

**Urban surface water runoff on Dalhousie University's Studley campus
(Halifax, N.S.)**

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Abstract:

As an urban environment continues to grow and densify, consequences such as increased surface water runoff become ever more prominent as urban landscapes seal off previously permeable surfaces. Stormwater management infrastructure has been developed to drain rainfall from the urban environment. Thus, surface runoff is discharged in high volumes into alternate systems, leading to landscape damage, enhanced delivery of contaminants to receiving water bodies, and immense stress on water treatment facilities during high rainfall events. Moreover, should drainage systems fail or become inundated with water, urban residents are faced with flooding. Here, a geographic information system (ArcGIS) was employed to geospatially assess Dalhousie's Studley campus by surface area and type. 65% of Studley campus is composed of impermeable surface material. Utilizing rainfall data for the 2016 calendar year, runoff volume is approximated to be $2.6111 \times 10^5 \text{ m}^3$. While 35% of the campus is permeable, the remainder is made up of roads, sidewalks, and parking lots (29%), buildings (31%) and recreational surfaces (5%). Furthermore, alternate precipitation management methods, such as sustainable drainage systems and low impact developments, are considered to combat urban surface impermeability, with locations for potential sites indicated herein. The impermeable regions yield 5 high risk zones suited for management strategies.

Key Terms:

Combined Wastewater System: The combination of both wastewater and sewage management systems with surface water runoff sewers into a single hybrid system.

Permeable: The ability of a gas or liquid (such as water) to pass through a surface.

Raster Data: Spatial data composed of pixels organized into a grid, forming a raster image, wherein each pixel is assigned a value (such as elevation, temperature, etc.).

Runoff Buffering: The absorption of additional precipitation shed off by impermeable surfaces by permeable ones.

Surface Saturation: The state of otherwise permeable surfaces wherein they are unable to absorb any more precipitation, resulting in their becoming effectively impermeable.

Vector Data: Spatial data composed of points, lined, and polygons.

Introduction:

The construction of urban landscapes has had many negative consequences for natural environments, which are well known and documented. Such consequences include alterations to the local hydrology of an environment (Leopold, 1968). At the forefront of these effects are overloading of water treatment plants (Halifax Water, n.d.), mobilization of surface contaminants (Göbel et al., 2007), surface soil erosion (Palmer & Smith, 2013), and the overloading of the natural water capacities of adjacent systems (Armson et al., 2013). The issue of extensive impermeable urban surfaces is of particular importance to the Halifax Regional Municipality. With a combined wastewater (sewage) and stormwater system (responsible for capturing and directing rainfall), both substances are processed by wastewater treatment facilities (Halifax Water, n.d.). The problem is a result of two factors: the extent of impermeable surface, and the use of the combined wastewater system. While impermeable surface area directs precipitation into stormwater drains (and subsequently into water management infrastructure), the combined management system directs both wastewater streams into the treatment plant, resulting in an incoming volume that the system may not be able to process during significant rainfall events. Accordingly, the quantity of surface runoff is directly related to the impermeable surface area which feeds runoff water into the system (White & Howe, 2004).

As a landscape undergoes the process of urbanization, wherein a natural landscape is transformed into an urban one, aspects of the region will fundamentally change. Roads, building and parking lots will appear where once natural areas were found. Although the topography may remain the same, the resulting hydrology, how water interacts with the land, may certainly be altered, giving rise to the field of urban hydrology (Niemczynowicz, 1999).

The quantity of water from surface runoff is largely determined by the ability of the land to allow water infiltration. Runoff, and inversely, infiltration rates, are typically dictated by the slope of the surface, soil composition, and land use (Mahmoud, 2014). It is typical of urban structures to seal the ground's

surface, transforming permeable landscapes into less permeable, or impermeable ones. Therefore, as more surface area is transformed by urban landscapes, there is a direct effect on the amount of water allowed to permeate the land's surface (Leopold, 1968). The result yields greater volume of surface runoff over a shorter duration that moves faster across an urban landscape than it would a natural one, introducing the additional risk of surface erosion (Leopold, 1968; Palmer & Smith, 2013).

Arguably, surface water runoff should be processed and treated, given the likelihood of chemical contamination from dry-deposition and combustion products (Göbel et al., 2007). However, directing precipitation over green spaces or other permeable surfaces could be immediately absorbed surface runoff, reduce the contamination opportunities of surface water, and contribute to groundwater recharge. Meanwhile, the volume of water entering the management system would be reduced. In cases where it does not require processing, it places additional strain on water treatment infrastructure, leading to greater operational and maintenance costs. Additionally, the predicted increase in precipitation and frequency of storms (International Panel on Climate Change, 2007), as suggested by the advent of three independent 50-100 year storms between March of 2003 and February of 2004 (Halifax Regional Municipality, 2010), supports the need for an updated and sustainable urban water management system.

