRACT This project relates to “managing stormwater runoff in cold climates” and addresses the feasibility of low-impact development at a regional demonstration site in eastern Washington. The studies relate to seven large permeable pavement systems. The findings for similar climates and soils are as follows:

- The draindown times for retention in Palouse or similar clay soils may handle many typical storms.
- On average, every square foot of a permeable pavement system installed also receives run-on from another square foot of impermeable pavement, doubling its impact on both stormwater quantity reduction and stormwater quality improvement.
- Most of the clogged sections on various applications were downslope of other areas.
- Permeable pavements installed in areas targeted for additional stormwater quantity control and quality improvement may be feasible.
- On average, the cleaning for installations is less frequent than annually. Power washing plus vacuuming appears to be an effective method for pervious concrete.
- Surface distress was usually where vehicles turned, or from placement activities.
- Preliminary studies on various surface treatments on pervious concrete show promise for added safety benefits under wintry conditions.
- Both detention-type and retention-type permeable pavement systems appear to have little negative impact on neighboring soils in the winter under the study conditions. However, further research is needed for different designs of retention-type systems to ensure that water volumes in the aggregate storage bed do not allow for sufficient water flow into neighboring soils that might result in ice lens formation or other negative impacts.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

Note: Volumes greater than 1000 L shall be shown in m^3

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2 m^2
	meters squared	10.764	square feet	ft^2 km^2
	kilometers squared	0.39	square miles	mi^2 ha
	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb mg
	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

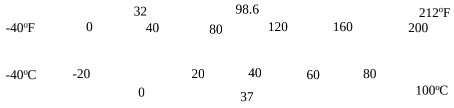

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

This project relates to "managing stormwater runoff in cold climates," and addresses the feasibility of low-impact development in support of the Washington State University (WSU) Pullman campus master plan and of the University as a regional demonstration site. The study relates to seven large permeable pavement systems, both pervious concrete and porous asphalt, on the WSU Pullman campus and one in Spokane, Washington. The findings to date with respect to areas with similar climates and soils are as follows:

- The draindown times for retention in similar clay soils may handle many typical storms.
- On average, every square foot of a permeable pavement system installed also receives run-on from another square foot of impermeable pavement, doubling its impact on both stormwater quantity reduction and stormwater quality improvement.
- Most of the clogged sections on various applications were downslope of other areas.
- Permeable pavements installed in areas targeted for additional stormwater quantity control and quality improvement may also be feasible, but more research is needed.
- On average, the cleaning frequency for installations is less than annually. Power washing has been shown to be an effective method for cleaning surface clogged pervious concrete.
- Surface distress is usually where vehicles have turned, or from placement activities.
- Preliminary studies on various surface treatments on pervious concrete show promise for added safety benefits under wintry conditions.
- Both detention-type and retention-type permeable pavement systems appear to have little negative impact on neighboring soils in the winter under the study conditions. However, further research is needed for different designs of retention-type systems to ensure that

water volumes in the aggregate storage bed do not allow for sufficient water flow into neighboring soils that might result in ice lens formation or other negative impacts.

CHAPTER 1.0 INTRODUCTION AND TASK 1

1.1 Introduction

This project, which has both research and implementation aspects to it, has been funded jointly by the Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC), a Tier I U.S. Department of Transportation University Transportation Center, and the Washington State Department of Ecology (Ecology) Husseman Fund. The City of Spokane and Washington State University (WSU) Facilities Services funded some of the associated permeable pavement installations used in this research as part of their ongoing work. For simplicity, the report's format follows the task outline from the Husseman Fund proposal, with additional information from the CESTiCC Phase I and Phase II Stormwater Pavement Interface project. This project relates to the second research thrust of "managing stormwater runoff in cold climate through improved training, monitoring, advanced technology and pervious concrete" from CESTiCC. The research addresses the need in eastern Washington for a feasibility study of low-impact development in support of the WSU Pullman campus master plan and for a regional demonstration site of associated permeable pavement technologies in response to the Husseman Fund objectives. Major portions of this report were previously submitted to the Washington State Department of Ecology as the final report for Ecology project # G1400639: Husseman Fund.

Low-impact development (LID) represents a suite of policies and practices that are implemented to manage stormwater runoff from developed sites and infrastructure in a manner that effectively mimics natural hydrological processes. Major efforts are underway to advance LID technologies, policies, and implementation criteria in western Washington and in other regions of the country, and the Washington State University (WSU) Puyallup extension campus is developing a research center for many LID practices. However, LID technologies appropriate for eastern Washington and other cold regions of the Pacific Northwest, particularly regions with soils that drain poorly and steep slopes, are not well developed, and implementation sites are few. Many of the technologies being implemented for new development (e.g., constructed wetlands) may be inappropriate for existing areas due to lack of physical space or lack of jurisdictional authority to force owners to modify their current landscaping.

Implementation is likely to be further hampered by both real and perceived differences in best management practices (BMP) due to climate and soil variations across the state and region (Emerson and Traver 2008, Houle 2008). For instance, the application of deicer and sand on roadway and parking surfaces in the hilly Palouse area during snow events is essential in winter months when most stormwater runoff occurs. Deicers have been shown to impact many receiving waters (Eppard et al. 1992). Rain gardens may prove problematic because the long, dry summer periods typical of eastern Washington require supplemental irrigation, exacerbating an already severe problem with water availability. Moreover, BMP that rely on vegetation uptake are severely limited due to dormant winter seasons, and those relying on infiltration are thwarted due to frozen soil conditions or low infiltration rates of local soils. On the Pullman campus, some biological-based technologies such as swales are appropriate at certain locations, but with ongoing campus development, a more detailed look at permeable pavement efficacy is warranted.

Many stakeholders such as the City of Spokane, the Washington State Department of Transportation (WSDOT), and similar agencies and communities in Montana and Alaska are interested in using the low-impact development technology of pervious concrete or other permeable pavements for managing stormwater quantity and quality. Besides providing demonstration projects, research on remaining questions, particularly with respect to cold climates, is paramount to expanded application of permeable pavements. The main issues surrounding the use of pervious concrete involve (1) its durability and infiltration capabilities in winter conditions and during snow-removal activities, (2) the impact of storing water for extended periods under permeable pavements, and (3) the subsequent impact of this water on neighboring pavements/soils. The third issue is important for regions with significant frost depth or repeated freeze/thaw conditions, if this stored water migrates under neighboring pavements it may result in frost heave or spring weakening of pavement. Finally, outreach and extension are important, and the work has been and will be featured in various venues, and has potential for forming the baseline for other research endeavors.

1.2 Task 1 – Evaluation of Campus Area for Stormwater Issues and LID Permeable Pavements

The Interim Report on Task 1 was completed and submitted to the Washington State Department of Ecology on December 15, 2014 (Adams et al. 2014). The report related to interest in permeable pavement applications in areas of the WSU Pullman campus. The following section is a summary of the contents of the report. Aid in completing Task 1 was obtained from Gene Patterson (Public Health Manager for WSU Environmental Health and Safety), Dave McCarroll (Campus Planner for WSU Facilities Services), and Judy Nilsson (graduate student in Landscape Architecture). Five sub-duties were completed in Task 1:

1. Work with Environmental Health and Safety to determine areas of campus associated with stormwater priorities.
2. Analyze impervious and pervious surfaces, estimate existing stormwater flows, and incorporate information from the WSU Facility Services ongoing hydrologic/hydraulic survey.
3. Compile known effectiveness and applications of these technologies.

4. Work with WSU Facility Services to determine maintenance and capital plans and considerations for these technologies applicable to the region.
5. Evaluate options for implementation of Tasks 2–5.

Areas of interest were identified on the WSU Pullman campus regarding stormwater issues, specifically the total maximum daily load (TMDL) requirements for fecal coliforms in discharge to the South Fork Palouse River or Paradise Creek. It was hypothesized that one area of interest for fecal coliforms in stormwater runoff is the area surrounding the WSU Veterinary Medical School, where large animals are stabled and off-loaded for treatment. Four sites near the Veterinary Teaching Hospital were chosen for study, referred to as McCoy North (A), McCoy West (B), Bustad South (C), and Allen Center Addition (D). Figure 1.1 indicates the location of these sites on the WSU Pullman campus. Background information was gathered on each site, including site permeability (areas of standard pavement, pervious pavement, or non-paved) and stormwater drainage routes (catch basins, drainpipe location, and discharge sites). Table 1.1 summarizes some of the key traits of each study site. Drainage areas were mapped by Judy Nilsson. Details of these sites can be found in the Task 1 Interim Report (Adams et al. 2014), the final report to the Washington State Department of Ecology (Haselbach 2016) or under Task 6 of this report.

Figure 1.1 Areas of interest around the WSU campus veterinary facilities

Table 1.1 Summary of key traits of the four study sites for Task 1

	McCoy North	**McCoy West**	**Bustad South**	**Allen Center**
Size (sq. ft)	8621	9113	34,300	66,160
Pavement	Impervious Asphalt	Impervious Asphalt	Impervious Asphalt	Mixed Impervious, Pervious, non-Paved
Catch Basins	2	3	6	1 (armored ditch)
Drainage Site(s)	South Fork Palouse River McCoy Dry Well	Manhole → Unknown Site	South Fork Palouse River	Carver Farm Ponds Cougar Ponds → Paradise Creek

The four sites surrounding the veterinary medical facilities were under consideration for modeling in Task 6.3. Site A, McCoy North, was not considered further due to gradation at the site. Installation of permeable pavements at this site could result in shunting of stormwater to the building foundation and basement, and replacement of deep sewer and drainage pipes in the area might not be cost-effective. Site B, McCoy West, was also not considered further due to the high rate of heavy equipment traffic to and from the waste bedding compactor and the option of moving the compactor to a different site.

Site C, Bustad South, remained under consideration for Task 6.3. Currently, stormwater issues in this area are to be managed by placement of a small berm to direct stormwater flows away from the loading dock to the sanitary sewer. However, the idea of adding a pervious installation instead of the berm is being modeled as an alternative solution, since this type of installation may both reduce stormwater flow from the area and divert that stormwater away from the loading dock.

Site D, Allen Center Addition, also remained under consideration for Task 6.3. A 33,000 sq. ft (square foot) addition to the Allen Center has been proposed, which would convert nearly half of the area of this site from pervious or non-paved surfaces to an impervious roof surface. This change may result in increased stormwater runoff from the site into the armored ditch and Carver Farm Bio-detention Ponds (Nilsson 2014). It is unknown whether the existing drainage system will be able to handle this increase in runoff, and it is hypothesized that use of permeable pavements could assist in stormwater management at the site.

As of December 2014, five major permeable pavement installations had been completed on the WSU Pullman campus. Two major installations were added in 2015. Some of these installations are being studied over time to monitor changes in surface infiltration rates. Table 1.2 summarizes some of the key characteristics of these pervious pavement sites.

Table 1.2 Summary of seven pervious pavement sites at WSU Pullman as of summer 2015

Sites	Age (yr)	Size (sq. ft)	Mix
VetMed Circle	4	2827	Concrete
Sloan Hall Sidewalk	3	960	Concrete
East Valley Playfields	5	4277	Concrete
Center Valley Playfields	4	7262	Concrete
Allen Center Walk and ADA Parking	4	5924	Asphalt
Community Hall	0	130	Concrete
PACCAR	0	9370	Concrete

Concerns about site functionality and maintenance were considered for all existing permeable pavement sites. It was hypothesized that clogging of the pervious surface occurs due to silt, soils or debris (garbage, leaves or other organic matter such as fruit from overhanging trees), or snow and ice lodged in the upper layer of pores. Prior to 2015, the two Valley Playfield sites had been cleared of artificial soil using a leaf blower, but no other maintenance had been performed on any site. In October 2015, part of the Sloan Hall Sidewalk installation was cleaned using a garden hose and hand-held spray nozzle. Results of this cleaning are discussed in Task 4, along with other infiltration study information. Other methods of cleaning that were tested and discarded are sidewalk sweepers and vacuum equipment used for pumping out catch basins under dry operations. Snow removal has been performed by plow or rotary brush. Deicers have been used sparingly, and it has been seen that calcium chloride may cause less raveling than magnesium chloride deicer. Despite minimal maintenance, most of these sites were still draining at acceptable average aerial rates of >50 in./hr.

After much consideration by the research team and WSU Facility Services, one of the new sites (Community), where the existing section of traditional concrete sidewalk slated for replacement was amendable for research on neighboring soil impacts, and could provide small underground basins for draindown studies, was chosen for implementation of Tasks 2, 3, and 5:

Task 2 – Evaluation of Time to Drain for Extended Retention Installations

Task 3 – Testing Moisture and Temperature in Neighboring Soils

Task 5 – Surface Installation Design Modifications for Improved Winter Conditions

Preliminary rounds for Task 2 selected Sloan Hall Sidewalk and VetMed Circle as candidates for the time-to-drain (sub-surface infiltration) study. The ADA Parking Lot was initially considered, but was disqualified since that site will be removed in the future. Sloan Hall Sidewalk was equipped with a monitoring well, and Ground Penetrating Radar (GPR) might be used at both Sloan Hall and VetMed Circle. However, the soils at Sloan Hall are fast draining, so are not representative of the slow-draining soils of the region. VetMed Circle was also not chosen, as the underground bed is large and would require a lot of water to fill, and there were no previously installed observation wells. The Community Hall installation, which was added after the submission of the Task 1 Interim Report, has been equipped with monitoring wells, GPR targets, and a subsurface dam.

Soil moisture monitoring in Task 3 was an important consideration because the clayey soil in this region is known to retain moisture longer, making it ideal for agricultural development. Higher moisture content may decrease subsurface infiltration rates and impact neighboring soils over time. As reported in the Task 1 Interim Report, the Community Hall installation has been equipped with soil moisture and temperature sensors. The data from these sensors are discussed in Task 3.

Surface infiltration rates of the five sites existing prior to 2015 have been monitored over time. These rates are summarized in Task 4 as an indication of hydraulic performance, and they provide additional infiltration data from newer sites on the Pullman campus.

Under winter white-frost conditions, pervious pavement surfaces can become slick. Task 5 regards the search for a permanent surface treatment for pervious concrete to increase surface traction under icy conditions. Surface treatments considered were the use of a commercial product, broom finishing of the surface, and the application of sand to the top of the uncured pervious concrete surface. Laboratory samples were made, surface treatments were applied, and these samples were installed abutting the Sloan Hall Sidewalk installation, on the west edge next to the raised-bed garden. Prior to installation, porosity and infiltration rates of the samples were determined using ASTM C1754 and ASTM C1701 procedures (ASTM 2012, 2009a). The efficacy of the surface treatments was determined using a survey type approach. These results are discussed in Task 5. Initially, the most effective treatments (broom finishing and sand treatment) were also chosen for application of these surface treatments on the Community Hall sidewalk, but the pervious concrete mix design used by the producer was not similar enough to the laboratory mix to continue the study.

CHAPTER 2.0

TASK 2 – Evaluation of Time to Drain for Extended Retention Installations

The intention of Task 2 was to establish a method to determine how fast a permeable pavement system on clay soils in this area of the country (Palouse region) drains down. This task involved installing one or more observation wells at a permeable pavement site on clay soils, and recording draindown during controlled flooding events. The main reason for researching time to drain was due to concerns that the soils in this region might not drain well enough for retention systems of permeable pavements. The associated sub-tasks under the Ecology project were itemized as follows:

- Work with WSU VetMed and Facility Services to draft plans and obtain approvals.
- Install standpipe/observation well.
- Flood underground storage facilities and record infiltration rates.
- Evaluate data

The research team worked with WSU entities to determine that the new pervious concrete sidewalk at a location near Community Hall (herein referred to as *Community*) would be an optimum location for this task. The location has clayey types of soils, irrigation lines nearby for water flooding, and underground beds that are small enough to flood fairly rapidly without using excessive amounts of water. The team planned to install observation wells to physically measure draindown easily.

