Let This Soak In:
An Investigation into the Viability of Permeable Pavement on Dalhousie University's Studley Campus

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Executive Summary

Storm water runoff that collects over impervious pavement in urban areas has the potential to negatively affect the environmental, social and economic well being of a community through pollution runoff, high costs, and flooding or icing. Alternatively, Permeable pavement systems have an extensive list of environmental, economic, and social benefits that could potentially reduce the negative impacts of surface water runoff from impermeable surfaces. Considering this information, this paper explores and analyses the feasibility of implementing permeable pavement systems on Dalhousie University's Studley Campus in Halifax. Permeable concrete, permeable asphalt, interlocking pavers, and conventional asphalt are examined. Suggestions are provided regarding how the university can move forward when deciding which type of pavements to use when potentially renovating or constructing paved areas. The paper concludes that permeable pavement systems are a feasible and beneficial option that Dalhousie University should consider. Furthermore, it is shown that permeable concrete is the best option after analysing 15 aspects of each pavement type. However, further research is required to expand on this pilot study and should make use of cost quotes and company-specific data to understand the best option for Dalhousie.

Introduction

Urban storm water runoff is a significant threat to the environmental, social, and economic well being of communities, especially in urban areas such as the Dalhousie University Studley Campus in Halifax, Nova Scotia. This is largely due to the widespread built environment in these areas, particularly large swaths of impervious pavement such as parking lots (Revitt, Lundy, Coulon, & Fairly, 2014). These impervious pavements, such as conventional asphalt and conventional concrete, allow storm water to accumulate on their surfaces through rainfall and snowmelt, as they do not have the capacity to absorb or filter water (Imram, Akib, & Karim, 2013). As this storm water collects, it travels over these impervious surfaces and flows into storm grates and sewers, which transport the storm water to natural areas such as lakes, rivers, and seas (Revitt et.al, 2014). This process is environmentally destructive, as storm water runoff accumulates a variety of pollutants as it travels over pavements. Examples of these pollutants include gasoline and other hydrocarbons, heavy metals, pathogens, and biological agents such as phosphorus and nitrogen (Tota-Maharaj & Scholz, 2010). This harmful runoff can transform natural water systems such as lakes and rivers through eutrophication, increased water turbidity, toxicity, and erosion (Tota-Maharaj & Scholz, 2010). This threatens both the functional health of watersheds as well as the wildlife that relies on it. However, storm water runoff is not merely an environmental issue. Human health is also impacted through exposure to storm water as storm water runoff can often contain harmful bacteria such as *Escherichia coli* and faecal *streptococci,* which could have health effects on humans including typhoid, hepatitis, and ear infections (Tota-Maharaj & Scholz, 2010). Moreover, rapid accumulation of water from heavy rainfall events and flash floods create puddles on impervious pavements, which inhibits safe walking and driving conditions and may actively prevent humans from utilizing said impervious area (Revitt, et al., 2014). Additionally, in a location such as Halifax, these puddles can freeze and pose a risk to people. Impervious surfaces also require constant maintenance, as well as installation of infrastructure to support storm water runoff such as storm drains, which can be costly (Hunter, 2007). In fact, in many cities, including Halifax, Nova Scotia, taxes are implemented on properties that contain impervious surfaces in order to supplement payment for storm water management practices (Halifax Water, 2016). As such, impervious surfaces can impose a financial burden. It is therefore evident that impervious pavements are environmentally, socially, and economically harmful and that it is thus worthwhile to investigate other paving systems for Dalhousie University.

Fortunately, there are many solutions to the issues that impervious pavements pose, including the implementation of permeable pavement: the avenue that is examined in this research. Permeable pavement systems (PPS) include any paving materials that allow water to be absorbed or filtered through the surface material and into the ground (Drake, Bradford, & Maraselek, 2013). These systems are typically designed with a permeable surface material atop an underground bedding made of coarse material such as gravel, which acts as a filter and reservoir for stormwater runoff (Drake, Bradford, & Maraselek, 2013; Huang et al., 2016). This coarse bedding filters pollutants and stops them from entering the watershed, and in turn, harming the environment (Drake, Bradford, & Maraselek, 2013). This method of pollutant removal is more efficient than most other environmental solutions to runoff, such as highway gullies or berms (Tota-Maharaj & Scholz, 2010). In general, permeable pavement filters approximately 98% of suspended solids, 70% of phosphorus, and up to 50% of total nitrogen within the absorbed storm water (Zhi-Guang, N., Zhi-Wei, L., Ying Z., & Zhen-Zhen C., 2016). Permeable pavement also reduces the amount of standing storm water that collects on the surface, thus reducing the aforementioned health risks associated with exposure to storm water (Drake, Bradford, & Maraselek, 2013; Tota-Maharaj & Scholz, 2010). Finally, despite its high implementation costs, permeable pavement tends to cost less than impervious pavement in the long term, as they require far less maintenance and implementation of storm water infrastructure (Tehrell, Cai, Chiu, & Murphy, 2015). It is thus clear that permeable pavement has the potential to be an improvement on impervious pavements, and reduce the environmental, social, and economic harm that they can impose.

Considering these benefits, it is clear that permeable pavement systems tend to be particularly useful in environments that receive a high amount of rainfall and therefore produce a higher amount of storm water runoff. This can be seen in Halifax, as the city frequently experiences over 100 cm of rain monthly, on average (Fig. 1) (Environment Canada, n.d). Additionally, between 1981 and 2010, the maximum daily rainfall measured was 118 cm, meaning that heavy rain can occur; however it is unlikely permeable pavement in Halifax would not be inundated due to excessive rainfall (Environment Canada, n.d). It is thus clear that the applicability of permeable pavements in this environment is worth investigating.

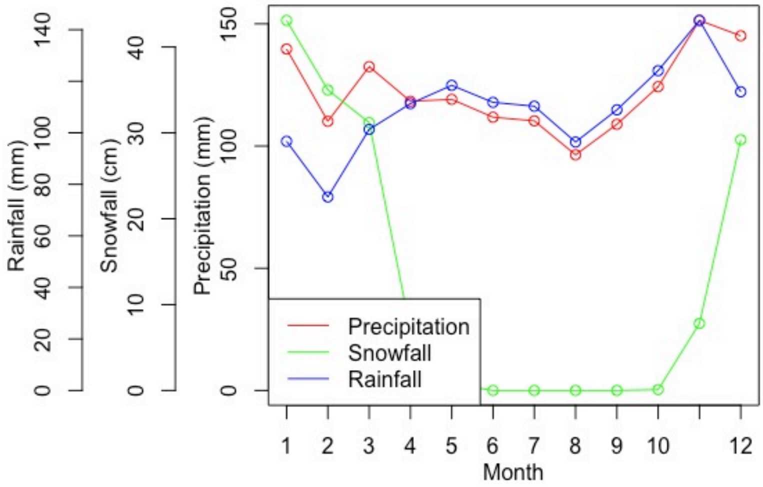


Figure 1. Average monthly precipitation, snowfall, and rainfall at Environment Canada Station Halifax Citadel, averaged from 1981-2010. Months 1-12 denote January-December (Environment Canada, n.d.).