It is therefore critical to assess the structure and distribution of impermeable, permeable, and green surfaces in our urban landscapes for opportunities to reduce surface runoff. This study examines Dalhousie University's Studley campus, located in the south end of Halifax, Nova Scotia, to determine its overall permeability and volume of surface runoff produced using GIS techniques and ground truthing, with the objective of delineating the types and sizes of surface area found across the campus.

Methods for surface water modeling include the use of geographic information systems (GIS) technology. One function of GIS is the ability to generate maps using vector data, which is a type of GIS that utilizes points, lines, and polygons to compose the map. These features can be assigned values or types corresponding to real world features such as land use (forested, grassland, etc.), elevation, or permeability.

Large studies using GIS for flood hazard mapping have been published (El Osta & Masoud, 2015; Elkhachy, 2015; Haq et al., 2012). This project seeks to follow a similar model to Mahmoud (2014) –who generates a nationwide surface runoff profile based on surface characteristics using GIS technology– on an institutional scale. Additionally, the surface runoff map will serve to identify regions of the Studley campus as sites for further development of Dalhousie’s Natural Environment Plan (Dalhousie University, 2014) to combat surface water runoff.

Apart from limiting urbanization, solutions to the issue of high surface runoff in urban regions have been offered. Sustainable drainage systems (SuDS) provide the opportunity increase urban drainage while avoiding typical responses such as augmented sewage and drainage systems. Focusing on addressing the problem at the source, SuDS utilize technology such as permeable pavements and vegetation integrated into urban land cover to absorb precipitation and mitigate surface runoff (Armson et al., 2013). The usage of urban forests as stormwater management systems has accordingly been identified as a potential method to reduce runoff (Bartens et al., 2008). Similar to SuDS, low impact development (LID) strategies have been implemented as a pilot project in New York city (USA) to test their savings and installation expense in terms of energy and green house gas (GHG) emissions avoided (Spatari et al., 2011). By decentralizing the management of stormwater and installing green infrastructure as runoff management strategies, LIDs promotes infiltration of rainfall at the site of impact to reduce stress on combined wastewater systems. Despite a high initial investment of energy and GHGs to produce the LID infrastructure, compared to annual savings, Spatari et al. (2011) demonstrate their importance in both reducing the pressure on water treatment facilities and implementing long term energy and GHG savings.

Dalhousie’s Studley campus, being located on the Halifax peninsula, is integrated into Halifax’s storm and waste water management system (Dalhousie University, 2014). As such, the university’s sustainable motives have a stake in the Halifax Regional Municipality’s (HRM) water management system. With sustainable runoff management goals and features already in place, Dalhousie is poised for further

development of sustainable drainage infrastructure and runoff mitigation (Dalhousie University, 2014).

Peninsular Halifax utilizes an array of stormwater and wastewater systems, which in some areas are combined, resulting in the collection and delivery of sewage from the municipality with precipitation from the city's surface (Halifax Water, n.d.). The combined system terminates at the Halifax wastewater treatment facility, which empties treated effluent into the Halifax harbor (Halifax Water, n.d.). Thus, both wastewater and precipitation are treated by the plant. However, during high rainfall events, the system becomes overwhelmed with water and the treatment facility must detour the combined contents directly into the harbour (Halifax Water, n.d.) to avoid damage to local properties from backflow and flooding (White & Howe, 2004). Prior to the plant's installation, sewage was discharged directly into the Halifax Harbour, resulting in the contribution of numerous marine debris (such as plastics, Styrofoam, and cigarettes) (Walker et al., 2006) and nutrient loading (Dalziel et al., 1991). This previous state of affairs is an indicator of effects on Halifax Harbour when the treatment plant is forced to forego its operations by high input volume.

Below (displayed in Figure 1), a simple model of urban water management is displayed to demonstrate the contributing factors to surface runoff and the volume of waste water directed into the treatment plant. While permeable surfaces can serve to buffer the runoff from impermeable surfaces, decreasing the area's contribution to stormwater management (Armson et al., 2013), they may become inundated with water and contribute to further runoff (Hsu et al., 2000; Zhu et al., 2016). Should the urban area have a combined waste water management system, that collects both surface runoff and sanitary sewage, then they will both be directed to water treatment before their discharge. Thus is the case in peninsular Halifax (Halifax Water, n.d.).