The Community installation was completed in May 2015; it is unlike many other permeable pavement installations in that it contains a subsurface dam near the uphill (east) end. The Community installation has a 6-inch layer of pervious pavement on top of an aggregate storage bed layer. Most of this aggregate storage bed is 30 inches deep; however, 6.5 feet from the east end of the installation is an impervious dam that rises 24 inches from the bottom of the installation. The dam is composed of subsurface soil covered by an impermeable layer of Stego Wrap. A 6-inch layer of aggregate is on top of the dam, between the dam and the pervious concrete layer. The dam is 5 feet long, and the remaining underground storage area below the dam is 14.5 feet long. The entire installation is 26 feet long and 36 inches deep. The bottom surface of the installation is covered by a layer of permeable Mirafi 500X geotextile fabric, in direct contact with the surrounding soil. Figure 2.1 is a diagram of this installation. There are two observation wells in the installation. The observation wells can be used now for draindown tests. As shown in Figure 2.2, the two observation wells are installed on the north face of the installation, one just above the dam, and one at the lowest corner of the installation.

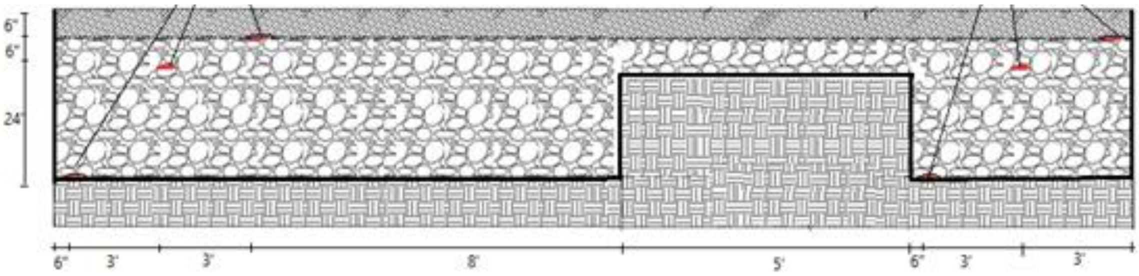


Figure 2.1 Profile of Community Hall pervious installation and subsurface dam (left is west, right is east)

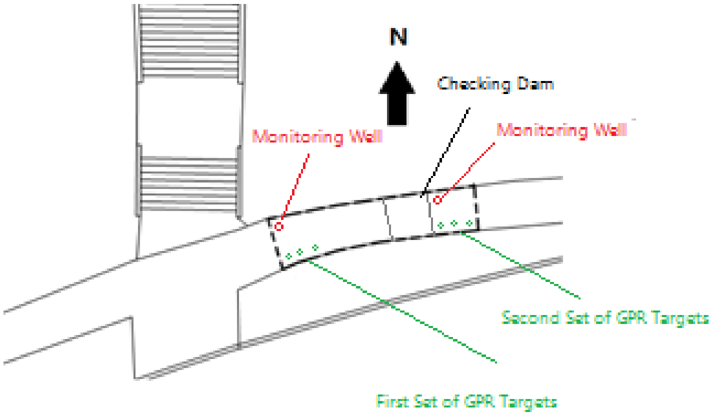


Figure 2.2 Plan view of position of installation, dam, observation wells, and ground penetrating radar (GPR) targets not used in this research.

Draindown tests were planned to help define the subsurface (bottom of the underground storage bed) infiltration rate of the soils in this region, which are known to have high clay content and as a result may hold moisture longer. At the end of the summer season, the soils are very dry in the Palouse. In the spring, soils are saturated. Draindown tests were completed in both seasons so that infiltration could be compared between wet and dry soils. Seasonal temperature fluctuations can change the infiltration and storage conditions; wintertime temperatures and subsurface freezing can decrease infiltration rates. These conditions may also cause changes in capillary action of the infiltrate and freeze-thaw trends. This section focuses on the results of late summer and fall 2015 fairly dry soil draindown tests and the saturated soil draindown tests performed in the spring of 2016.

In 2015, the late summer and fall draindown tests were completed by flooding the basin above the dam until the basin overflowed over the dam. Water depth was monitored over time. Tables 2.1, 2.2 and 2.3 show data from draindown tests completed in August and October 2015. Figure 2.3 is a plot of the results of these three draindown tests.

Table 2.1 Draindown test results from August 17, 2015

Time (minute)	**Water Depth (in.)**	**Time (minute)**	**Water Depth (in.)**	**Time (minute)**	**Water Depth (in.)**
0	18.3	20	8.8	40	4.8
2	17.7	22	8.1	42	4.3
4	16.1	24	8.0	44	4.2
6	15.3	26	7.4	46	3.4
8	14.3	28	7.1	48	3.2
10	13.2	30	6.6	50	2.8
12	12.4	32	6.2	52	2.4
14	11.3	34	5.8	54	1.9
16	10.8	36	5.3	56	1.8
18	9.4	38	5.1	58	1.6

Table 2.2 Draindown test results from Test 1 October 17, 2015

Time (minute)	Water Depth (in.)	Time (minute)	Water Depth (in.)	Time (minute)	Water Depth (in.)
0	20.25	16.57	16.25	39.42	12.25
0.75	19.75	17.93	15.75	41.67	11.75
1.20	19.25	20.63	15.25	43.32	11.25
3.32	18.75	23.15	14.75	45.40	10.75
5.20	18.25	25.13	14.25	47.03	10.25
10.40	17.75	29.15	13.75	48.33	9.75
13.23	17.25	33.72	13.25	50.73	9.25
15.02	16.75	36.22	12.75	52.03	8.75

Table 2.3 Draindown test results from Test 2 October 17, 2015

Time (minute)	Water Depth (in.)	Time (minute)	Water Depth (in.)	Time (minute)	Water Depth (in.)
0	19.75	32	10	72	4.25
2	18.75	34	9.25	74	4
4	17.75	36	9	76	3.5
6	17	38	8.938	78	3.25
8	16.5	40	8.5	80	3
10	15.5	42	8	82	2.75
12	15	46	7.75	88	2.5
14	14.25	48	7.25	92	2
16	13.5	50	6.938	96	1.75
18	13	52	6.25	100	1.5
20	12.75	54	6	102	1.25
22	12.25	56	5.75	104	1
24	12	64	5.25	108	0.75
26	11	66	4.75	110	0.25
30	10.5	68	4.5	112	0

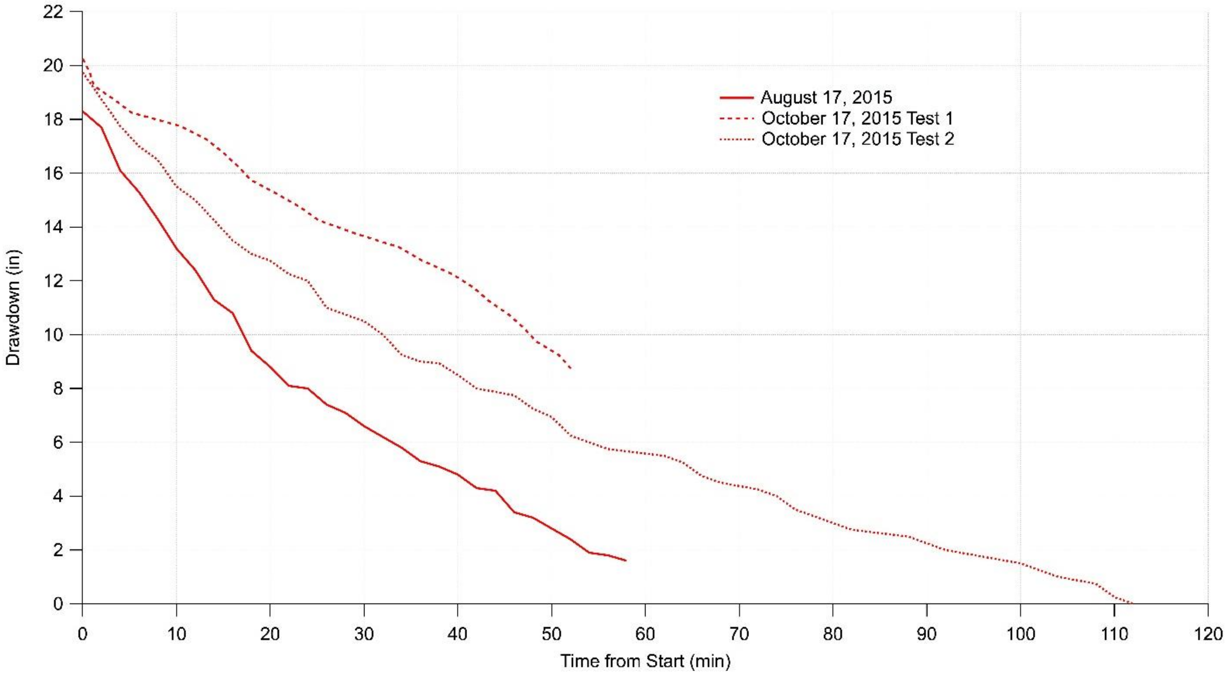


Figure 2.3 Draindown test results for 3 tests completed in August and October 2015

Figure 2.4 is a plot of the draindown test in April 2016. The upper zone (C) was flooded until the dam overflowed, and flooding continued until the lowest zone (A) reached water levels similar to the upper zone. Flooding stopped and water levels were recorded until they dropped to approximately 20 centimeters, and then Zone C was again flooded to the dam level. As can be seen in Figure 2.4, both zones drained similarly, indicative of little variation in the soils in either zone, such as drainage channels from roots. In addition, Zone C drained similarly during both consecutive flooding events on the same day, suggesting little negative impact from previous saturation. Under these damp spring conditions, the Community site fully drained in about 2 hours. Based on the volume of the storage bed and typical porosities of storage bed aggregate, the total depth of water that drained in 2 hours was approximately 10 inches. Thus, rainfall and contributions from run-on from upslope areas together at this depth are easily handled in similarly designed retention systems.

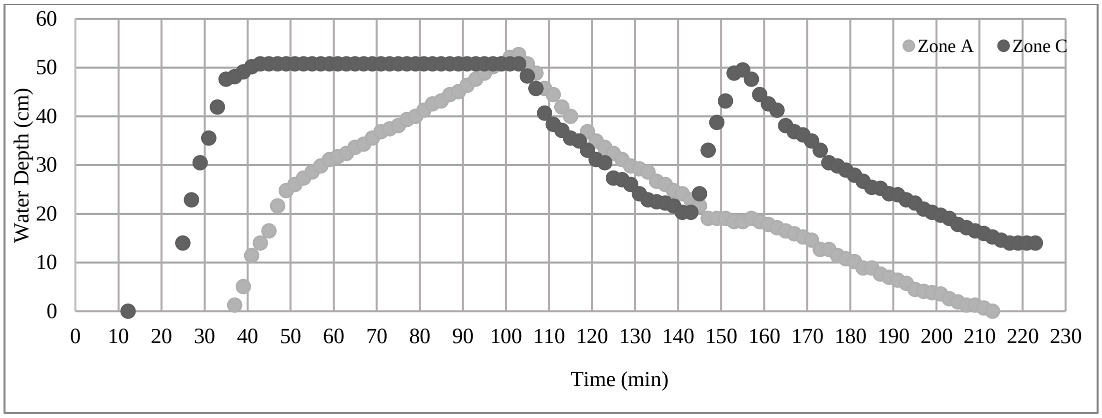


Figure 2-4 Draindown test results for April 2016 (Yekkalar et al. 2017)

Figures 2.3 and 2.4 indicate that permeable pavement retention systems function well in soils similar to the Palouse region of Washington during both dry and wet seasons. Figure 2.4 provides more information for designers in determining retention volumes needed to handle various storms based on storm intensities and contributing areas.

CHAPTER 3.0

TASK 3 – Testing Moisture and Temperature in Neighboring Soils

Task 3 dealt with stormwater runoff management in cold climates using permeable pavement systems. In spite of the expanded application of permeable pavements, questions remain, especially with respect to applications in cold climates. One issue is related to the impact of storing water for extended periods under permeable pavements and the water's impact on neighboring pavements/soils, an issue that is of particular importance in regions with significant frost depth or repeated freeze/thaw conditions. The focus of Task 3 was an initial investigation of moisture and temperature of soils next to permeable pavements to determine if the storage of water near other pavements leads to ice lens formation or other moisture issues that might impact neighboring pavement structurally. This possibility is particularly of interest if permeable pavement systems are used as shoulders on roadways. Task 3 addressed the installation of sensors into soils next to one or more permeable pavement systems so that data could be collected over seasonal periods (phases).

For Task 3, temperature and soil moisture sensors manufactured by Decagon Devices, Inc. (depicted in Figure 3.1) were installed in soils next to the underground aggregate storage beds at two locations. The first location is next to the pervious concrete sidewalk at Community Hall (*Community*) in Pullman, Washington, which was installed in late May 2015. The Community location has an underground storage bed that is essentially a retention system, with no underdrains. The second location is next to the porous asphalt parking lot at the Finch Arboretum (herein referred to as *Finch)* in Spokane, Washington, installed in early October 2015. The Finch location has underdrains in the bottom of the underground storage bed and is therefore a detention system. Task 3 included the collection of data on temperature and soil moisture in soils next to the two placements and the correlation of these results to various seasonal and weather conditions over the winters of 2015/2016 and 2016/2017. Both sites chosen for testing have predominantly clayey soils, which under other conditions (such as extended periods of standing water in the aggregate storage beds) might cause concern over capillary action and negative water impacts to neighboring soils. Samples of soils from both locations were collected and were laboratory tested for soil calibration to modify the Topp Equation for clayey soils (Topp et al. 1980).

Figure 3.1 Moisture and temperature sensors

Community Hall Sidewalk, Pullman, Washington: The pervious concrete section of the sidewalk in front of Community Hall is approximately 26 feet long. The sidewalk, which is sloped longitudinally, draining east to west, was built with a 6-inch pervious concrete layer, with a river rock aggregate storage bed of approximately 30-inch depth. Inside the aggregate bed, an internal dam was built to divide the bed into two sections, the upper portion of which is approximately 6 feet long. Additional features such as two observation wells and some ground penetrating radar (GPR) targets were also installed for complementary internal draindown research, although the GPR targets were not used in this research. A southern profile is depicted in Figure 3.2. The sidewalk and underground storage bed were installed by WSU Facilities Services as part of its sidewalk replacement program and funded as a match to this research.

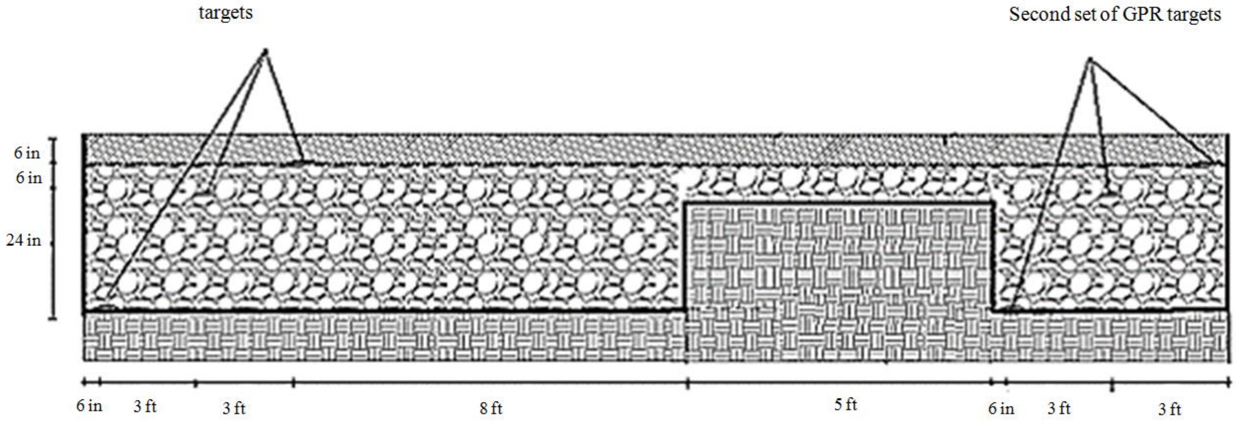


Figure 3.2 Profile of aggregate storage bed at Community Hall (➜East)

Soil moisture and temperature sensors were installed in the soil next to the Community Hall sidewalk on the side closest to the building (north side). The soil there, which was tested using ASTM D2488-09, was determined to be mainly clay type, which is typical of the Palouse region (ASTM 2009b). The sensors were installed in three zones—A, B, and C—with Zone A most downslope in the sidewalk (west) next to one observation well, Zone B upslope in this lower aggregate bed section, and Zone C just upslope of the dam in the upper aggregate storage bed section. Zone C is expected to receive the most stormwater from upslope run-on. Zone B is expected to receive very little runoff. Zone A is expected to receive somewhat less stormwater than Zone C. In each zone, one sensor array hole was dug close to the sidewalk (approximately 0.5 feet), and another was dug approximately 1 foot further away; 5TM sensors were installed at three depths in these six holes. The plan view shown in Figure 3.3 indicates where the zones and holes are located. Figure 3.4 contains profiles of the two rows of sensor arrays in the three zones.