Research regarding the benefits of permeable pavement and its applicability to Halifax’s climate has lead to an understanding of the advantages that this research could yield, and thus it is valuable to pursue information specifically relevant to Dalhousie. The latter will allow for conclusions to be drawn as to whether or not permeable pavement implementation would be appropriate on campus in the future. For these reasons, this study seeks to conclude whether or not permeable pavement would be an environmentally, socially, and economically feasible project at Dalhousie University’s Studley Campus. We will specifically examine two large parking lots with heavy traffic: the Dunn parking lot and the Dalplex Parking lot. To do so, we will map our study area using GIS technology, and perform a mixed-comparative analysis (MCA) on four types of pavement. This will include permeable concrete (PC) and permeable asphalt (PA), both similar to conventional pavements, but with small voids that drain water in the place of the fine sediment material that conventional pavement is comprised of (University of Maryland, 2016). Additionally, interlocking pavers will be examined, which consist of brick pavers joined together with permeable material

(University of Maryland, 2016). Finally, conventional asphalt will be studied alongside these three permeable options, as it is the pavement currently used at Dalhousie University (Wilkinson, personal communication on March 16, 2017). We will examine 15 different aspects of each of the four pavement types, including environmental indicators (e.g. pollutant reduction yield, water diversion), social implications (e.g. accessibility and health issues), and economic indicators (e.g. cost, tax benefits). We will then identify how each type of pavement performed in each of the 15 categories, and using a ranking system, assign a quantitative value to the potential performance of each. In doing so, we hope to conclude not only whether permeable pavement is environmentally, socially, and economically feasible at Dalhousie, but also which type of permeable pavement would be best suited to the Studley Campus environment. In turn, we hope that this information can be used to inspire worthwhile sustainable change at Dalhousie University.

Methods

GIS mapping of the study area

Geographic Information System (GIS) mapping was used as a research tool to determine the physical characteristics of the study areas. A GIS map was constructed that graphically illustrates (a) the impervious surfaces in the two parking lots on Dalhousie University's Studley campus that were examined and (b) relevant information related to those surfaces. GIS was chosen as the research tool because it is accurate and inexpensive to implement, and is therefore fitting given the constraints of this research. The characteristics determined were the square-metre area that the parking lots occupy, and the depth-to-water-table (DtWt) data in the study area. This data was collected in order to be able to calculate the costs and benefits of each alternative PPS and to be aware of any issues regarding infiltration into the water table.

The geographical data was collected in a four-segment method. First, the definition of impervious surfaces was considered: for the purpose of this study, ground-level concrete, asphalt, and other consistent pavement were deemed impervious. These surfaces were deemed impervious because they are durable, do not allow water to pass directly through them normally, and are anthropogenic, as opposed to packed dirt or rock outcroppings. Second, the study area was defined. While there are many parking lots on Dalhousie campus. large lots that withstand heavy use were considered optimal for study given the study's exploratory nature. The areas of study selected were therefore the Dalplex parking lot and the Sir James Dunn Building parking lot, as they both fulfil these criteria. The third segment of this process was defining the research criteria, and thus the information that needed to be derived from the GIS map. It was concluded that for the purpose of determining the feasibility of permeable surface replacement, the current geological, hydrological, and infrastructure information was required. The layers that represent these components include the DtWt and a city base-layer. The mapping components were retrieved from the GIS Centre at Dalhousie University. The fourth section consisted of compiling the layers and analysing the data. The layers were compiled as such from bottom to top: base-layer and then 0-50 metre deep water table. The layers were arranged in this matter to illustrate the size of the parking lots and their proximity to the water table. The analysis consisted of measuring the impervious area of the two study areas, and their proximity to the near-surface water table using the built-in measurement tool. The final measurements were integral in estimating the costs and benefits of implementing permeable surfaces on the parking lots on Dalhousie.

Analysis

An analysis was completed to understand the properties of the three possible permeable pavements as well as the current asphalt used on the Dalhousie University Studley campus. All information found was divided into 15 research topics in order to understand the differences between the four possible parking lot solutions. The 15 aspects of the pavement types were as follows: cost, compliance to Dalhousie University regulations, permeability, surface clogging, bedding type, water diversion and performance during high rainfall, winter maintenance, construction properties, longevity, traffic capacity, scale applications, health, pollution reduction, taxes, and social, accessibility, and safety implications. In-depth results were researched and subsequently outlined, while the general information pertaining to each of the 15 aspects and the four pavement types was compiled as one, in a table (Appendix A). This was done in order to have a clear method with which to compare pavement types. The aspects were then assigned a weight on a scale of 1 to 10 (i.e. their value) based on their importance to the Dalhousie community. Each of the paving solutions was also scored on a scale from 1 to 10 regarding how well it rated in each category, as outlined below. In the event that there was only a positive or negative (i.e. one pavement type is 'good' and the other types are 'bad' due to a lack of quantitative results) the pavement type deemed to be positive was assigned a score of five and the pavement type deemed to be negative was assigned a score of zero. To compute a final score for each pavement type the weight of the aspect was multiplied by the score given to the pavement type. The values obtained from this calculation were then summed for each pavement type, yielding a single final value. This process allowed for a recommendation to be made regarding which pavement type Dalhousie University should consider in its parking lots moving forwards.

This Analysis is especially helpful considering that if this study were to be replicated with different weights assigned to each aspect of the pavement types, the same process could be used and adjusted. This is made possible because of the ability to take into account qualitative information pertaining to the pavement types.

Weighting of analysis aspects

As outlined, our group weighted the 15 different research topics studied subjectively in order to determine their value with regards to the Mixed Category Analysis. The weights were determined as follows. The cost was assigned a weight of 9 based on the critical importance of a financially feasible project, as for a university facing multiple financial responsibilities the cost of different pavements will in all likelihood be of great importance. The permeability of the pavement types was assigned a weight of 7 because it is in this category that many of the benefits are centred: though they may be assessed individually this is a central component. The surface clogging was given a weight of 6 based on the necessity of low-clogging potential. A sizable impact can be had on the effectiveness of the PPS if there is a high-clogging potential. The bedding criteria was given a weight of 5 because bedding type moderately changes impacts, but is not critical to the success of implementing a PPS. Water diversion and performance during high rainfall, as well and winter maintenance were given weights of 7 and 8, respectively, because of Dalhousie's geographical location in Halifax where there frequent intense precipitation and snowfall. This is because the implications weather maintenance can have on the normal operations of the university are large and could be costly. The construction properties was given a weight of 5 because it is a moderately important aspect of a PPS, but will not influence decision as much as many other criteria. The longevity of the pavement types is weighed at 7 because durable pavement is very important to the university and reduces long-term implicit costs associated with maintenance and replacement over the lifetime of the pavement. A consideration that should be made when assessing possible pavements is to determine its scalability; however all of the pavement types examined are similar and as such this aspect was given a weight of 2. The potential health impacts of the type of pavement used for parking lot surfaces is somewhat significant; however, it is challenging to quantify. Therefore this section was assigned a weight of 4. Pollution reduction is an important aspect of the choice of pavement and the significance of this research, therefore it was assigned a weight of 5. For both health and pollution reduction it was understood that while these factors may be of moral importance to the university, they may be unlikely to be the major deciding factors with regards to whether or not Dalhousie proceeds with PPS. Due to the non-critical nature of traffic frequency, this aspect was given a weight of 3. The role of taxes was weight as a 5 because there are potential future tax savings that could be of value in the decision-making process. Finally, a weight of 2 was given to social, accessibility, and safety implications because it is unlikely to feature overly highly in Dalhousie's decision-making process.