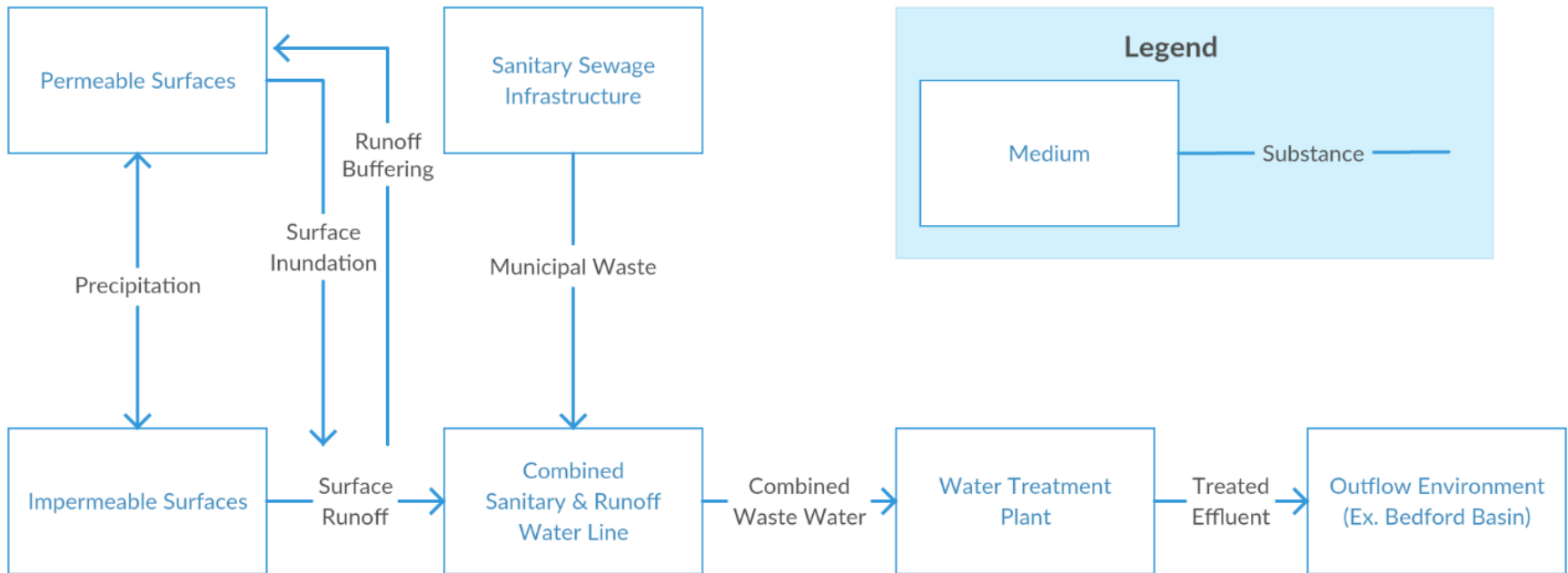


Figure 1: Process flow diagram of urban precipitation runoff, management, and processing. Model graphic generated with Creately.

The field of urban hydrology is arguably well established in the literature, with previous publications indicating the effects of urbanization on local hydrology (Armson et al., 2013; Boving & McCray, 2007; Leopold, 1968). Given that the theory and principles behind urban hydrological systems is already in place, it is prudent to expand the field in the direction of land use analysis and corresponding to surface water runoff. Although previous studies such as Palmer & Smith (2013) have established a medium for quantitative analysis of surface water flow and the resulting impacts on the landscape, it is imperative to address the issue of surface water runoff on a local basis, so as to assess a more manageably scaled environment, and demonstrate appropriate solutions that can be practically applied. This study seeks to provide such solutions.

Given that surface runoff volume is dependent on surface conditions and infiltration capacities, a methodology suited to Studley campus is necessary to accurately reflect its surface profile. Infiltration is the defining mechanism behind surface water runoff, and is geographically dependent on terrestrial conditions (Leopold, 1968). Mahmoud (2014) provides a regionally scaled example of surface water runoff, and serves as a basis for runoff analysis methodology via the factorization of potential runoff coefficient. However, to best improve local infrastructure, local conditions need to be studied. A case study of Dalhousie's Studley campus is necessary, as it is currently lacking in the literature and the university's sustainability plan. Moreover, this project may serve as a basis from which to launch a broader investigation into the HRM's runoff management strategies.