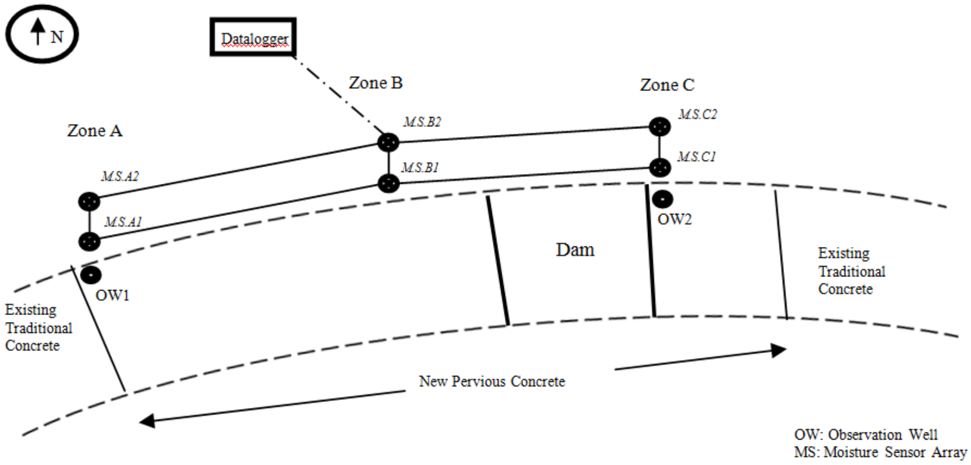


Figure 3.3 Sensor (MS) plan view of Zones A, B, and C at Community Hall

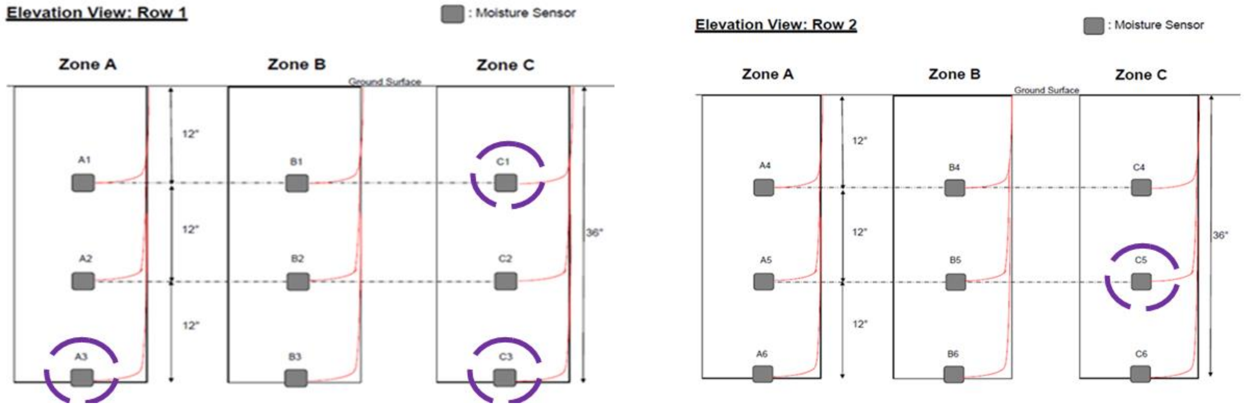


Figure 3.4 Sensor depths in the two rows of Zones A, B, and C at Community Hall

Note in the plan view that the Community location has observation wells, and the relatively small storage volumes and natural conditions can be used for partially controlled water infiltration experiments, similar to the aforementioned draindown studies. Additional applicable weather data were collected by a weather station on the roof of Sloan Hall on the Pullman campus nearby and the station at Pullman (PUW) airport.

Some data were also collected during the warmer summer season. Results during summer 2015 at the Community site are really only applicable for temperature, as there is little precipitation in a Pullman summer. However, temperature profiles are already indicating a slight impact on neighboring soils from underground storage beds. Figure 3.5 depicts these profiles during June 2015 for Zone B. The most variation is seen at the top sensor closest to the pervious concrete (light blue at the top), with a bit less variation at the top sensor farther away (dark blue near the top of the graph). The two lines on the bottom represent the deepest sensors, and the two middle lines are the middle-depth sensors, the top one being closest to the underground aggregate bed. The wintertime results for the Community site are reported later in this section.

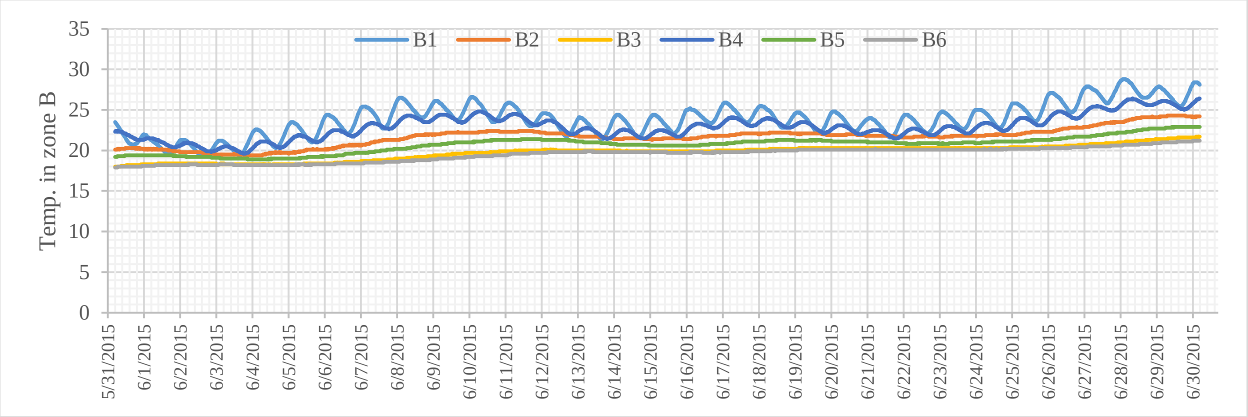


Figure 3.5 Temperature sensor readings June 2015 Zone B at Community Hall

Finch Arboretum Porous Asphalt Parking Lot, Spokane, Washington: In October 2015, twelve 5TE soil moisture and temperature sensors were installed in the slow-draining soil (predominantly clayey) next to the northwest corner of the new porous asphalt parking area at the Finch Arboretum in Spokane, as shown in Figure 3.6. This area is where the porous asphalt system is sloped to drain. Unlike the system at Community Hall, the Finch permeable pavement system is equipped with underdrains at the bottom of the underground storage bed, effecting a detention system. The sensors were installed in two zones: Zones A and B. In each zone, two holes were dug, and 5TE sensors were installed at three depths in these four holes as shown in Figures 3.7 and 3.8.

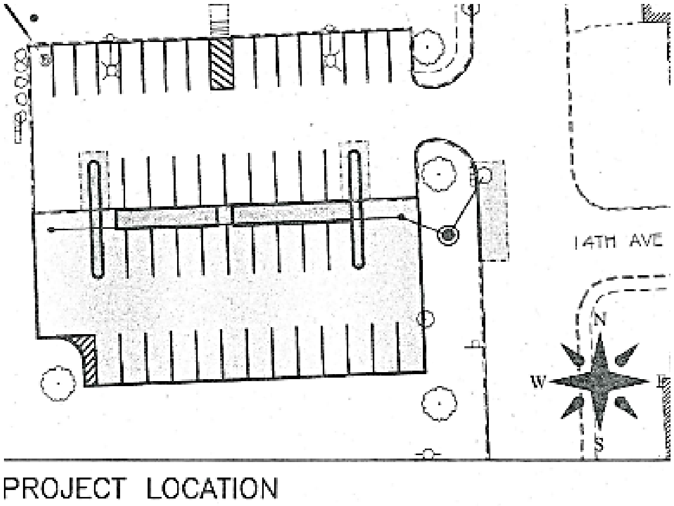


Figure 3.6 Location of the sensor installation at Finch parking at the northwest corner of the new porous asphalt area

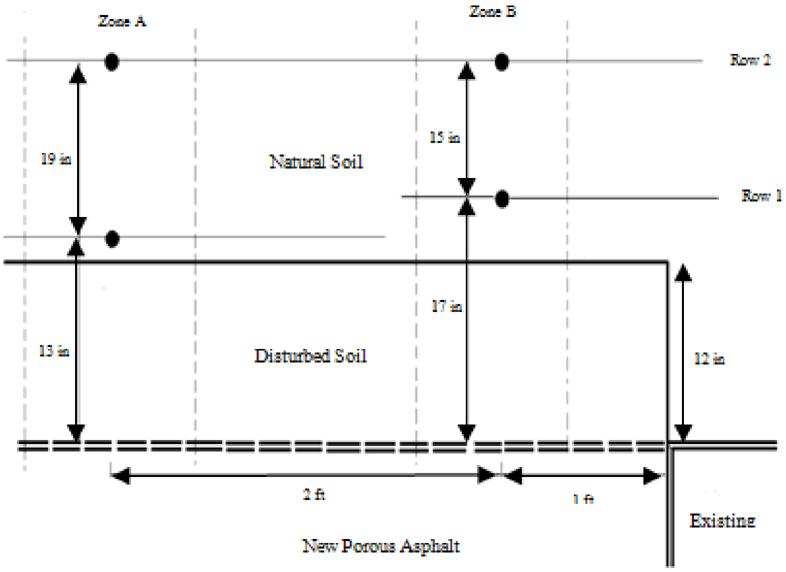


Figure 3.7 Sensor plan Zones A and B at Finch Arboretum porous asphalt parking lot

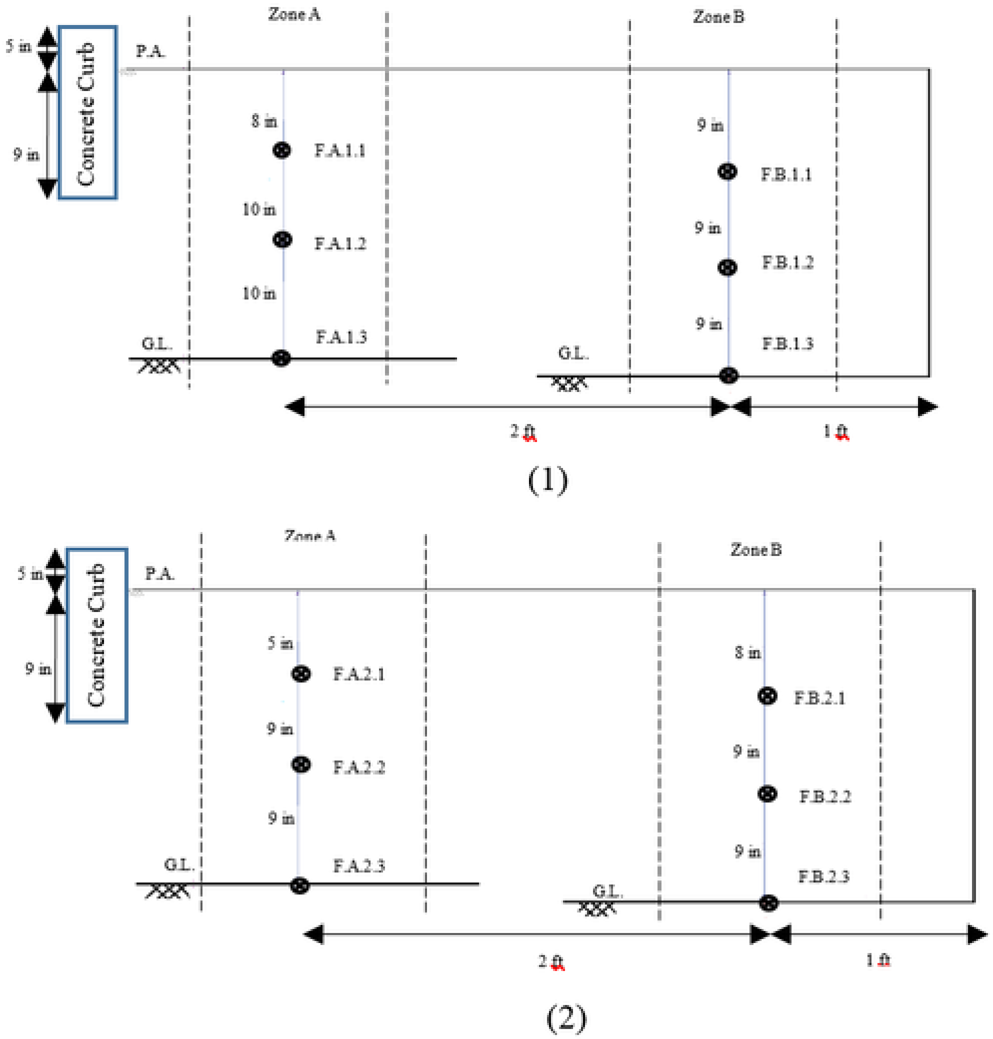


Figure 3.8 Sensor depths Zones A and B at Finch Arboretum porous asphalt parking lot in Rows 1 and 2 (note that soil height is level with the top of the concrete curb as shown)

The data collection at Finch started in late October 2015 and ended in March 2017, when the sensors were removed. Ancillary data such as weather were also collected from a weather station located at Spokane International Airport (GEG).

Community Hall Sidewalk Results: As previously mentioned, the pervious concrete system installed on the sidewalk near Community in May 2015 represents a retention type of permeable pavement system. In other words, no underdrain is at the bottom of the aggregate storage beds in this system so that stormwater that enters the storage beds is removed mainly through infiltration of the surrounding soils. The main concern in installing these types of systems in colder regions, especially when contiguous to a roadway such as a shoulder, is that the water that infiltrates might move into the areas under the nearby roadway, and if the frost depth reaches these levels, might cause roadway issues such as frost heave. The data obtained from the Community site are encouraging, indicating that this probably would not occur in regions with a climate similar to that of Pullman. The first winter (2015/2016) that the sensors recorded temperature and volumetric water content (VWC) at the sensor locations next to the installation was a mild one in that region of the country. However, the next winter (2016/2017) was very cold. Therefore, data from this second winter are included in the following description to depict the performance of the system under these severe wintertime conditions.

Figure 3.9 is a plot of temperature during the winter season of 2016/2017 for the shallowest sensors next to the Community site. All of the sensors were located approximately 12 inches below the top of the soil in a grass bed. Sensors A11 and B11 were located near the sidewalk, approximately 6 inches from its edge. Sensors A12, B12 and C12 were located farther away, approximately 18 inches from the sidewalk edge. Accordingly, the sensors located closer would be more influenced by water and the temperature of the sidewalk and its associated aggregate storage bed then the sensors located farther away. The temperatures in Figure 3.9 were recorded at or near midnight of each day so that diurnal variations would be minimized. Although, the data indicate little or no diurnal variation in temperature at these and deeper soil depths, the variations are instead seasonal. Diurnal variations in temperature were evident in the pervious concrete pavement layer itself, as has been well established in the literature. Figure 3.10 is the same plot as Figure 3.9, with the temperature recorded by a sensor in the middle of the pervious concrete layer of the sidewalk during this same period. Figure 3.10 depicts the pavement layer temperature on or around midnight to avoid diurnal variations. As can be seen, the winter was cold, with temperatures typically below freezing during the night for all but a few weeks in late winter.