Results

Area of study

The area of evaluation selected includes the Sir James Dunn Building parking lot and the Dalplex parking lot. The total surface area of the combined parking lots was determined to be 18751 m^2 (Fig. 2). Using GIS, it was also found that neither of the parking lots were located in areas with groundwater less than 50m from the surface, and as such infiltration will not contaminate the groundwater that may lead to a reservoir (US EPA, 2016) (Fig. 3).

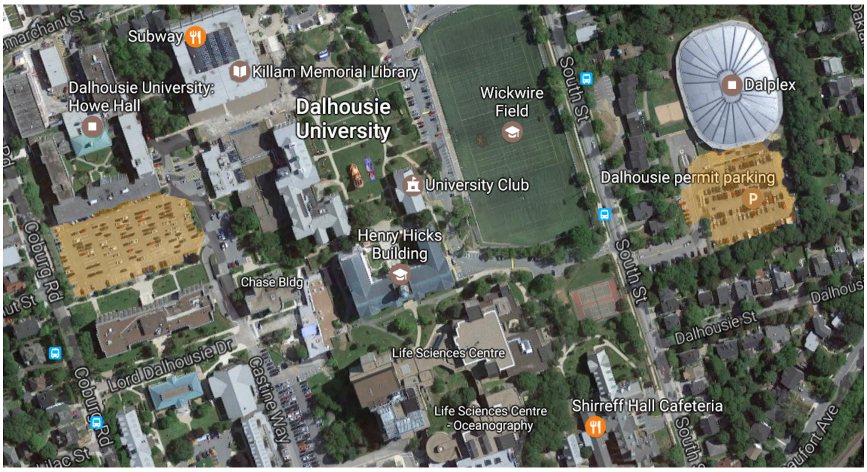


Figure 2. Map of the study area obtained through GIS mapping. Areas denoted in yellow represent the study areas and are, from L-R: the Sir James Dunn Building parking lot, and the Dalplex parking lot.

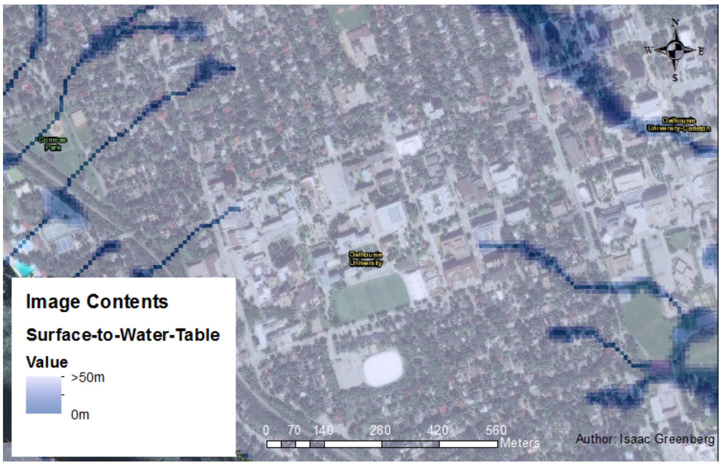


Figure 3. Map of the depth to water table in the study area obtained through GIS mapping. Darker shades denote regions that have a shallower depth while lighter shades denote regions that have a greater depth.

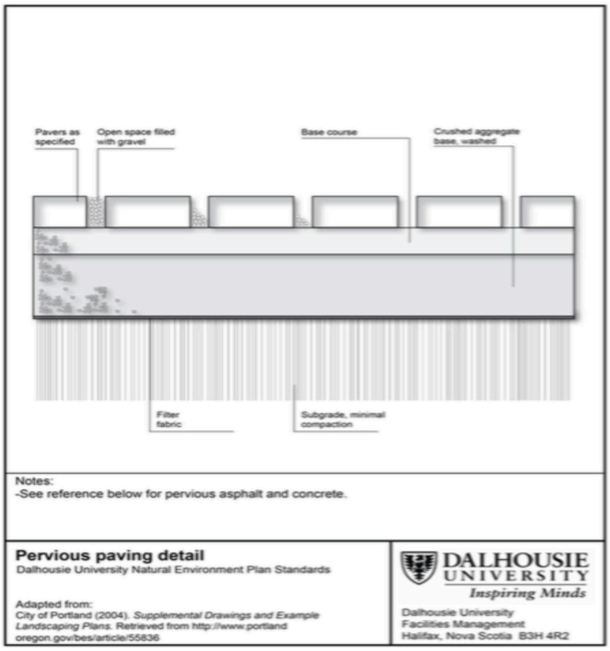
Research on pavement aspects

The 15 research topics outlined below give an overview of the feasibility of all four pavement types examined. The aspects included attempt to be specific to Dalhousie University (i.e. the ability for the pavement type to fall within the current Dalhousie regulations). Each topic seeks to provide insight into both the positive and negative impacts for each of the possible parking lot solutions—depending on the literature that is publically available.

Cost. The cost of implementing each alternative PPS is critical to determining which type of pavement might be favoured by the university for construction. The total present value (TPV) of costs were retrieved from Rehan (2016), and the nominal price for interlocking pavers retrieved from The University of Maryland (2016). Rehan (2016) calculated the maintenance costs and future replacements over 40 years with a discount rate of 4%. The total nominal construction cost of interlocking pavers was obtained from the price per square foot value in a report by the University of Maryland (2016) and then presented in price per acre, for ease of understanding.

The TPV of costs for implementing permeable concrete was found to be 368,500 USD per acre. The TPV of costs for permeable asphalt was 263,800 USD per acre. Finally, the last TPV of costs was 240,800 USD for conventional asphalt. There was no available data for the TPV of costs for interlocking pavers. The nominal costs of interlocking pavers were detrimentally high, calculated at between $504,908 and $555,632 per acre, and therefore did not warrant further research. It is important to note that costs could change slightly, based on the economies of scale that would occur from paving both parking lots.