The purpose of this study is to generate an account of the volume of surface water runoff produced by Dalhousie's Studley campus. Doing so will require a synthesis of precipitation data with geospatial information that delineates the boundaries of each surface type on Studley campus. In the process, the study should help illuminate ways to increase water retention and surface permeability. Specifically, the research questions associated with this project are:

1. *What quantity of surface water generated by rainfall events was shed off the surface area of Dalhousie's Studley campus in 2016 by impermeable regions?*
2. *What features can Dalhousie practically introduce to promote greater water retention in this urban context?*

Furthermore, given the urban structure of the Studley campus, the following hypothesis is postulated:

The majority of water input from precipitation events was lost to runoff by impermeable surfaces such as roads, parking lots, and tiled or sealed roofs covering the majority of Studley campus' surface area.

The scope of this study is constrained to the 2016 calendar year, for which precipitation data are readily available (Government of Canada, n.d.). Geospatially, this study is limited to the confines of Dalhousie's Studley campus in central Halifax. This research specifically focuses on changes in surface permeability resulting in urbanization, and the resulting increase in surface runoff.

Chapter 2 – Literature Review:

The literature examined in this review will largely pertain to the causes of urban flooding, surface water runoff, and mitigation strategies. Although this study focuses specifically within the boundary of Dalhousie's Studley campus, studies from other regions will be reviewed, adapted, and compared to this study to help develop further research in the field of urban water management. Furthermore, this research will serve as an indicator for Dalhousie governance as to the state of urban water affairs. The journal *Water* will prominently feature in the following discussion, along with contributions from the *Journal of Contaminant Hydrology* and a range of other peer reviewed sources. The current literature's address of urbanization, surface runoff, and urban hydrology is consequence focused and centered around precipitation management on regional scales. The lack of attention to institution specific accounts of surface hydrology provide this study with the means to contribute a delineated quantification of surface runoff as induced by the urbanization of Dalhousie's Studley campus.

The process of urbanization has an immense effect on the hydrology of an area; resulting in less infiltration and an increase in the speed and volume of surface water runoff (Holman-Dodds et al., 2003). The large concentrations of impermeable infrastructure, as seen in urban regions, make the area more prone to flooding than the adjacent environments (Sørensen et al., 2016). Urban infrastructure such as roadways, buildings, and commercial structures created during urbanization is designed to transport precipitation from the immediate area to existing water channels (Göbel et al., 2007). As such, the increased density of urban areas, changes in land use, and the effects of climate change is of growing importance as urban flooding increases (Sørensen et al., 2016). The resulting propagation of urban building techniques that cover and seal large areas of surface area directly contribute to high surface water runoff, and the prevalence associated negative consequences such as erosion and flooding.

The consequences of urbanization and widespread impermeability are expected to worsen in the face of climate change due to accelerated sea level rise, and an increased prevalence of storm intensity and

frequency. Climate change necessitates that flood management be brought to the forefront of future urban design strategy (Ven et al., 2011). Recent flooding in regions such as Copenhagen in 2010, 2011, and 2014, New York in 2012, SW England in 2013-14, and the French Riviera in 2015 are indicative of the consequences of both climate change and urbanization (Sørensen et al., 2016). Average flood damages between 2000 and 2012 are approximately 4.9 billion euros per year, which is predicted to rise to 23.5 billion euros per year by 2050 (Jongman et al., 2014). Urban regions are suggested to account for substantial climate change effects, with particular reference to extreme weather phenomena. Accordingly, greater storm intensity and precipitation and expected to increase the frequency of flooding (Coumou & Rahmstorf, 2012). Climate related data such as precipitation amount and storm frequency gathered over the last two decades clearly illustrate a changing climate context in which a new urban water management system must be developed.

Geologically speaking, Halifax is already at a disadvantage. Resting on a bedrock landscape of slates, granitoids, metasandstones, and exposed stony till (Lewis et al., 1998), the natural landscape is disposed to impermeability. With an increasing prevalence of hurricanes in the North Atlantic, wherein nine of the eleven years prior to 2007 featured an above normal number of hurricanes (Thompson et al., 2009), a modernized urban water management is more critical than ever. The advent of Hurricane Juan on September 29th of 2003 produced record flooding, water levels, and damage, exemplifying the intense history of storms in Atlantic Canada, and serves as a plausible indicator for future weather events. Reports estimated rainfall ranging from 25 to 40 mm, with sustained wind speeds of up to 151 km h⁻¹ (Bowyer, 2003). An expected increase in future precipitation events necessitates a modern solution to the marked increase in urban flooding.