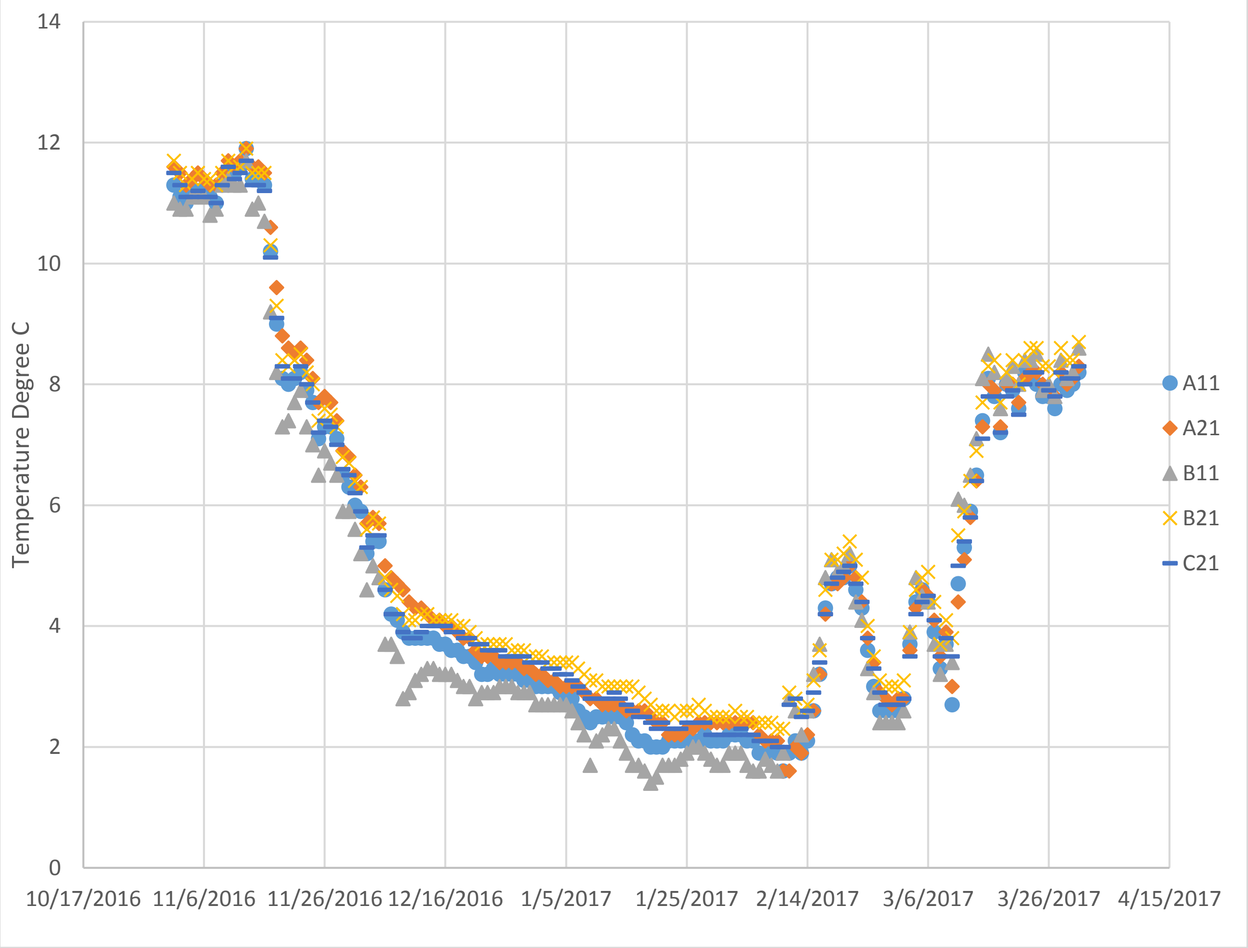


Figure 3.9 Shallow depth temperatures of Community neighboring soil, winter of 2016/2017 (midnight readings)

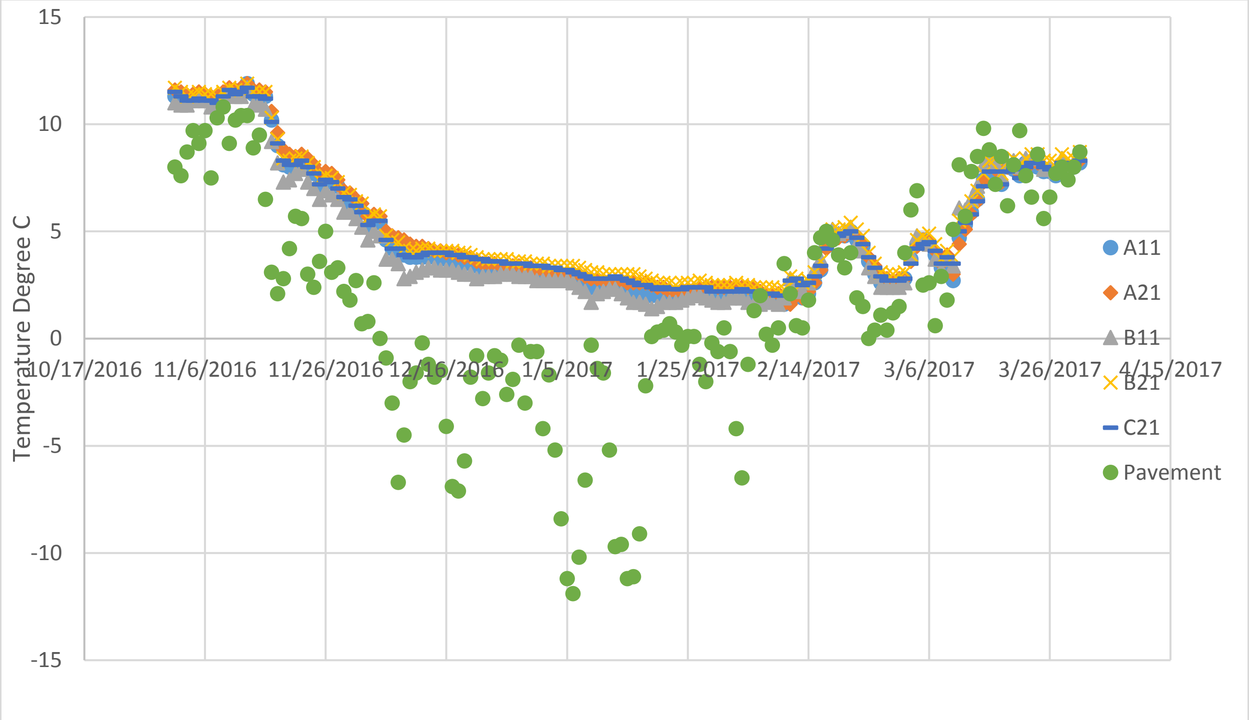


Figure 3.10 Shallow depth temperatures of Community neighboring soil and mid-depth temperatures in the pervious concrete layer, winter of 2016/2017 (midnight readings)

As can be seen in Figure 3.9, the temperature profiles at this shallow depth are similar regardless of nearness to the sidewalk, implying little or no impact from placement at these temperatures. The one exception is Sensor B11, which always read cooler than the others. However, it was noted in the field that after installation, the sod was not replaced on the soil above this sensor, and although some grass growth eventually formed here, the decreased insulation from an established sod layer above Sensor B11 might have impacted the data. Regardless, the temperatures at these shallow depths never dropped below zero, even under the coldest winter conditions. Without freezing conditions in the upper soils, little or no frost heave can be expected. However, it is still important to determine if these upper soils are saturated should an even deeper freeze occur. Figure 3.11 depicts the VWC (m^3/m^3) at these same shallow sensor locations during the same wintertime period.

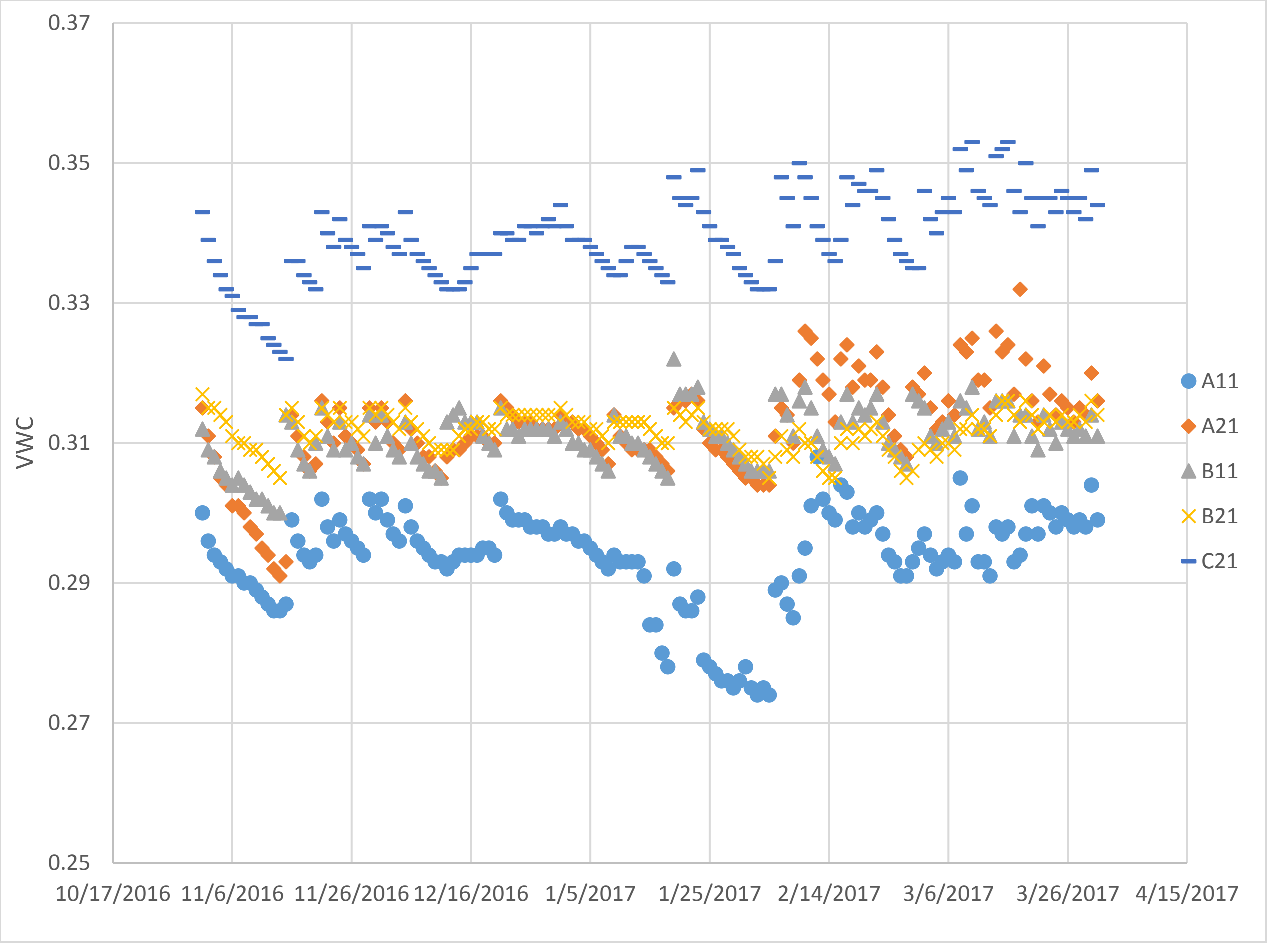


Figure 3.11 Community shallow depth volumetric water content of neighboring soil winter 2016/2017 (midnight readings)

With some exceptions, VWC is similar at shallow locations, with only slight variation over the entire winter, as seen in Figure 3.11. Sensor C21 consistently shows a higher VWC reading, and Sensor A11 consistently shows a lower VWC reading. However, these variations could be due to location, with more snowpack at one location and less at the other, but these variations are most likely due both to differences in sensor readings and slight variations in soil composition right next to each sensor. Regardless, the sensor readings for all shallow locations during the entire winter are well below a saturated condition. It was found during the previously draindown tests that the water content recorded in Sensor C12, the one closest to the underground storage bed that was artificially flooded the most, reached a VWC of 0.417. This level was not seen in any soil sensors at the Community site except during artificial flooding events. In fact, soil moisture in the sensors did not vary much with location or time. For instance, during the entire winter season, the B sensors nearest the sidewalk, regardless of depth, recorded values only between 0.291 and 0.312. During the entire two-year period of record, the sensor most likely to receive stormwater impacts, Sensor C12 since it was nearest the first upslope aggregate storage bed, never recorded a VWC of greater than 0.37 except during artificial flooding events.

The conclusion from these data on the retention system at the Community Hall sidewalk site is that if designed similarly, with flooding in the aggregate storage bed that does not fill the bed during winter, the system would have little to no chance of ice lens formation. However, the soil moisture might rise if the water level in the bed is high, as was seen during artificial flooding events. During the artificial flooding event on April 28, 2016, the critical sensor, C12, recorded a VWC of 0.304 just prior to flooding, a maximum of 0.409 during the two-hour flooding experiment, with a decrease to 0.350 within two hours of the flooding experiment ending. However, it took over two weeks for the VWC to decrease to its pre-flooding value of 0.304. Additional testing is needed for systems designed with higher water levels in the winter, although temperature profiles in Figure 3.9 show promise that little negative impact would be expected in climates similar to Pullman, Washington.

Finch Arboretum Parking Lot Results: As previously noted, the porous asphalt parking lot at the Finch Arboretum was built as a detention facility, with low underdrains in the aggregate storage bed. It was postulated that a detention-type facility would promote positive drainage from the neighboring soils, into the aggregate storage bed, decreasing negative impacts on neighboring facilities from ice lens formation. As with the retention facility in Pullman, Washington, this detention facility in Spokane, Washington, experienced a severe winter in 2016/2017. The following description summarizes the results from this winter.

Figure 3.12 shows that the upper level temperatures farther away from the permeable pavement system, A21 and B21, are nearly the same. The closer sensor at A11 reads a slightly cooler temperature, and the closer sensor at B11 reads a slightly warmer temperature. It is postulated that since the row closest to the porous asphalt system in Zone A was disturbed with geotextiles and construction debris, the reading is not as valid for undisturbed soil such as in Zone B. However, in a real installation, many areas might be disturbed with irregular compaction, etc. Therefore, both might be representative of field conditions. Regardless, with the snowpack on top of the lawn area next to the porous asphalt system, the temperature never went below freezing at these shallow, approximately 12-inch depths.