Compliance to Dalhousie regulations. Dalhousie regulation states that to effectively manage storm water and storm water runoff, permeable pavements should be considered when designing paved areas to encourage slow infiltration and increase the release of surface water from these paved areas (Department of Facilities Management, 2013). In accordance with Dalhousie regulations asphalt should be limited to temporary repairs and not be used for pedestrian walkway systems. However, there is very limited regulation on material uses for roads and parking lots (Department of Facilities Management, 2013). Moreover, all paved surfaces must have a life cycle of at least 15 years under the average weather conditions of the Halifax area (Department of Facilities Management, 2013). Appendix F from Dalhousie University's Natural Environment and Landscape Policy and Guidelines shows an example of how permeable pavement may be implemented and can be seen here (Fig. 4).



Notes:
-See reference below for pervious asphalt and concrete.

Pervious paving detail
Dalhousie University Natural Environment Plan Standards

Adapted from:
City of Portland (2004). *Supplemental Drawings and Example Landscaping Plans*. Retrieved from http://www.portland oregon.gov/bes/article/55836

Dalhousie University
Facilities Management
Halifax, Nova Scotia B3H 4R2

Figure 4. Example of the potential implementation of PPS at Dalhousie University, as per the university's guidelines (Department of Facilities Management, 2013).

Permeability. The most prominent benefit received from implementing permeable pavement is, unsurprisingly, diversion of water from the water system to the ground. The factor of how prominent each benefit of permeable pavement is expressed is determined by the permeability. Permeability is measured in feet of rain per day that is absorbed. The permeability of permeable concrete, permeable asphalt, and interlocking pavers were determined to be 10 feet per day, 6 feet per day, and 2 feet per day, respectively (Rehan, 2016; University of Maryland, 2016). Conventional asphalt provides no permeability, and therefore has a value of 0 feet per day for this aspect of the pavement types. The possible impact of this category will be determined by the amount of rainfall expected in the study area, as seen in Figure 1 above.

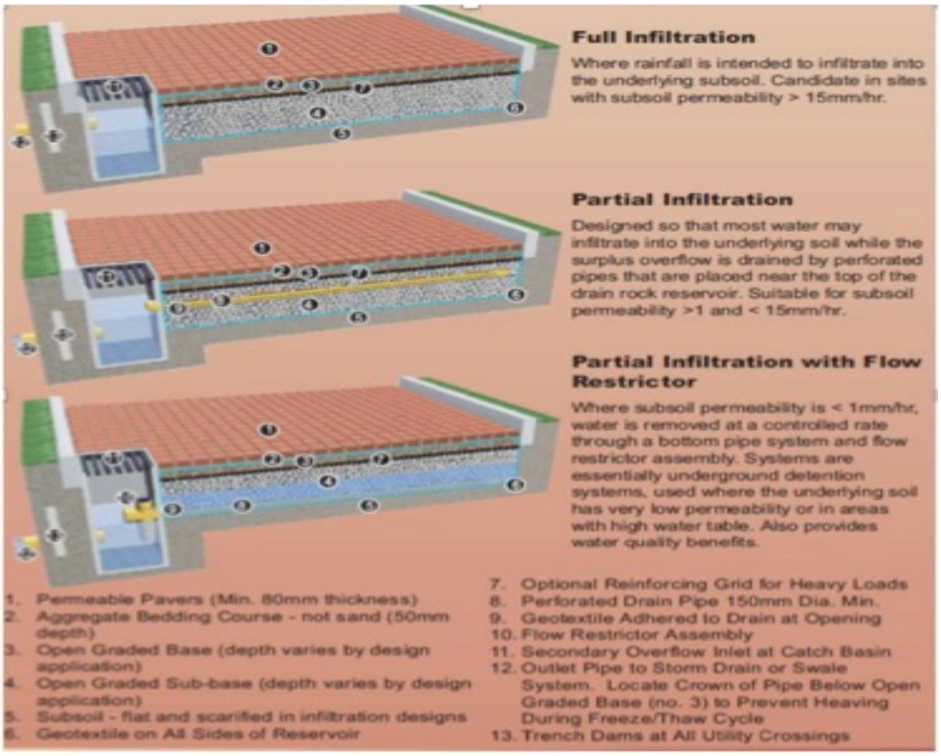
Surface clogging. Surface clogging can be a major concern for permeable pavements as small particles can block the hydrologic conductivity of the pavement. The sediments that cause the most concern are finer particles that can fit within the porous areas of the pavement (Pezzaniti, Beecham, & Kandasamy, 2009). The sediments that cause the most damage to these pavements occur naturally from the surrounding environment (Pezzaniti, Beecham, & Kandasamy, 2009).. In particular this occurs in ecosystems and habitats with more arid conditions that retain a lot of dust and sand (e.g. deserts or sandy coastal zones) (Pezzaniti, Beecham, & Kandasamy, 2009). In these areas it would be irresponsible to use permeable pavement as the benefits that permeable pavements offer would be limited due to the reduction in hydraulic conductivity. In this case, however, Halifax does not have this problematic climate, and thus clogging might not be as serious as an issue. It has been shown that over a 35-year period small particles causing surface clogging can reduce the effectiveness of hydrologic conductivity by 59% to 74% when the average sediment retention is approximately 94% (Pezzaniti, Beecham, & Kandasamy, 2009).

Porous asphalt is most affected by clogging at the surface, causing there to be obvious pooling on the surface, thereby reducing the lifespan of the pavement considerably Interlocking pavement is affected by surface clogging only at the geotextile layer (Yong, McCarthy, & Deletic, 2013). This implies that once the interlocking pavements hydraulic conductivity is no longer effective it would not be visible unless tested professionally.

Therefore, there would be greater upkeep requirements because it would need greater monitoring. Permeable concrete showed little to no sign that sediment had any effect on the hydraulic conductivity or life span of the pavements (Yong, McCarthy, & Deletic, 2013). These tests were performed in an area where sediment was naturally occurring and would potentially damage the pavement. However, again, Halifax is unlikely to experience sediment loading in the ways that these study environments did and therefore this aspect is less of a concern when deciding which pavement to implement.

Bedding. Bedding practices are independent of the type of pervious pavement implemented. This therefore allows the university to make an independent evaluation of the desired permeable or impermeable surface separate from the bedding-type, as long as the two are in compliance with regards to regulations and the necessary durability. Figures 5, 6, and 7 outline the different levels of bedding possible for permeable surfaces.

Figure 5 shows one possible solution to deal with overflow when the ground is oversaturated with water such that it is no longer able to absorb additional water from rainfall or snow melt. This type of system could be implemented along with other types of bedding solutions (Greater Vancouver Regional District, 2005). The overflow seen could be directed to the current Halifax water treatment system to prevent unintended run off.



Full Infiltration

Where rainfall is intended to infiltrate into the underlying subsoil. Candidate in sites with subsoil permeability > 15mm/hr.

Partial Infiltration

Designed so that most water may infiltrate into the underlying soil while the surplus overflow is drained by perforated pipes that are placed near the top of the drain rock reservoir. Suitable for subsoil permeability >1 and < 15mm/hr.

Partial Infiltration with Flow Restrictor

Where subsoil permeability is < 1mm/hr, water is removed at a controlled rate through a bottom pipe system and flow restrictor assembly. Systems are essentially underground detention systems, used where the underlying soil has very low permeability or in areas with high water table. Also provides water quality benefits.