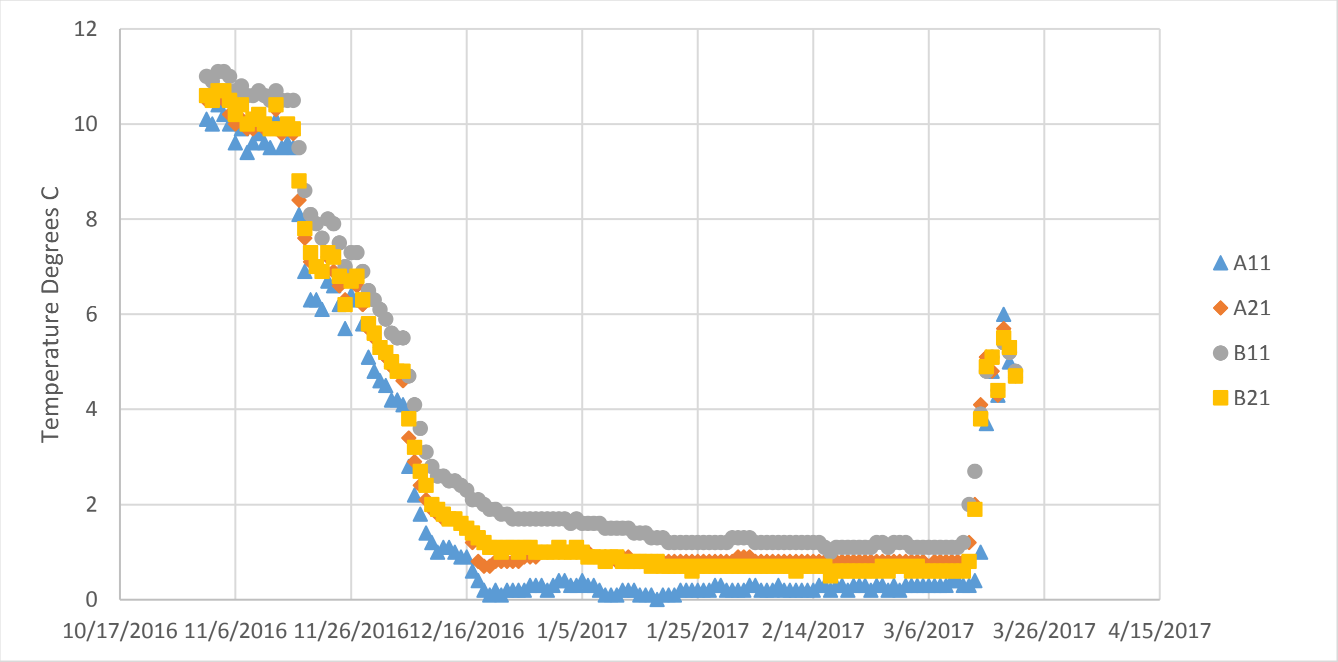


Figure 3.12 Shallow depth temperatures of Finch neighboring soil winter of 2016/2017 (midnight readings)

Figure 3.13 depicts the temperatures at all depths for Zone B. Even 3 feet down, the soil is very cold in this severe winter. In general, the sensors closer to the bed are slightly warmer than the sensors farther away during the worst part of winter. This was hypothesized, in that the insulating capabilities of the aggregate storage bed due to air voids would also have a small impact on the nearest soils.

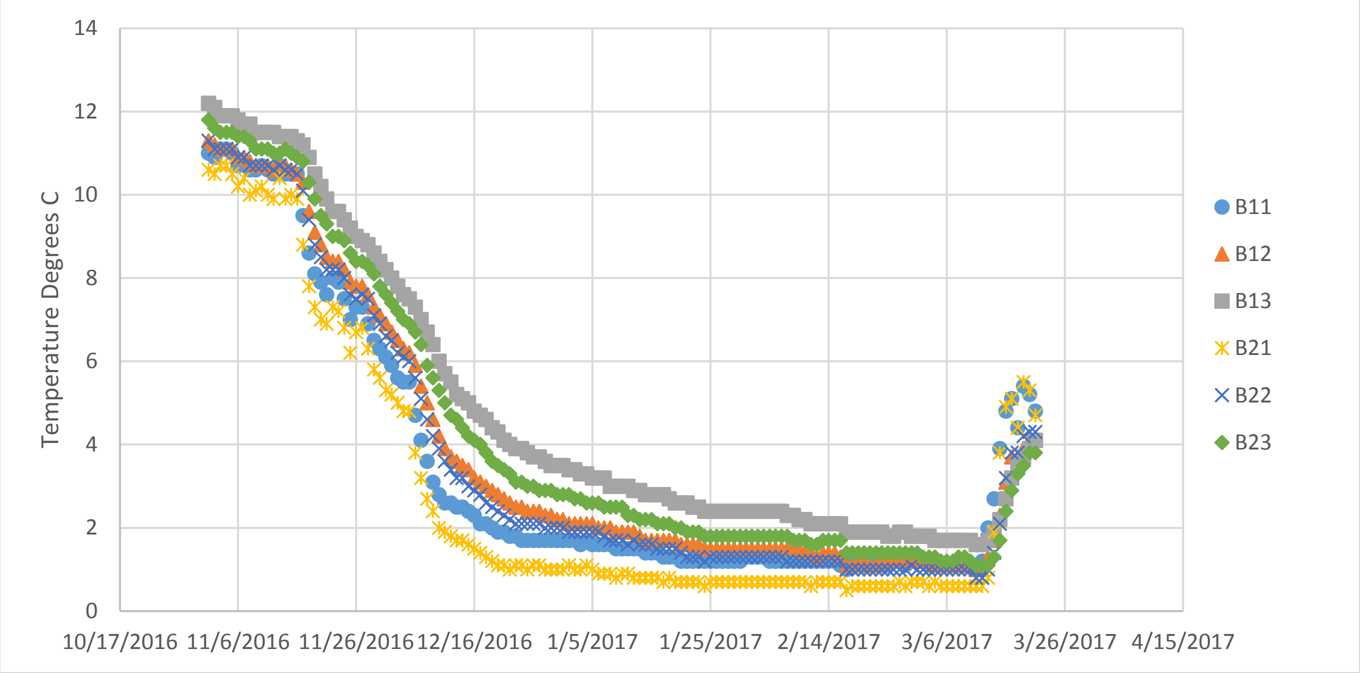


Figure 3.13 Zone B temperatures of Finch neighboring soil winter of 2016/2017 (midnight readings)

Since temperatures do drop so low in the soil, even at deeper depths, it is important to look at the VWC (m^3/m^3). Figure 3.14 is a plot of the VWCs in Zone B. Sensor B21 is not included since the reading remained at a constant 0.307 the entire time, indicative of a reading error. As can be seen, the soils are always drier lower down. It was expected that the aggregate storage bed would provide for positive drainage toward the bed from the soils. Based on these readings, it is likely that the water is entering from the top downward, not from the side of the aggregate storage bed inward.

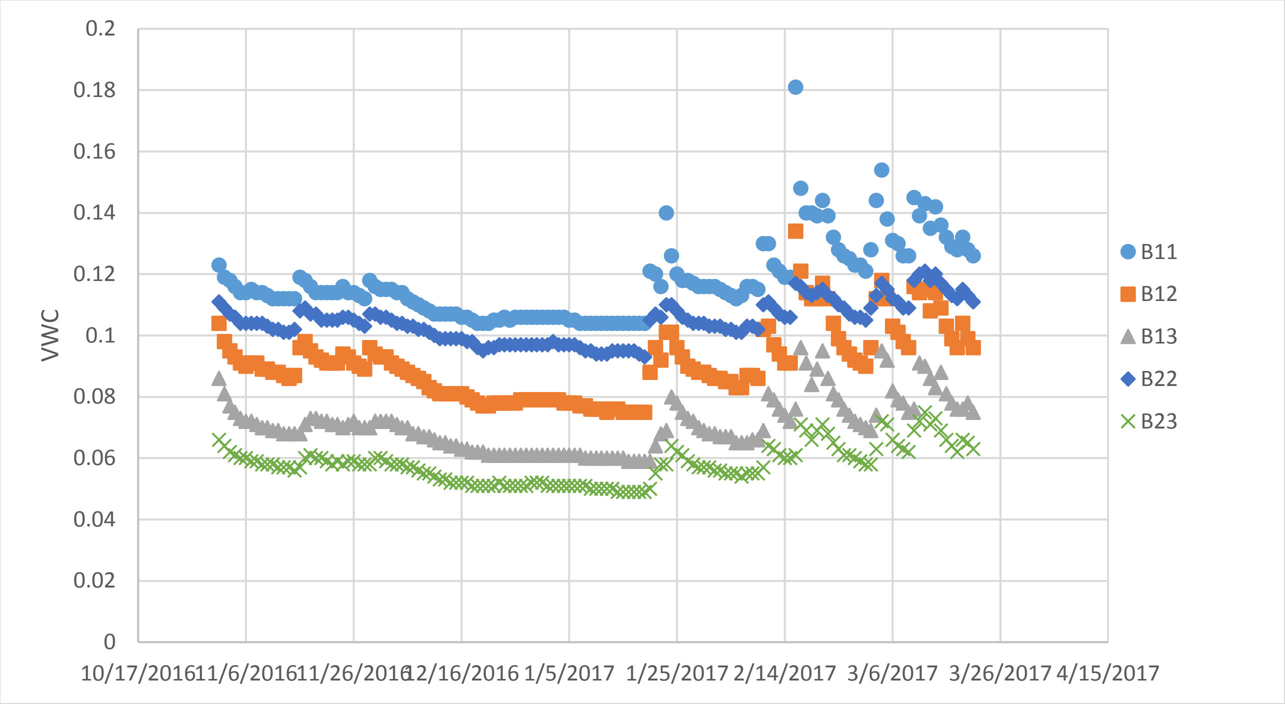


Figure 3.14 Zone B volumetric water content of Finch neighboring soil winter of 2016/2017 (midnight readings)

Figure 3.15, which is a plot of the VWC in Zone A, is an even better indicator of this drainage from the soil to the bed. As previously mentioned, the nearest sensor array in Zone A is in disturbed soil. This is evident in the varying VWC recorded by the upper sensor. Yet the lowest sensor has very low VWC, noticeably lower than the deep sensor farther away.

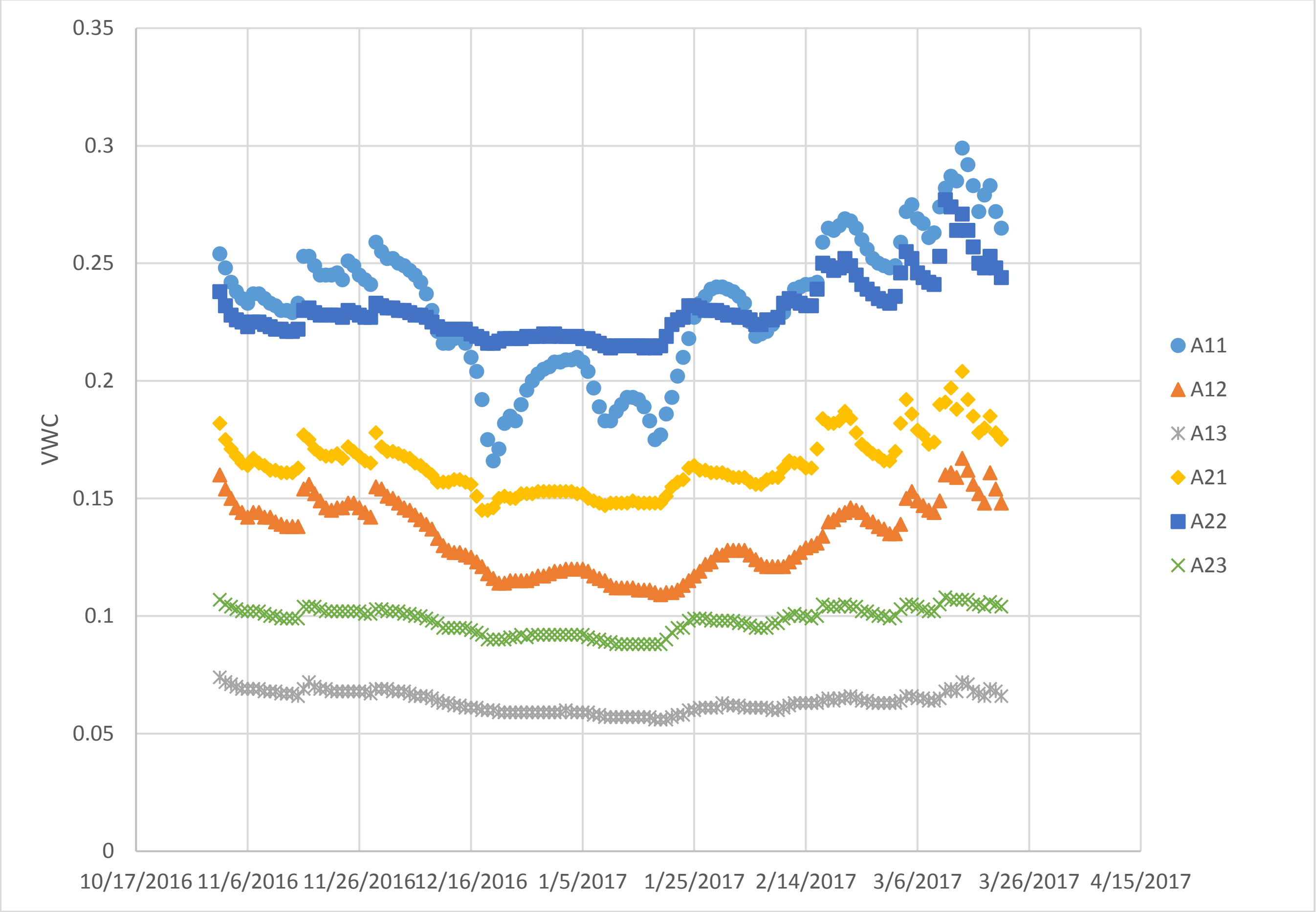


Figure 3.15 Zone A VWC of Finch neighboring soil, winter of 2016/2017 (midnight readings)

It is interesting to note the different VWC readings in the Pullman soil versus the Spokane soil. Although both have some clay content, the Palouse soil in Pullman retains much higher VWCs throughout the winter than the better draining soil at the Finch Arboretum.

Based on sensor readings in soils next to the detention-type porous asphalt system at the Finch Arboretum, it is likely that detention systems built in similar climates and soil conditions will not have a negative impact on neighboring facilities. Although soil temperatures drop, water appears to be draining into the aggregate storage bed from the neighboring soils.

CHAPTER 4.0

TASK 4 – Pavement Performance Evaluations of Facilities

In Task 4, six pervious concrete pavement installations on the WSU campus in Pullman, Washington, were tested for surface infiltration rates. The four oldest sites are Valley Playfields East (VPE), Valley Playfields Center (VPC), Veterinary Medicine Circle (VMC), and Sloan Hall Sidewalk (SHS). Some of these sites were tested at different times. The Community Hall Sidewalk (CHS or Community) and PACCAR sites are much newer; preliminary data were collected on them too. The data collected on Community and PACCAR are representative of how a newly laid pervious concrete pavement site performs. The most extensive data collection over time was from the SHS (Sloan) site. Infiltration rates were found using the single ring infiltrometer setup and procedure described by ASTM C1701 (ASTM 2009a).

A primary concern as pervious pavement ages is clogging of surface pores by particulates and debris carried onto the installation by traffic, or particulates and debris washed onto the installation from neighboring landscaping and traditional concrete installations. Surface clogging can often be seen with the naked eye, making it easy to identify. However, quantitative determination of the extent of clogging is best done by monitoring changes in infiltration rates over time (Haselbach and Werner 2015).

The SHS was installed in 2012. Eight points along the installation were marked for infiltration testing. Two of these points (G and H) were along a portion of the pervious concrete, adjacent to a non-raised flower garden, and received run-on from approximately 2000 sq. ft of impermeable concrete pavement upslope of it, with point H receiving run-on first. Points E and F were near concrete stairs, and points A and B were along a portion bordered by a raised landscape bed. Point A was also near the edge abutting a downslope non-pervious installation.

Figure 4.1 shows the placement of these points. In April 2014, the average infiltration rate for the entire installation was about 500 in./hr. By October 2015, the average infiltration rate had decreased by over 50% (to less than 200 in./hr).

Figure 4.1 Testing points for infiltration testing at SHS (Werner and Haselbach 2017)

It has been hypothesized that certain areas near the edges of pervious installations would be the first to experience clogging, due to debris from run-on from landscaping or non-pervious installations upslope. Sampling points A and B experienced heavy clogging from the neighboring landscape bed and from snow piles, resulting in negligible infiltration rates as early as February 2015 and remaining fully clogged through September 2015. Points C and D averaged 621 in./hr in April 2014, which decreased to 178 by February 2015, and dropped to only 58 in./hr by October 2015. Location H was clogged in early 2015. This distribution of infiltration rates seems to corroborate the hypothesis that areas not near adjacent gardens or bordering non-pervious installations maintain the highest rates of infiltration, suggesting that run-on from raised soiled areas and run-on from paved areas may cause severe clogging over time.