1. Permeable Pavers (Min. 80mm thickness)
2. Aggregate Bedding Course - not sand (50mm depth)
3. Open Graded Base (depth varies by design application)
4. Open Graded Sub-base (depth varies by design application)
5. Subsoil - flat and scarified in infiltration designs
6. Geotextile on All Sides of Reservoir
7. Optional Reinforcing Grid for Heavy Loads
8. Perforated Drain Pipe 150mm Dia. Min.
9. Geotextile Adhered to Drain at Opening
10. Flow Restrictor Assembly
11. Secondary Overflow Inlet at Catch Basin
12. Outlet Pipe to Storm Drain or Swale System. Locate Crown of Pipe Below Open Graded Base (no. 3) to Prevent Heaving During Freeze/Thaw Cycle
13. Trench Dams at All Utility Crossings

Figure 5. Stormwater control system that allows for water that exceeds the absorbing capacity of the permeable pavement to be directed into a treatment system, as per the *Stormwater Source Control Design Guidelines* (Greater Vancouver Regional District, 2005).

Figures 6 outlines a bedding solution that is commonly utilized with interlocking pavers. The curb of the surface (i.e. parking lot, road) acts a barrier to encourage the water to be filtered through the installed bedding. This system does not have a dedicated overflow system available; however the overflow system discussed above with regards to Figure 5 could be used in tandem with this bedding system.

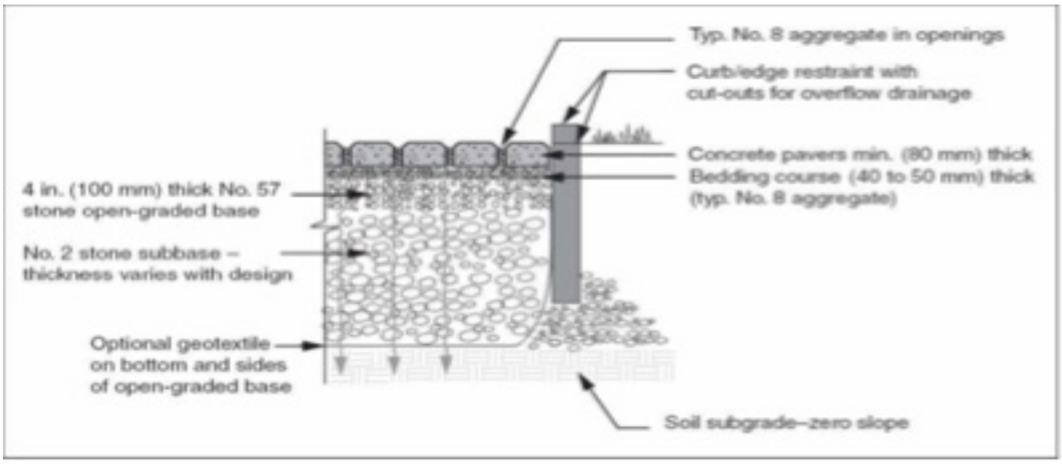


Figure 6. Close up, cross-sectional view of permeable pavement infiltration design that utilizes the curb to direct water flow (Smith, 2006).

Figure 7 outlines a bedding solution for permeable asphalt. It is hypothesized that this bedding solution could be used for other PPS as well. This system allows for a simple overflow system when the porosity of the PPS is not great enough in comparison to the rainfall or snowmelt (Cahill Associates, 1993). Furthermore, this bedding system allows for variation in the porosity (Cahill Associates, 1993)—which can occur with different permeable pavement types because of surface clogging due to sediment, as outlined above.

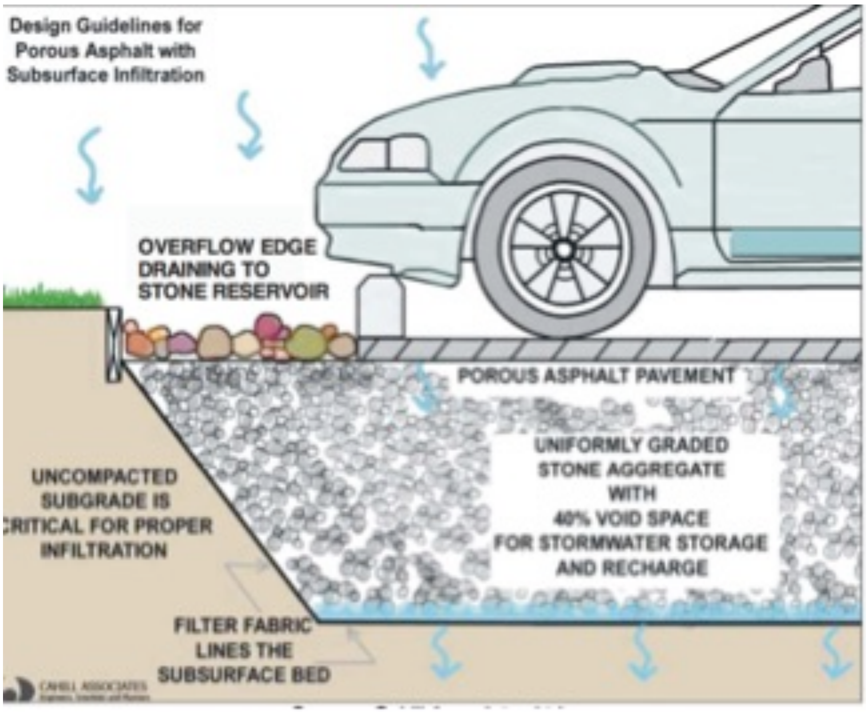


Figure 7. PPS featuring an overflow edge, represented with multi-coloured rocks, as a potential bedding type (Cahill Associates, 1993)

For impervious pavement, the thickness and bedding type utilized are found from calculations and, as such, there are no additional options available. Impervious pavement therefore lacks the benefits of bedding customization that permeable pavements have, as as seen in Figures 5, 6, and 7.

Water diversion and performance during high rainfall. Permeable pavements are able to accommodate significant rainfall, thus diverting 100% of the rainfall on any given day. Given that the maximum historic rainfall reported in Halifax was 118.1 mm (Goverment of Canada, 2017), this value was used as that maximum any surface would be required to handle. All permeable pavement types examined were able to accommodate this rainfall total (Table 1). A degree of error should however be accommodated for these values, since permeable surfaces are prone to clogging, up to a maximum of 74%, as seen previously. The permeability was reduced significantly with clogging; however, all three PPS were able to accommodate the Halifax rainfall nonetheless. For non-porous surfaces there is no change from the current system used as all water enters the water treatment system in Halifax. Conventional asphalt is not permeable and there requires culverts, permeable shoulders, and run-off collection in order not to flood.

It should also be noted that all these values were averaged over a single day. Information was not available to determine how much rainfall the PPS could take over a shorter time span (e.g. 1 hour). Therefore there is the possibility that all porous surfaces may not perform well if rainfall is larger quantities, at a greater rate. If a situation with greater rainfall did occur, secondary solutions such as overflow bedding, presented above, would be essential.

Table 1. *Per cent rainfall absorption for each of the three permeable pavement types examined and conventional asphalt during heavy rainfall. Maximum rainfall, used in the calculations herein was 1.1181 m/day, as presented above.*

Attribute	Permeable Concrete	Permeable Asphalt	Interlocking pavers	Conventional Asphalt
Permeability (m/day)	3.048	1.8288	0.6096	0
Permeability with a maximum surface clogging of 74% (m/day)	0.79	0.473	0.15	0
Per cent of rainfall absorbed under maximum daily rainfall (%)	2580	1548	515	0
Per cent of rainfall absorbed with a maximum surface clogging of 74% (%)	668.9	400.5	127	0

Winter maintenance. Winter maintenance is an important consideration of pavement choice in at Dalhousie University, due the fluctuating seasons and precipitous winters of Halifax. Permeable concrete, when under saturated, should remain unaffected by the freeze-thaw cycle; however, if saturated, damage can occurs from this cycle (NRMCA, 2004). The latter can occur when if there is clogging from salt or sand, extended periods of temperatures below freezing, or when the water table is 3 feet or less from the surface (Henderson, 2012). If permeable concrete is well maintained it should rarely become fully saturated (NRMCA, n.d.). However, anti-icing pre-treatments, various de-icers, and de-icing agents cannot be used, as per the NRMCA (n.d.), as runoff of these products could pose an environmental problem. It is also recommended that snow plowing should occur with plows that have a barrier between the plow itself and the concrete (NRMCA, n.d.). However, other sources have said that conventional snow clearing methods can be used (Henderson, 2012). Permeable asphalt requires plowing after every storm, as is currently done, and anti-icing is also to be applied; however, de-icing is not required (Roseen, Ballestero, Houle, Houle, & Briggs, 2011). Additionally, porous asphalt requires between 0% and 25% less salt than conventional concrete, though sand should not be used (NAPA, n.d.). Interlocking concrete pavers do well with regards to free-thaw cycles and are resistant to salts and snow and ice removal with conventional methods (ICPI, 2017). Moreover, if there are cracks that do appear it is possible to replace individual pieces—a feature that is more convenient than other pavement types. Finally, conventional asphalt wears out through the freeze-thaw cycle as is typically expected, though it can withstand conventional de-icing, anti-icing, sand, and plowing.

Construction Properties. The construction properties of a pavement denote the process that is required to put this pavement in place. At a university, which is active for the majority of the year this is an important consideration because limiting the use of parking lots can be detrimental to the users of the campus.

Porous concrete is cast in place, and thus requires seven days to cure, and must be covered (University of Maryland, 2016). The latter may prove to be challenging for the two Dalhousie parking lots being considered, as they may be difficult to cover in their entirety. Due to this processes, many users of Dalhousie University could be inconvenienced during construction. Permeable asphalt must also be cast in place and requires 24 hours to cure. Alternatively, Interlocking pavers do not have a cure period but uses “manual or mechanical installation of pre-manufactured units” (University of Maryland, 2016). Finally, conventional asphalt must not be touched for 2-3 days (DCT Paving and Concrete, 2016).

Longevity. The longevity (i.e. the period over which the pavement remains in good condition) in terms of an exact duration of different pavement types will likely vary depending on a variety of factors including weather, temperature fluctuations, and daily use, among others. However, understanding the longevity of the different potential types is vital to the decision regarding which pavement type would be best for Dalhousie. The University of Maryland (2016), and references therein, denote a time period “based on pavement being maintained properly” and state that “[resurfacing] or rehabilitation may be needed after the indicated period.”

Porous concrete has a longevity of 20 to 30 years, porous asphalt has a longevity of 15 to 20 years, interlocking pavers have a longevity of 20 to 30 years (University of Maryland, 2016), while conventional asphalt has a longevity of 20 to 30 years (Alpha Paving Industries LLC (2016); Fahrner Asphalt Sealers LLC (2017).

Traffic capacity. Traffic capacity is important to take into account when considering which pavement choice would be the best for Dalhousie. Traffic capacity refers to the maximum amount of cars or traffic that a certain type of pavement can uphold at a given time and the regularity the parking lots will be used (Matthew & Krishan Rao, 2007, p.35.1). The traffic capacity for permeable concrete, permeable asphalt, and interlocking pavers all depend on the bedding layer that is used in the project at hand (University of Maryland, 2016). Since the traffic capacity of these pavements is dependent on the bedding layers used, with the right planning all three of these permeable pavements can handle all traffic loads and, depending on the planning, can allow for the necessary traffic capacity (University of Maryland, 2016). The traffic capacity for the standard asphalt that is used on Dalhousie's Studley Campus depends on the size of the lot being put into place, as well as the thickness of the asphalt being used (Lavin, 2003, pp. 58). It is thus clear that traffic capacity is a variable and customizable aspect of pavement implementation.

Scale application. Scale application refers to the size of projects that these different pavement types can be applied to. Scale application is an important consideration because the pavement used needs to be able to fit the size of the project. The type of pavement chosen for Dalhousie would of course be required to fit the parking lots chosen on the Studley campus. Both permeable concrete and permeable asphalt can be applied to small and large projects (University of Maryland, 2016). Interlocking pavers can be applied in both small and large projects as well, but can also be applied to micro paving projects (University of Maryland, 2016). Standard asphalt, like permeable concrete and permeable asphalt, can be applied to both small and large projects (Ontario Hot Mix Producers Association, 2016). Thus, any of these pavement options would be appropriate for Dalhousie Campus.

Health. Though not immediately noticeable, storm water runoff hosts many chemicals and bacteria which are hazardous to human health. For example, as previously mentioned, storm water often contains *Escherichia coli* and streptococci bacteria, both of which can lead to serious illnesses in humans (Tota-Maharaj & Scholz, 2010). When this bacteria remains stagnant in storm water puddles atop impervious pavement, humans are exposed to these dangers (Tota-Maharaj & Scholz, 2010). Permeable pavements can therefore have a positive impact on human health by eliminating surface water on pavements, thereby ensuring humans are not exposed to the harmful bacteria within the storm water (Tota-Maharaj & Scholz, 2010). PPS also keep these pathogens from flowing directly into the water table and spreading throughout Halifax. Therefore, these pavements could, in theory, keep people from contracting a disease, missing work or school, or having to pay for costly medical bills. Though it is difficult to estimate the monetary value of these benefits, due to the variability of contagion, exposure rates, hospital bills, and medical expenses, it is assumed that by reducing exposure to harmful pathogens, permeable pavements will provide a general improvement in human health and reduce the need for medical spending.