It is important to manage clogging of pervious pavement, since clogging can contribute to increased freeze-thaw damage and inland flooding (Haselbach and Werner 2015, Deo et al. 2010). Previous studies have suggested the use of a modified Ditch Witch (Brown and Sparkman 2014), or a regenerative air street sweeper (Haselbach and Werner 2015, Hunt 2011) to clean pervious installations. In this study, a portion of SHS was cleaned using a simple hand-held hose equipped with a spray nozzle. Only one infiltration test has been completed since this cleaning procedure, but the test indicates that the infiltration rate improved after cleaning. In October 2015, points G and H at SHS, which were heavily clogged by neighboring run-on (resulting in negligible infiltration rates), were cleaned, afterward indicating infiltration rates of about 130 in./hr. Uncleaned portions E and F—which were not as heavily clogged to start with—had an average infiltration rate of about 60 in./hr at this time. These rates indicate that simple spray washing was effective in reducing clogging of the pervious pavement surface. Table 4.1 is a summary of the aforementioned studies for the seven major permeable pavement placements on the WSU Pullman campus.

Table 4.1 Average infiltration rates and corresponding ages for each installation

Site	**2014 Average (in./hr)**	**Winters Experienced by 2014 Testing**	**2015 Average (in./hr)**	**Winters Experienced by 2015 Testing**
Valley Playfields East	498	4	178	5
Valley Playfields Center	594	3	no data	4
VetMed Circle	413	3	234	4
ADA Parking Lot (asphalt)	123	3	no data	4
Sloan Hall Sidewalk	513	2	233*	3
Community Hall Sidewalk			1820	0
PACCAR			977	0

Note: Locations were not chosen randomly and therefore the numbers may be biased to clogged areas.
*This data point reflects a partial cleaning of the pervious installation. Prior to cleaning, this value was likely closer to about 190 in./hr.

New installations at Community and PACCAR have infiltrations rates of 900–2000 in./hr—over 7 times the infiltration rate of the cleaned portion of SHS. This infiltration rate indicates that the cleaning procedure was not capable of returning the pavement to a completely clean state, but this is not significant for determining hydraulic functionality, since as long as the surface infiltration rate can handle the stormwater, the system is functioning well with respect to surface infiltration. Hunt (2011) suggests a cleaning frequency of 4–6 times yearly. However, as shown in Figure 4.2 and Table 4.1, the placements on the Pullman campus have all been functioning for several years without maintenance, and an annual cleaning for severely clogged areas or cleaning every 2 years appears to be sufficient.

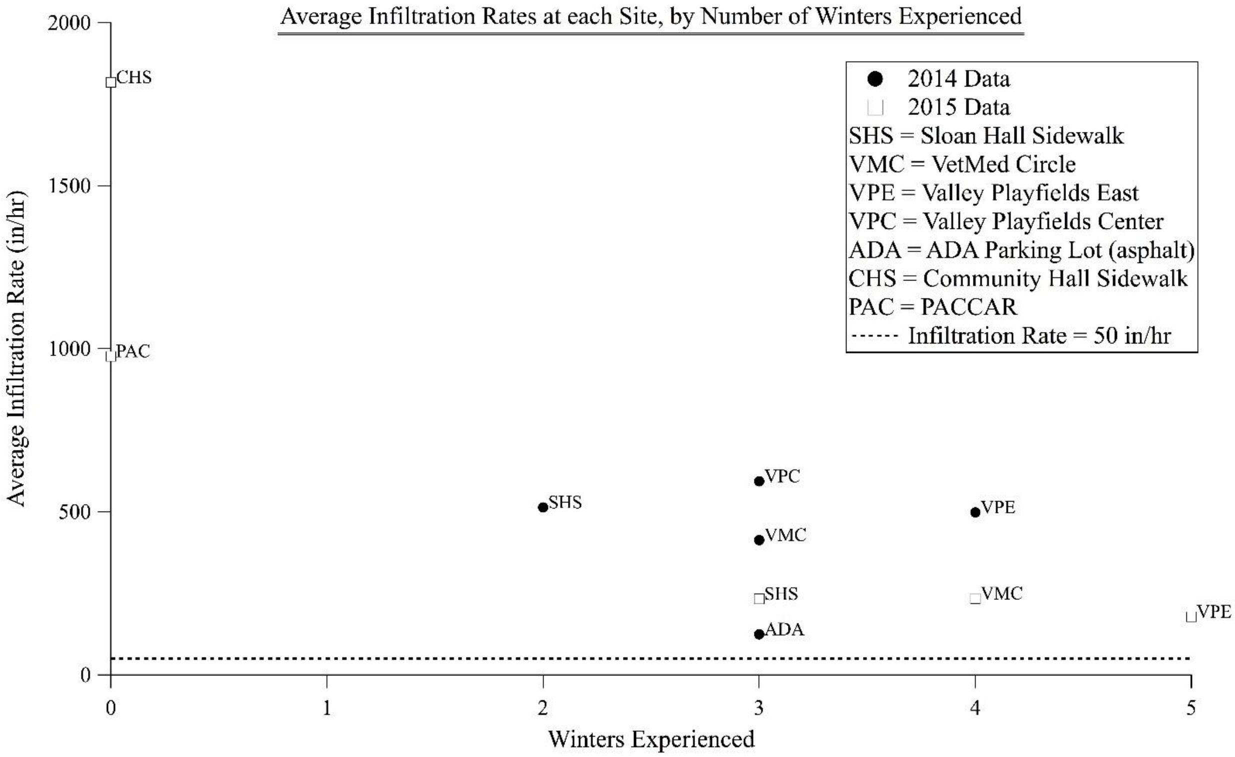


Figure 4.2 Average infiltration rates determined for each installation at varying ages, based on Table 4.1 data (the 2015 SHS data were taken after a partial cleaning of the pad)

A second factor to consider when monitoring infiltration rates of pervious installations is the temperature effects caused by seasonal temperature variations. Changes in temperature can affect the viscosity of the water, therein altering the hydraulic conductivity of the water (Werner and Haselbach 2016 and 2017, Emerson and Traver 2008). The infiltration rates of points B–D at SHS were monitored from January–October 2015, and the air temperature, surface temperature, and relative humidity were recorded for each test. Infiltration rates and temperature versus time have been plotted for each testing point, as shown in Figures 4.3–4.5. These figures were taken from Werner and Haselbach (2016). The traces for infiltration and temperature do not always exactly follow the same trends; however, they follow each other often enough to imply that temperature can have a significant effect on infiltration rate. Infiltration rates were estimated to decrease by about 50% between freezing and 80°F (Werner and Haselbach 2016).

Though a clear seasonal temperature effect on infiltration rates is evident, clogging has a much larger influence. Figure 4.6, from Werner and Haselbach (2016), shows a year-long overall decreasing trend in infiltration rate due to clogging, and that changes in temperature produce only relatively minor oscillations in infiltration (Werner and Haselbach 2016 and 2017).

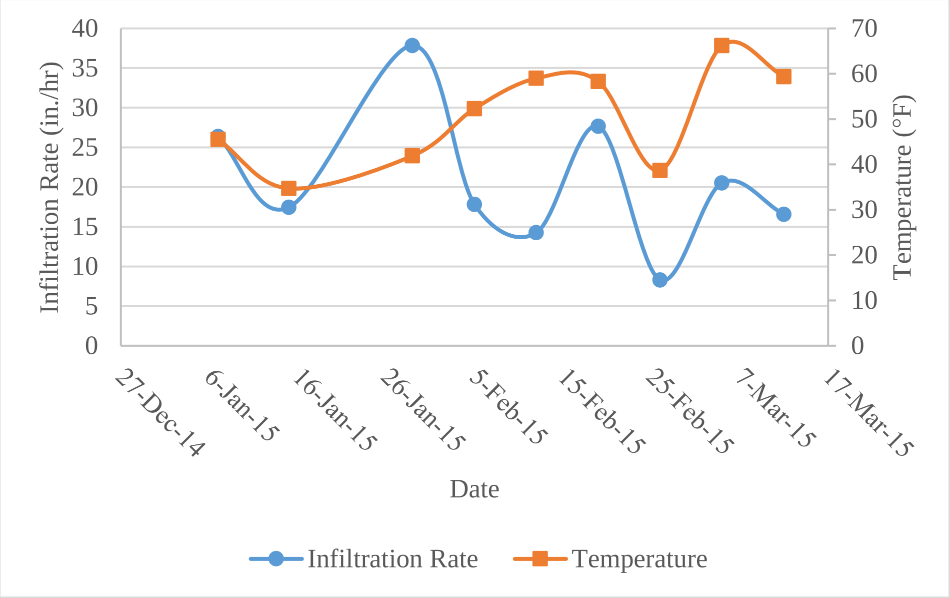


Figure 4.3 Infiltration rates and temperatures for SHS point B

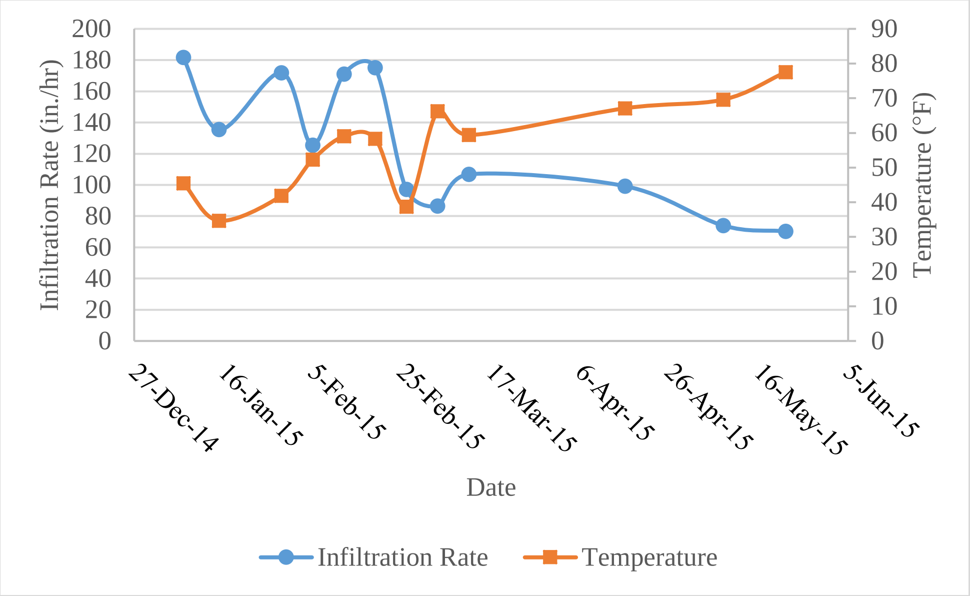


Figure 4.4 Infiltration rates and temperatures for SHS point C

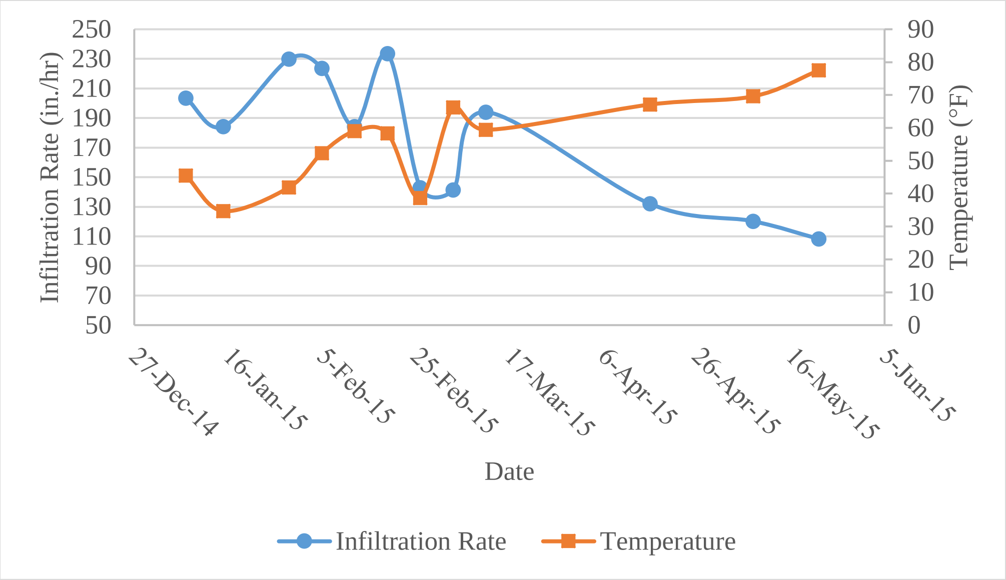


Figure 4.5 Infiltration rates and temperatures for SHS point D

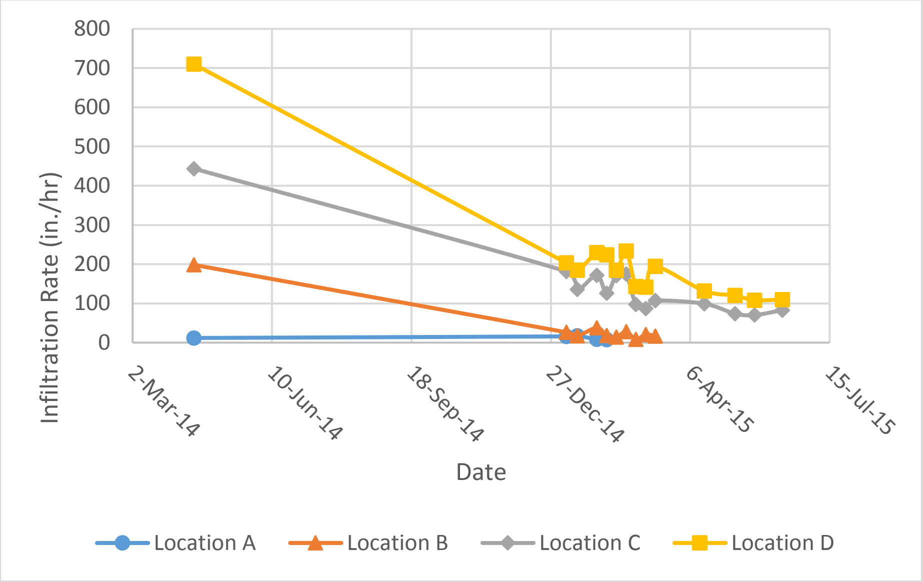


Figure 4.6 Infiltration rates for SHS points A–D from April 2014–June 2015

A preliminary pavement-condition index evaluation was performed in 2014 on the four older existing pervious concrete installations and one existing porous asphalt placement, using ASTM D6433, *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys* (ASTM 2011), with the intent of exploring options for modifying this standard to include these types of permeable pavements. At most locations, the pavements were in good condition, with raveling observed at locations that receive a significant amount of turning or truck traffic, or which had initiated from original placement activities. It is hoped that the suggestions for further developing this standard to include these pavements will be included in future research.

CHAPTER 5.0

TASK 5 – Surface Installation Design Modification for Improved Winter Condition

The idea behind Task 5 involved enhancement of the surface microtexture of pervious concrete, which may be beneficial under icy conditions to help reduce the possibility of pedestrians slipping. In this task, different surface treatments were evaluated, qualitatively by personal observations and quantitatively by using a spring balance for “slipperiness.” It is hypothesized that increased microtexture surface roughness of pervious concrete reduces the amount of deicing materials needed during icy conditions and, therefore, the use of deicing materials, which might impact the concrete’s structural performance (Litzka 2002).

Based on previous experiments in the Washington State University laboratory and on discussions with various concrete pavement professionals, five surface treatments were chosen for testing. These treatments are listed and described in Table 5.1. Two specimens of each type were prepared. The specimens were made in molds to have surface dimensions of 350 mm (13.7 in.) by 200 mm (7.8 in.) and an approximate depth of 100 mm (3.9 in.). All of the specimens were surface compacted using a flat board and a mallet to effect a porosity of around 20–27% in most cases. Details are provided in Yekkalar et al. (2016).