One might also consider that permeable pavements reduce the pollutant load in a city's water table. In turn, the water system will be less likely to contain any chemicals and pollutants that may have survived any treatment process. Therefore the city could have better access to reliably fresh water for bathing, cooking, and drinking. Seepage of pollutants into groundwater drinking water sources is unlikely, unless the permeable pavement is located in close proximity to a well or other drinking water source (US EPA, n.d). This can be avoided by spatial planning. In summary, the three types of permeable pavement examined are thought to provide equal health benefits while conventional asphalt does not provide these benefits. One may assume that permeable asphalt will remove pathogens and protect the watershed from pollutants and chemicals with the most reliability and effectiveness, as is the most effective at removing general pollutants, as outlined below.

Pollution reduction. As mentioned above, permeable pavements have a vast capacity for the removal of pollutants from storm water runoff, and thus their elimination from the water table. This protects natural ecosystems such as lakes and rivers from harmful pollutants and their detrimental impacts (Tota-Maharaj & Scholz, 2010). Specifically, permeable concrete tends to perform well as a pollutant removal service, and is estimated to remove approximately 91% of sediment and 54-60% concentration reduction in heavy metal pollutants such as zinc and lead (Drake, Bradford, & Maraselek, 2013). Porous asphalt performs comparably, with approximately a 93% reduction in sediment and 70-80% reduction in heavy metals (Drake, Bradford, & Maraselek, 2013). Meanwhile, interlocking pavers tend to eliminate less total sediment from storm water (approximately 73%), but remove 60-90% of the heavy metal pollutants from storm water, a comparatively slightly higher average than the other permeable options. It is thus clear that while each type of permeable pavement is environmentally beneficial, porous asphalt seems to perform the best in consideration of the concentration of pollutants in storm water runoff.

It should also be noted that although there are benefits, runoff generated from permeable pavement tends to have a more basic pH level than runoff generated from impervious asphalt, sometimes as high as 9.5 (Drake, Bradford, & Maraselek, 2013). This leads to an inability to break down heavy metals (Drake, Bradford, & Maraselek, 2013). In general, aquatic systems require a pH between 6.5 and 9 to function properly, thus, permeable pavements could challenge the health of aquatic environments due to the basic pH that comes from them. However, in general, the pH of runoff from permeable pavements does tend to be under 9, and the inability to break down heavy metals is less important considering most heavy metals are filtered out of the water system by the pavement itself before water runs off the structures. Thus, in general, permeable pavement is still more beneficial for the environment than impervious asphalt.

Tax. In the Halifax Regional Municipality (HRM), there is currently a “Right of Way” tax charge on residential and non-residential areas that host impermeable pavement structures (Halifax Water, 2016). Each year, non-residential properties such as Dalhousie University pay 0.135 CAD per square metre of impermeable pavement surfaces to the municipal government, who in turn uses these funds for storm water services (i.e. constructing culverts or repairing storm water systems) (Halifax Water, 2016). This means that Dalhousie is charged $2531 CAD per year for the two impervious parking lots being examined. If these surfaces were to be replaced by permeable surfaces this tax would not apply and this money could be saved.

Social, accessibility, and safety implications. Rehan (2016) identified accessibility issues associated with impermeable pavement, mainly induced by water pooling on the surface. In Halifax, this effect could be furthered as pooling water forms into ice during the winter season. As such, conventional asphalt can be hazardous when frozen or when encountered by people with reduced mobility. PPS can alleviate this problem as water does not pool on the surface. However, interlocking pavers may be somewhat less accessible, depending on the type used, because the surface is not entirely even.

Analysis of pavement aspects

The literature reviewed yielded the results outlined above and, as such, provided the necessary information to quantitatively rate each aspect of each of the pavement types through a mixed-comparative analysis (MCA) (Table 2).

Table 2. *Attributes, weights assigned, and scores given for each of the four pavement types examined. Total scores were calculated by multiplying the pavement types' score in a given aspect with the weight assigned to that aspect and then calculating the sum of those values. This was repeated for each pavement type.*

Aspect	Weight	Permeable Concrete	Permeable Asphalt	Interlocking pavers	Conventional Asphalt
Cost	9	7	8	4	9
Compliance to Dalhousie regulations	7	8	7	8	5
Permeability	7	9	6	3	0
Surface clogging	6	8	4	5	0
Bedding	5	7	7	7	5
Water diversion and Performance during high rainfall	7	8	7	8	3
Winter maintenance	8	2	8	8	6
Construction properties	5	1	7	8	5
Longevity	7	8	5	8	8
Traffic Capacity	3	7	7	7	7
Scale Application	2	8	8	8	8
Health	4	6	6	6	4
Pollution Reduction	5	7	8	7.5	3
Tax	5	2	2	2	0
Social, accessibility, and safety implications	2	5	5	4	1
Total		468	467	431.5	317

This MCA thus found that permeable concrete had the highest score with permeable asphalt a close second (Table 2). Interlocking pavers had the third highest score, and all three permeable pavement types had scores greater than 400. In contrast, conventional asphalt had the lowest score by a wide margin (Table 2).

Discussion

Using the evidence synthesized above, we were able to understand the significant benefits of permeable pavement implementation on the Dalhousie University Studley Campus. This is made evident by the high scores of the three permeable pavements studied, compared to conventional impervious asphalt, which scored over 100 points below even the lowest-performing permeable pavement (Table 2). Impervious asphalt failed to perform nearly as well as permeable pavement in multiple categories. This included permeability itself, as conventional asphalt was found to not exhibit any permeable properties, and was assigned a value of 0, as any permeability would have been an improvement. With this lack of permeability, impervious asphalt does not perform well during rainfall, especially compared to interlocking pavers, permeable asphalt, and permeable concrete, which filter 2, 6, and 10 feet per day, respectively. A similar pattern was seen in consideration of winter maintenance needs: though permeable asphalt, interlocking pavers, and conventional asphalt were all highly rated because of their ability to use a broad range of conventional snow management techniques, conventional asphalt scored lower as it is more likely to crack from freeze-thaw cycles. Permeable concrete did not fair well in this category because many conventional snow management techniques cannot be used with it. Additionally, impervious asphalt scored poorly in pollution reduction abilities, because it does not filter pollution independently whatsoever, and relies on the HRM to treat any pollution through its system. Impervious asphalt also performed poorly in Dalhousie-specific categories such as regulations, as the Dalhousie regulations actually recommend that permeable surfaces are implemented when it is feasible. This displays how permeable pavement could explicitly benefit the vision that the Dalhousie administration and Facilities Management have for the campus, and the university as a whole. This, coupled with the high ranking of permeable pavements compared to impervious asphalt in the majority of other categories, displays that permeable pavement is a useful regional solution to the problems that impervious pavement presents.