Table 5.1 Microtexture specimens and porosities and infiltration rates (Yekkalar et al. 2016)

Surface Treatment	Description	Specimen	Porosity* (%)	Infiltration Rate** (m/hr)
Broom	Broom finishing applied after compaction	Broom 1	20	30
		Broom 2	20	30
Pre-Sand	20 grams fine sand applied before compaction	Pre-Sand 1	27	35
		Pre-Sand 2	25	37
Coating	Sealant mixture applied after curing	Coating 1	27	48
		Coating 2	25	42
Post-Sand	20 grams fine sand applied after compaction	Post-Sand 1	23	38
		Post-Sand 2	26	37
Control	No treatment after compaction	Control 1	32	37
		Control 2	26	42

* (ASTM 2012) ** (ASTM 2009a)

The adapted methodology for the qualitative “slipperiness” classification of the microtexture was mainly based on assessment by means of subjective inspection. For this purpose, the specimens were placed outdoors in a landscape bed next to a pervious concrete sidewalk, and during this period (1/25/2015 to 4/7/2015), the operator conducted qualitative assessment by sliding his/her foot on each specimen in order to gain a general idea about the performance of different treatments in terms of skid resistance. The specimens were not labeled as to the treatment type to avoid any possible prejudice. (This practice also allowed the specimens to weather under normal wear and exposure conditions for approximately a half year.) Using this method, a score of 5, 4, 3, 2, or 1, which corresponded to “considerable,” “high,” “medium,” “low,” and “negligible” skid resistance, respectively, was assigned to each specimen in a checklist designed for this purpose. The operator performing the test also noted the weather conditions so that the observations could be separated into either wet or dry surface conditions. Figure 5.1 provides the results from the qualitative evaluation as averaged for 74 daily observations on each specimen.

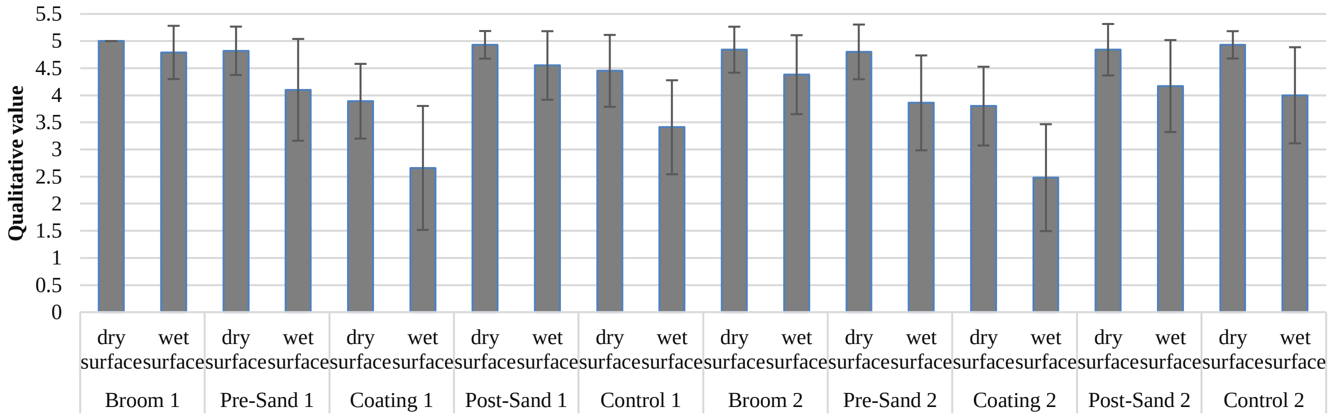


Figure 5.1 Summary of qualitative microtexture evaluation (Yekkalar et al. 2016)

Since this type of qualitative evaluation may be insufficient due subjective judgment (Santos and Julio 2013), it was decided to develop a quantitative method to compare the different treatments with respect to surface roughness. For this purpose, the specimens were transported to the laboratory and evaluated using the spring balance method. As a friction measurement method, the spring balance approach was chosen because of its simplicity, being practical for horizontal placements. The idea is that if one puts a solid object on a rough surface and starts to pull on it, a point is reached at which the object starts to slide. Then, the coefficient of friction is calculated as:

$$\mu = \frac{F}{(m \times g)} \tag{5.1}$$

where μ is the coefficient of friction, F is the external force applied on the board as measured by the spring balance, m is the mass of the weights and board, and g is acceleration due to gravity (Gao et al. 2004).

By using different combinations of weights on the board and their corresponding external forces, several “static coefficient of frictions” (SCOFs) are evaluated. As with other experimental measurements, it is suggested that the test be conducted in at least two different locations and three times for each location to increase the accuracy of the results. In this experimental setup, the tests at each location were done with three different normal forces, one test for each, and the SCOFs were averaged at each location. Conducting the test with different operators can be helpful for this purpose. In this way, 360 friction tests were conducted by three different operators on pairs of specimens with five different textures under both dry and wet surface conditions. Figure 5.2 is the summary of average values of measurements on two locations of each specimen (average of three trials for each location) reported by the three different operators for the spring balance method (Yekkalar et al. 2016).

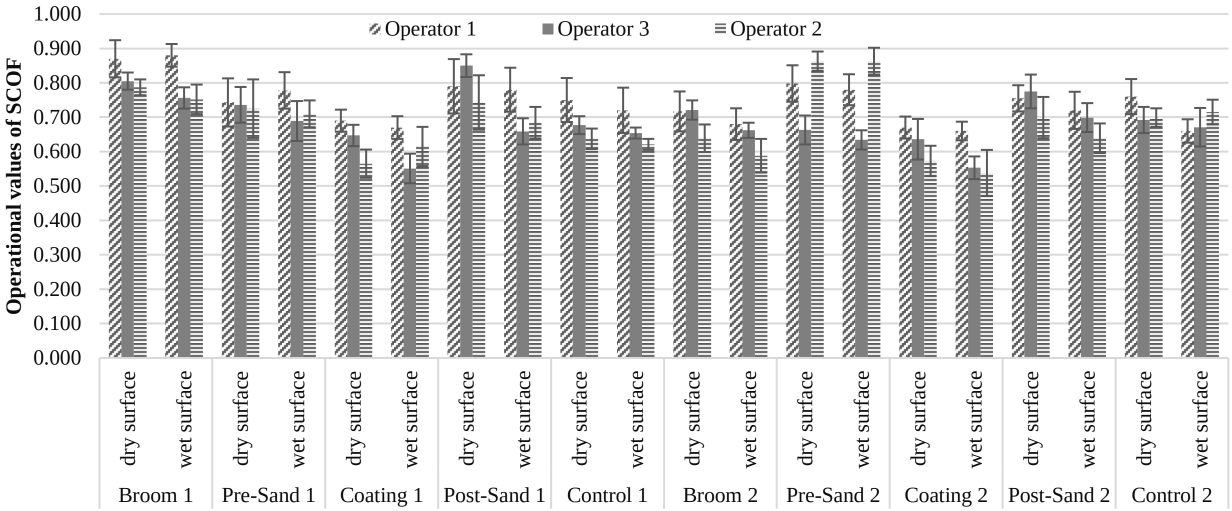
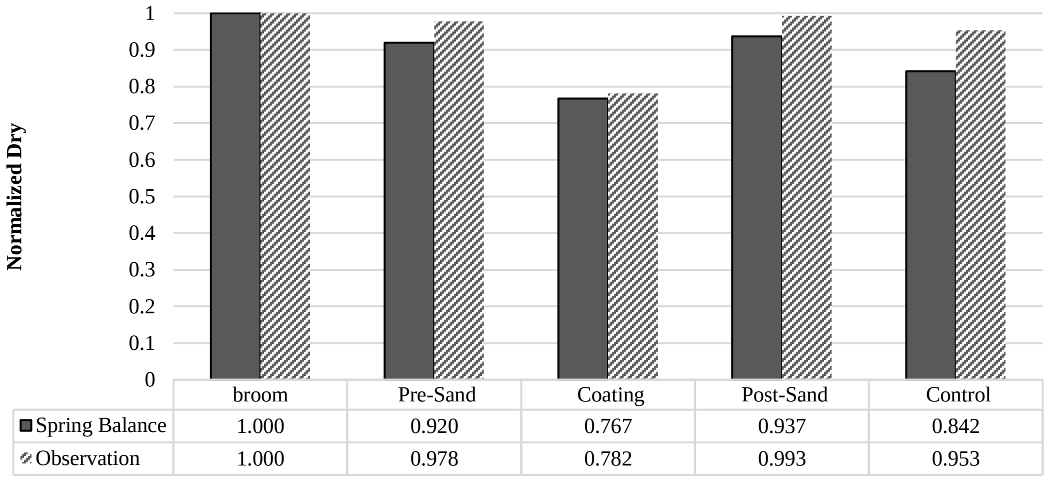


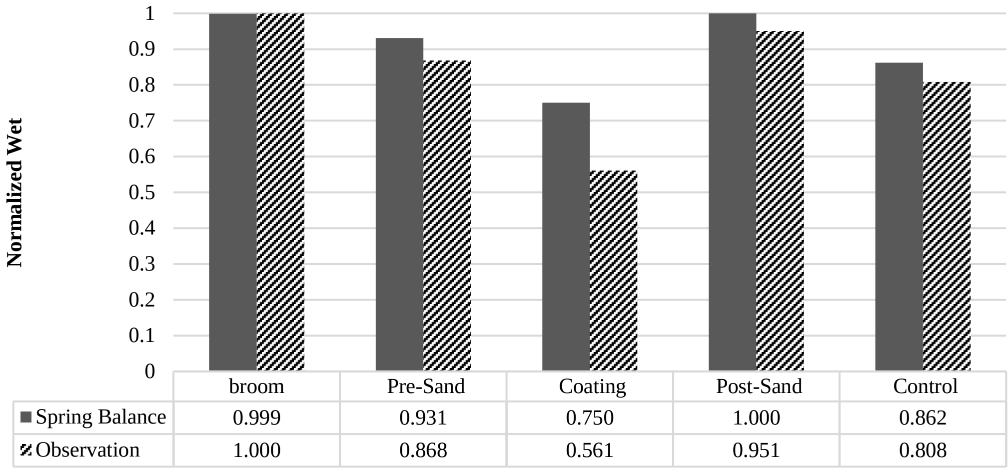
Figure 5.2 Summary of spring balance tests conducted by three operators (Yekkalar et al. 2016)

To compare the two methods visually, the values in Figures 5.1 and 5.2 were normalized. This was done by dividing the average values for each surface treatment by the highest average value for either the wet or the dry condition for the respective methodology. Figures 5.3 and 5.4 compare the normalized values of the surface evaluations for both the spring balance and the qualitative observations under dry and wet conditions.



	broom	Pre-Sand	Coating	Post-Sand	Control
■ Spring Balance	1.000	0.920	0.767	0.937	0.842
▨ Observation	1.000	0.978	0.782	0.993	0.953

Figure 5.3 Normalized average results for both methods in dry conditions (Yekkalar et al. 2016)



	broom	Pre-Sand	Coating	Post-Sand	Control
■ Spring Balance	0.999	0.931	0.750	1.000	0.862
▨ Observation	1.000	0.868	0.561	0.951	0.808

Figure 5.4 Normalized average results for both methods, in wet conditions (Yekkalar et al. 2016)

The results from both the quantitative and the qualitative approaches show that broom finishing ranks the highest in terms of friction or lack of “slipperiness,” and it appears that sand treatments improve the microtexture of the surface under both dry and wet conditions. However, results show that the pre-compaction method is not as effective as the post-compaction method. Finally, the coating treatment seems to affect surface roughness negatively, especially under wet conditions.

To measure how much the operators agreed on ranking of items, it was decided to evaluate the consistency of multiple raters (more than two operators) by using Kendall's coefficient of concordance (KCC). In addition, Spearman’s Rho, which is based on paired comparisons (the two methods), was applied to evaluate the extent of correlation between the quantitative results and the qualitative results (Stemler 2004, Gwet 2012). In this reliability analysis, coefficients of 0.1, 0.3, and 0.5 are generally interpreted as low, medium, and high correlations, respectively (Cohen 1988). The reliability analyses showed a high level of consistency among the operators for the quantitative (spring balance) approach, and a high level of consistency between the qualitative results and the spring balance method results (Yekkalar et al. 2016). This analysis implies that the spring balance method may be an adequate substitute for other qualitative methods of evaluation of various surface treatments, and that the spring balance method holds promise for adequate consistency between different operators. These high levels of consistency are supported by similar trends in Figures 5.3 and 5.4.

Considering these findings, as well as the fact that brooming may be a cost-effective treatment, one might conclude that broom finishing is the most sustainable solution among the different treatment methods considered in this study. However, further fieldwork is needed to see if the curing period post-placement, with plastic sheeting over the slabs, affects brooming. Moreover, the benefits of sand treatments might change as the sand wears off the surfaces, just as ridges from broom finishing may wear and lose effect. Again, only long-term field study will provide these answers. The coating method with the lowest ranking appeared to be the least cost-effective and sustainable solution, and may not be better than the control method. Finally, evaluations should be performed in the field under icing conditions, such as with hoarfrost, as the winter period during which these specimens were evaluated was mild.

CHAPTER 6.0

TASK 6 – Predict Stormwater Impacts of Low-Impact Development Implementations and Campus Summary

In Task 6, we summarize some of the hydrologic characteristics studied on the WSU Pullman campus, apply the knowledge in an example of how it might extend to associated stormwater pollutant reduction, and depict how the work might be used in a hypothetical future application at WSU.

6.1 Summary of Hydrological Analyses Based on Monitoring and Study Results

Extended retention seems to be a possibility in the Palouse region, with draindown times of less than a day. However, more testing using soil moisture and temperature sensors will provide information on whether these permeable pavements can be placed next to other pavement installations without wintertime impacts, and studies following a wet winter season will aid in validating volumes of storage basins needed during various weather and seasonal conditions.

The amounts of impervious surface that might be positively impacted by stormwater quantity and quality control for every square foot of pervious concrete installed on the WSU Pullman campus might initially be estimated from the combination of the square footage of pervious installations and associated areas of impermeable pavement surfaces that run onto these installations, as can be seen in Table 6.1. These estimates imply that on average, decisions to substitute pervious concrete for a traditional pavement surface will result in the effective removal of double that area of impermeable surface.

Table 6.1 Pervious concrete and impermeable run-on areas (Haselbach and Werner 2015)

Site	Pervious Concrete Area	Paved Run-on Sources	Paved Approximate Area Producing Run-on	Total Area	Ratio of Total Area to Pervious Concrete Area
Valley Playfield East	4277 ft^2	Incline Standard Concrete	2500 ft^2	6777 ft^2	1.58
Valley Playfield Center	7262 ft^2	None	Negligible	7262 ft^2	1.00
Vet Med	2827 ft^2	Incline Standard Concrete	4000 ft^2	6827 ft^2	2.41
Sloan Sidewalk	960 ft^2	Incline Standard Concrete	2000 ft^2	2960 ft^2	3.08
				Average	2.02

Pervious concrete installations will need to be cleaned periodically, with frequency depending on run-on areas and usage. However, based on the many years of use cited in Table 1.2, cleaning would usually not be needed more often than yearly, perhaps even less frequently. Power washing is an effective remediation method.

Surface evaluation of the four earlier pervious concrete installations and the one porous asphalt installation showed signs of raveling at certain locations, predominantly where vehicles turn on pervious concrete or places with initial raveling from placement activities.

Preliminary studies on various surface treatments on pervious concrete show promise for further safety benefits under wintry conditions.

6.2 Estimate of Applicable Pollutant Loading Based on Total Maximum Daily Load and Other Supporting Studies

Based on the results shown in Table 6.1, any square footage of permeable pavement installed should handle stormwater runoff from most storm events, and most of the associated pollutants from double that area, especially dissolved components. Therefore, on average, any installation will potentially reduce the pollutant load by the ratio of double the surface area divided by the total impermeable area of the subject area draining to the permeable pavement placement. This might be portrayed by Equation 6.1:

$$R\ (\%) = 100*2(A_{PP}/A_{IMP}) \qquad 6.1$$

where R (%) = stormwater pollutant reduction in percent, A_{PP} = area of permeable pavement installed, and A_{IMP} = impermeable area in the subject drainage area to the permeable pavement.