On top of this useful conclusion, we were also able to discern which of the three types of permeable pavements would be the most beneficial to the Dalhousie campus. After extensive analysis of the three permeable pavement types, permeable concrete was indicated as the most beneficial. Permeable asphalt scored highly in a number of categories, proving its merits as a valid permeable pavement for Dalhousie to consider implementing. For example, surface clogging occurs predominantly on permeable asphalt and interlocking pavers, while permeable concrete has very low surface clogging potential. Permeable concrete also had lower implementation costs than interlocking pavers, and the highest rate of permeability of all three of the permeable pavements. However, permeable concrete scored higher than permeable asphalt by only a thin margin—scores of 468 and 467, respectively. In fact, permeable asphalt scored higher than permeable concrete in multiple categories, including pollution reduction, costs, and winter maintenance. In particular, its construction process is far more convenient, considering the detrimental seven-day curing process of permeable concrete, and the inconvenience it would bring to the highly used parking lots examined. It is therefore clear that both of these types of permeable pavements have considerable benefits, and should both be considered as viable options for Dalhousie University.

These results maintained the majority of evidence synthesized in current studies, most which conclude that permeable pavement is more environmentally and socially beneficial than impermeable pavement types. While impervious asphalt scored higher in our analysis in cost, which was weighted of high importance, these benefits were offset by the aforementioned social and environmental performance of permeable pavement in the final rankings. When one considers the individual cost benefits of permeable pavements such as tax benefits and low infrastructure and maintenance costs, the apparent cost benefits of impervious pavement compared to permeable pavement become less obvious and, as this study found, less valuable. Therefore, overall, this research agreed with the majority of the current literature that has been published to date.

Moving forwards, this topic merits further research. This research should, ideally, include community involvement (i.e. student involvement), the university administration, Facilities Management, and the Dalhousie Office of Sustainability. Between these organizations there is capacity for further investigations regarding the specific locations that PPS can be implemented on campus, beyond just two of the Studley campus parking lots. Furthermore, it is worth investigating the exact pavement types that are available in Atlantic Canada from the potential companies. Following a model similar to this pilot project, analyses of the available options could be undertaken to make concrete steps towards increasing the use of PPS on campus.

Conclusion

This study sought to examine the feasibility of permeable pavement on Dalhousie University's Studley Campus in light of the extensive precipitation that leads to large quantities of runoff in Halifax, Nova Scotia. This runoff was shown to have environmental, social, and economic impacts and, as such, an investigation into alternative solutions is worthwhile. This study used GPS mapping and a simple mixed-comparative analysis to determine that permeable pavement systems are a viable option for Dalhousie. All three permeable pavement types examined (i.e. permeable concrete, permeable asphalt, and interlocking pavers) were found to be superior to the impermeable pavement type that is currently used (i.e. conventional asphalt). Therefore, given that all permeable pavement types were shown to be better alternatives than the current pavement, this study concludes that it is feasible for Dalhousie University to implement permeable pavement on its Studley Campus, in particular in the Sir James Dunn Building and Dalplex parking lots.

In addition, this study found that permeable concrete and permeable asphalt are the best options moving forwards for Dalhousie. These results were found by placing the greatest emphasis on the cost of PPS implementation, the compliance to Dalhousie University's regulations, the permeability of the pavement types, performance during high rainfall, winter maintenance, and the longevity. Permeable concrete was found to be compliant with regulations, highly permeable, performed well under high volumes of precipitation, and will last a long time. In contrast, permeable asphalt is available at a lower cost, but is less permeable and will not last as long. It is noteworthy that permeable asphalt scored far better with regards to winter maintenance. Depending on what factors Dalhousie prioritizes this study provides a comparison of the benefits of each PPS examined. It is suggested that Dalhousie University use permeable concrete or permeable asphalt in their paving in the future.

The implications of this study are clear: permeable pavement has immense potential to solve the multiple issues presented by impervious pavement at Dalhousie, including harmful storm water runoff, winter wear, inconvenient flooding and ice floes, and tax costs. These therefore results provide valuable insight for the university in the future given that it is their goal to implement permeable pavement when possible (Department of Facilities Management, 2013). Although the data collected is limited in scope, this pilot project nonetheless serves as evidence that the potential of permeable pavement is worth considering on the Dalhousie Studley Campus, and motivates the undertaking of future potential studies in the field. This research provides the building blocks from which Dalhousie can continue the process of investigating PPS types and using permeable pavement where it deems it to be applicable.

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Appendix A: Summary of results obtained with regards to each pavement type.

Attribute	Permeable Concrete	Permeable Asphalt	Interlocking Pavers	Conventional Asphalt
Cost	$368,500/acre	$263,800/acre	$504,908-555,632/acre	$240,800/acre
Compliance to Dalhousie regulations	Encouraged	Not permitted except for temporary maintenance.	Permitted	Permitted
Permeability (feet/day)	10	6	2	0
Surface clogging	No susceptibility	Susceptible in certain environments.	Susceptible to clogging in the geotextile layer but not surface.	N/A
Bedding	Multiple options with overflow systems, lining for chemical contamination, or general aggregate filtration with multiple layers	Multiple options with overflow system, lining for chemical contamination, or general aggregate filtration with multiple layers	Multiple options with overflow system, lining for chemical contamination, or general aggregate filtration with multiple layers	Minimum thickness with aggregate underneath; Drainage systems feeds into HRM system
Water diversion (%)	2580	1548	515	0
Performance during high rainfall	Dependant on bedding type	Dependant on bedding type	Dependant on bedding type	Complete draining into the HRM system
Winter maintenance	Becomes fully saturated; is minimally affected by the freeze-thaw cycle; anti-icing agents cannot be used; snow plowing should only occur with specific barrier hardware equipped	Anti-icing agents are permitted; freeze-thaw cycles have minimal effect; traditional tools for snow removal can be used	Conventional snow removal methods are applicable; resilient in freeze-thaw cycles.	Wears out through freeze-thaw cycles; conventional snow control methods are permitted.
Construction properties	Cast in place; requires 7 days to cure; must be covered	Cast in place; requires 24 hours to cure.	No cure period; uses manual or mechanical installation of pre-manufactured units	Must be left in place for 2-3 days

Attribute	Permeable Concrete	Permeable Asphalt	Interlocking Pavers	Conventional Asphalt
Longevity (Years)	20-30	15-20	20-30	20-30
Traffic Capacity	Dependent on the bedding layer used	Dependent on the bedding layer used	Dependent on the bedding layer used	Dependent on lot size and the thickness of the asphalt used
Scale Application	Small and large scale projects	Small and large scale projects	Micro, small and large projects	Small and large projects
Health	Removes pathogens from surface with filtration to keep out of groundwater and other freshwater sources	Removes pathogens from surface with filtration to keep out of groundwater and other freshwater sources	Removes pathogens from surface with filtration to keep out of groundwater and other freshwater sources	Water remains on surface and in standing water with possibility for human contact; must be treated
Pollution Reduction	Removes 91% of sediments and 54-60% of heavy metal pollutants	Removes 93% of sediments and 70-80% of heavy metal pollutants	Removes 73% of sediments and 60-90% of heavy metal pollutants	Must be treated by the Halifax Regional Municipality (HRM)
Annual tax savings (CAD)	$2,531	$2,531	$2,531	$0; Must pay storm water maintenance
Social, accessibility, and safety implications	N/A	N/A	N/A	Pooling of water on the surface resulting in puddles that can be hazardous when frozen