In addition, targeted areas such as the one related to the potential for fecal coliforms, as described in the next section, might increase that removal ratio. (Note that if this ratio is increased substantially, the frequency of cleaning the facilities might also need to be increased.)

6.3 Comparison with Task 1

In order to compare this final work with Task 1, it may be beneficial to summarize the second sub-duty, to analyze impervious and pervious surfaces, estimate existing stormwater flows, and incorporate information from the WSU Facility Services ongoing hydrologic/hydraulic survey**,** as previously reported in Adams et al. (2014). Following this summary, the chosen site is evaluated for hydrologic performance.

The first steps taken toward completion of Task 1 of the low-impact development (LID) stormwater analysis were to identify stormwater priority areas on the WSU Pullman campus with respect to current total maximum daily load (TMDL) and to analyze those areas in terms of possible pervious pavement applications and resulting benefits. In working with people from Environmental Health and Safety and WSU Facilities Services, four sites of interest were identified surrounding the WSU Veterinary Teaching Hospital. This area of campus was considered high priority due to the possibility of fecal coliforms in the stormwater runoff; large animal transfers and related activities frequently occur here. These sites were considered candidates for further analysis for Task 6 of the LID Feasibility Project: Predict Stormwater Impacts of LID Implementations and Summary for Campus.

Of the four sites, three were located downhill from the Veterinary Hospital; the sites were labeled McCoy North (A), McCoy West (B), and Bustad South (C). The fourth site, labeled the Allen Center Addition (D), was located uphill of the Veterinary Hospital. The following paragraphs provide brief site descriptions, and Table 6.2 provides a summary of some of the key traits of each site.

A. McCoy North

The McCoy North site is located on the north face of McCoy Hall. The site is approximately 8621 sq. ft of impervious asphalt pavement, bordered on the west and south by McCoy Hall, and on the north and east by a cement barrier separating it from a driveway leading from Stadium Way to the McCoy/Bustad/Veterinary Hospital parking lot. The north side of McCoy Hall (the south side of this site) has a small parking area, as well as an animal loading ramp.

Stormwater at this site is directed to two catch basins: one on each side of the animal loading ramp. The eastern catch basin drains into a 12-inch concrete pipe, which joins a 24-inch concrete pipe near Stadium Way. The water from this drain is eventually discharged into the South Fork Palouse River. The western catch basin drains into a 10-inch clay pipe and discharges into a dry well near the northwest corner of McCoy Hall. This location was not selected for Task 6 due to its low elevation, which may hinder permeable pavement systems with gravity discharge.

B. McCoy West

The McCoy West site is located on the west face of McCoy Hall. The site is approximately 9113 sq. ft of impervious asphalt pavement, bordered on the west by Wegner Hall, except for the southwest corner which is the inlet for a driveway coming from Stadium Way. McCoy West is bordered on the north and east by McCoy Hall, and on the south by a cement wall separating it from trees and grass. The west side of McCoy Hall (the east side of this site) has a small parking area, as well as an animal loading zone and bedding compactor.

Stormwater at this site is directed to three catch basins: two located at the southeast corner and one located in the northwest corner. The southeast corner catch basins, as well as the foundation, drains from McCoy Hall into an 8-inch iron pipe, which leads to a manhole. The northwest corner catch basin also directs water to the manhole, through a 6-inch metal pipe. After the manhole, the water is directed west near the center of the site, but after this point it is unknown where the water drains. The McCoy West site was not selected for Task 6 due to the compactor, which may have other alternatives for pollutant control.

C. Bustad South

The Bustad South site is located on the south face of Bustad Hall. The site is approximately 34,300 sq. ft of impervious asphalt pavement, bordered on the west by McCoy Hall, on the North by Bustad Hall, and on the east by the Veterinary Hospital. The south side of the site is bordered partially by the Veterinary Hospital, but is also connected to a road leasing from the south side Veterinary Hospital parking lot near the Allen Center. On the north side, a small driveway leads past McCoy North to Stadium Way. The south side of Bustad Hall (the north side of this site) has a small parking area, as well as an animal loading dock.

Stormwater at this site is directed to six catch basins, one of which is located at the lowest elevation at this site, directly in front of the animal loading dock. Each of the catch basins drains into a 6-inch iron pipe, which drain into 10- and 12-inch concrete pipes heading toward Stadium Way. These pipes are shared with the McCoy North site and, therefore, drain into the South Fork Palouse River. Five roof drains contribute to runoff at this site. The Bustad South site has been selected for Task 6 due to its large stormwater discharge (and therefore greater potential to decrease runoff) and for the site's relative simplicity. This analysis would be as an alternative to an already proposed project that would berm the animal loading dock area, directing stormwater flow away from it.

D. Allen Center Addition

The Allen Center Addition site is much larger and much more complicated than the other three sites. It is located off the southeast corner of the Veterinary Teaching Hospital. The site is approximately 66,000+ sq. ft of mixed impervious and pervious pavement and non-paved (grass) surface; it is bordered on the east and north by the Allen Center, on the south by Olympia Avenue, and on the west by the Veterinary Hospital driveway and parking lot. The west side of this site (south of the Veterinary Hospital) has livestock corrals. Approximately 33,000 sq. ft of this site, on the west side of the Allen Center, is designated for an addition to the Allen Center.

Stormwater at this site is directed through a pipe to an armored ditch, after which stormwater is drained to the two Carver Farm ponds, where it infiltrates the groundwater system. Overflow from this system is directed via a culvert into a bio-infiltration swale leading to Cougar Ponds. Water from Cougar Ponds then discharges into Paradise Creek. It is currently known that this system of stormwater management results in the discharge of very clean stormwater into the South Fork Palouse River system. However, it is unknown whether this system can handle potential higher stormwater flow from the proposed addition and remain effective in removal of fecal coliforms and other stormwater contaminants. The Allen Center site was initially selected for Task 6 due to its large stormwater discharge (and therefore greater potential to decrease runoff), but the complexity of the alternatives for various stormwater systems at this site makes it difficult to model at present, and impacts on the existing discharge network are unknown.

Table 6.2 Area and runoff coefficients for Site C and sub-areas

	Surface	**Area**	**Unit**	**C – Runoff Coefficient** (Haselbach 2010)	
Area 1	Impervious	2918.5	sq. ft	0.95	Pavement, concrete
Area 2	Grass	2918.5	sq. ft	0.20	Vegetation, average
Area 3	Impervious	7405.2	sq. ft	0.95	Pavement, concrete
Area 4 w/o pervious	Impervious	12196.8	sq. ft	0.95	Pavement, concrete
Area 4 w/ pervious	*Impervious*	*11796.8*	*sq. ft*	*0.95*	*Pavement, concrete*
Area 4 w/ pervious (A_{PC})	*Pervious*	*400*	*sq. ft*	*0.00*	*Pervious concrete (0–1% slope)*
Area 5	Impervious	3484.8	sq. ft	0.95	Pavement, concrete
Area 6	Rooftop	19602	sq. ft	0.95	Roof, conventional
Site C total	Mixed	48525.8	sq. ft	0.90	(C_C)

Bustad South (Site C) – Analysis

The intention of the rest of this section is to evaluate the stormwater runoff reduction from Site C if an alternative design with a pervious concrete swath is used instead of a berm in front of the loading dock at the Bustad South location. First, Site C was analyzed for total area and the areas and surface types of the sub-areas. Surface types were determined from Figure 6.1. These areas and the sub-areas are listed in Table 6.2. Run-on calculations were performed using the rational method (Haselbach 2010, Valavala et al. 2006).

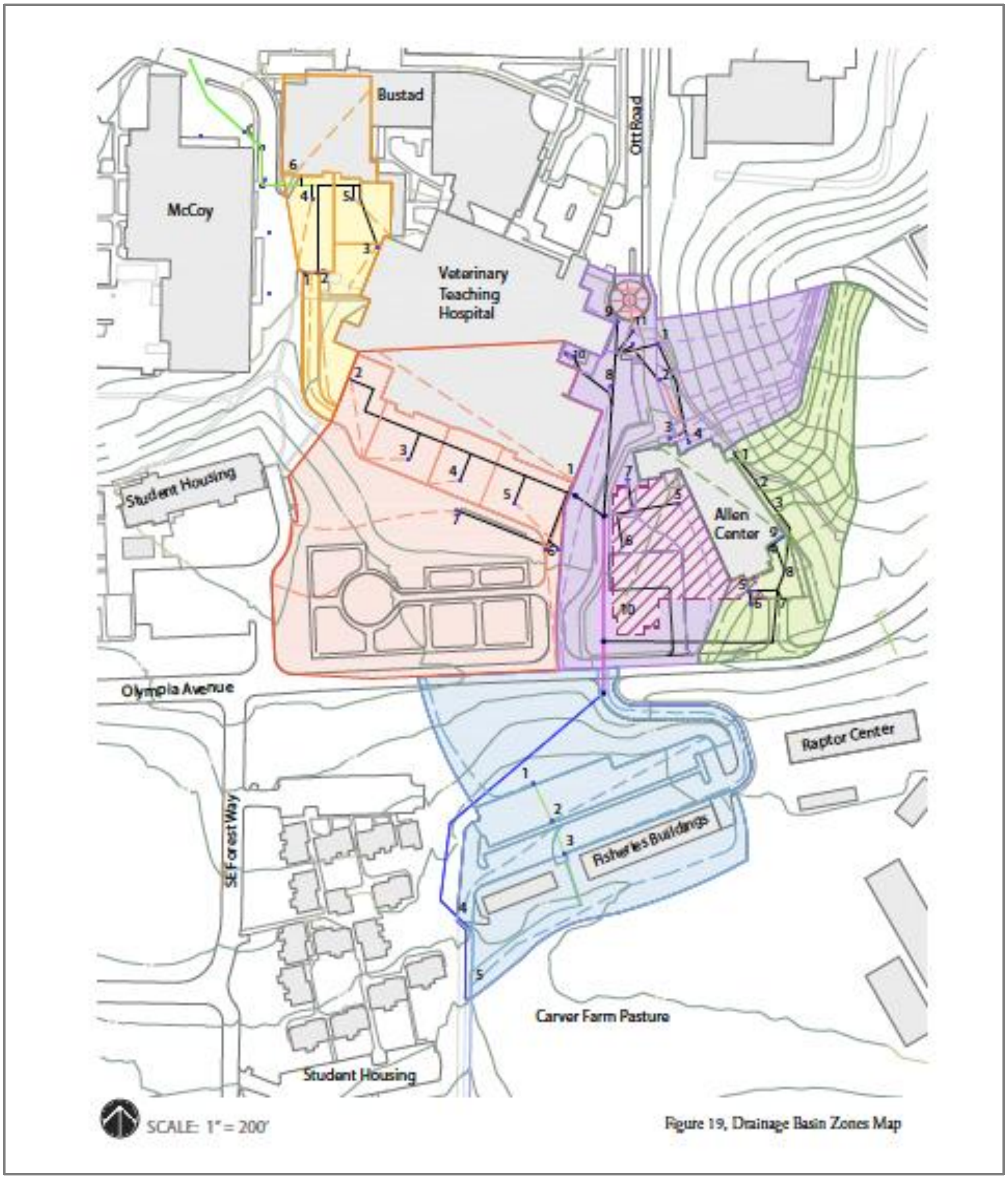


Figure 6.1 Map of location of Site C, indicated in yellow just to the east of the Veterinary Teaching Hospital (Area 4 is the area within Site C, labeled 4 [Nilsson 2014]

1. The runoff (Q) from Site C, not including Area 4, was determined using the following:

$$Q = CIA$$

where $C = C_{C\text{-}4} = 0.89$ (runoff coefficient), $I = 4$ in./hr = 0.33 ft/hr (100 year storm rational rainfall intensity), and A = Site C area – Area 4 area = 36,329 ft^2

giving $Q_{C\text{-}4}$ = 10,775 ft^3/hr.

2. The runoff from Area 4, if there is no pervious installment, was determined using

$$Q = CIA$$

where $C = C_4 = 0.95$, $I = 4$ in./hr = 0.33ft/hr (100 year storm), A = Area 4 area = 12,197 ft^2

giving Q_4 = 3862 ft^3/hr.

3. The runoff from Area 4, if there is a pervious installment, was assumed negligible.
4. The surface infiltration rate of the pervious concrete (R) was determined using

$$R = Q/A$$

where $Q = Q_4$ = 3862 ft^3/hr, and A = area of pervious installment = A_{PC} = 400 ft^2

giving R = 9.7 ft/hr = 116 in./hr.

Therefore, in order to handle a 100-year storm, the surface infiltration rate of the pervious concrete should be maintained on average at 116 in./hr or more. Any reductions in this surface infiltration rate less than 116 in./hr would increase the stormwater runoff from Site C as calculated in Step 1. These results, and an example with a lower infiltration rate due to clogging, are summarized in Table 6.3.

Table 6.3 Changes to stormwater runoff to Site C for 100-year storm

Minimum average surface infiltration rate for pervious concrete swath	116 in./hr	58 in./hr
Runoff without pervious concrete	14,637 ft^3/hr	14,637 ft^3/hr
Runoff with pervious concrete	10,775 ft^3/hr	12,706 ft^3/hr
Reduction in stormwater runoff quantity	**26%**	**13%**

In summary, the installation of a pervious concrete swath instead of the proposed berm would be an effective method to prevent animal-related waste at the loading dock area from entering the stormwater system. In addition, the pervious concrete option would help reduce stormwater flows and associated pollutants from upslope run-on areas, both paved and unpaved. However, due to large flows into the system, it is anticipated that more frequent cleaning might be needed than at the other installations currently on the WSU Pullman campus.

CHAPTER 7.0

TASK 7 – Outreach

Outreach associated with these projects, as Task 7, has been extensive. Since this report is an overview of research activities, only summaries of various outreach outlets follow:

- Many undergraduate students at WSU have been involved in the research activities.
- Numerous graduate students at WSU have been involved in the research activities.
- The work on this project has been in collaboration with WSU Facility Services, the City of Spokane, Premix of Pullman, the Washington State Department of Ecology, the Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC), the University of São Paulo, Brazil, and the Federal University of Rio Grande do Sul, Brazil.
- Much of the extended outreach, oral presentations, and poster presentations can be found on the CESTiCC website and in project progress reports. Additional outreach via peer-reviewed papers and presentations are planned or listed in the references.

CHAPTER 8.0 DISCUSSION

Many of the findings from this research activity are listed as bulleted items in Section 6.1 and discussed in Section 6.3. The findings for installation of permeable pavement systems on the WSU Pullman campus in eastern Washington and in other areas with similar climates and soils are summarized as follows:

- The draindown times for extended retention in similar Palouse clay soils seem to be sufficient for appropriate designs to handle typical storms in eastern Washington, although consideration will need to be given to contributory areas to provide additional data for storage bed and underdrain design.
- On average, every square foot of permeable pavement installed also receives run-on from another square foot of impermeable pavement, doubling the impact of run-on on both stormwater quantity reduction and stormwater quality improvement.
- Most of the clogged sections on various applications were downslope of other paved areas or next to upslope landscape areas.
- Permeable pavements installed in areas targeted for further stormwater quantity control and quality improvement may also be feasible, but more research on the cleaning frequency required for these targeted installations is needed.
- On average, the cleaning for installations is less frequent than annually. Power washing has been shown to be an effective method for cleaning surface-clogged pervious concrete.
- Surface distress occurs predominantly at places where vehicles turn, or places with initial raveling from placement activities.
- Preliminary studies on various surface treatments on pervious concrete show promise for safety benefits under wintry conditions.

- Based on sensor readings in the soils next to the detention-type permeable pavement system at Finch Arboretum, it is likely that detention systems built in similar climates and soil conditions will not negatively impact neighboring facilities.
- Retention-type permeable pavement systems, which are a viable option in the Palouse region of Washington, even with its slow-draining soils, would appear to be a viable option in areas of similar climate and soil conditions. However, care should be taken to ensure that aggregate storage beds have sufficient volume and overflow underdrains to prevent high volumetric water content conditions closer to the surface of neighboring soils caused by the water from the bed during severe events.

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