Impermeable surfaces such as pavement and roofing tiles serve as mediums for contaminant collection, and can feed into surface runoff. Surface water runoff can pickup a number of contaminants such as soluble salts, polycyclic aromatic hydrocarbons, and various heavy metals (lead, zinc, copper, cadmium)

that can degrade water quality (Göbel et al., 2007). Runoff from storm precipitation and surface flow exemplify non-point source pollution that distribute the aforementioned substances, and arise from a large scale distribution of contaminant deposition. Naturally occurring sorbents, such as bark, dead biomass, peat moss, and clay (Bailey et al., 1999), could be used to capture stormwater contaminants (Boving & McCray, 2007). A system that better addresses non-point-source pollution, such as seeding the urban landscape with sorbents, offers effective methods to combat surface water pollutants.

Separate and combined systems for stormwater management and sanitary water both have mixed qualities. Separate systems do not process contaminants picked up from surface flow, hence they are delivered via the outflow into adjacent water features. Combined systems, while being able to process both sanitary and surface water contaminants, are often unable to handle the volume of water experienced during high rainfall events. As such, 'combined sewer overflow' (the product of both storm and sanitary water) must, out of necessity, be discharged without any treatment to avoid flooding of urban features such as residences, businesses, and streets (White & Howe, 2004). Niemczynowicz (1989) indicates that the regional water treatment plant (Lund, Sweden) will no longer capture pollution loads in its input under higher rainfall conditions. Rather, they will flow directly into adjacent water systems. Increased precipitation associated with climate change will likely increase pollution associated with runoff, even when point-source or non-point-source pollution rates are consistent (Niemczynowicz, 1989). The consideration of drainage systems as the go-to solution for urban water management is a dated notion that does not address a modern understanding of surface contaminants or urban hydrology. Neither separate nor combined systems can entirely mitigate water pollutants or sewer overflow.

Mitigation strategies have been developed to combat the effects derived from urbanization. Water flow, volume, and pollution can be controlled by the use of SuDS (Armson et al., 2013), which intercept surface runoff prior to its entering a stormwater drain, thereby applying a more proximate solution to the issue of runoff induced flooding. Low impact stormwater management systems proposed by Holman-Dodds et al.

(2003) propose increased infiltration techniques to manage rainfall at point of contact, and are consistent with the methodology put forward by Armson et al. (2013) regarding the effect of street trees and grass. Viable alternatives to conventional drainage methodology exist and can be employed to combat surface water runoff and urban flooding before drainage infrastructure becomes inundated with water.

The typical response to urban water management and surface runoff that turns to improved and increased drainage is dated and unsuited to future requirements. The consideration of urban drainage in the UK has largely remained the same following the industrial revolution. The same surface water management has led to increased pollutant delivery, flooding, and a decrease in groundwater supply (White & Howe, 2004). The classic way of managing precipitation by engineers has been to increase the quantity and volume of sewers and drainage channels, a practice that is both disruptive to other subterranean infrastructure, and very expensive (Armson et al., 2013). Publications on the negative impacts of stormwater management via the conventional drainage methodology have long since observed a decrease in water quality, and an increase in the erosion of streams and frequency of flooding, with a consequential increase in costs from damages (Hammer, 1972; James, 1965). Meanwhile, modern management techniques are centered around absorbing water where it falls and diverting surface flow over permeable regions. Low impact, infiltration based techniques show the most success under more frequent and smaller rainfall events (Holman-Dodds et al., 2003). Typical stormwater management strategies that rely upon the export of urban water via drainage systems have clearly been shown to have substantial consequences on both the immediate urban environment, via the denial of surface infiltration, and on that of adjacent environments from increased water contamination and contaminant delivery.

The utilization of GIS technology to gauge surface runoff has been previously employed on larger, region based scales by previous studies for the purpose of flood hazard mapping and prediction (El Osta & Masoud, 2015; Elkhachy, 2015; Haq et al., 2012). Moreover, it has also been used in a similar manner that which has been proposed for this project: the analysis of surface runoff volume. However, in this case,

Mahmoud (2014) oriented GIS software to identify surface runoff harvesting sources for water supply to local populations. Mahmoud's analysis revolves around factoring hydrologic soil type, land use, slope, and rainfall, providing a parallel framework and reference for the methodology developed herein, given the similarity of approaches. While GIS based methods are commonplace in hydrologic analysis of surface water, there is room for the addition of institutionally scoped approaches that provide a specific accounting of their urban hydrology.

As an independent institution, Dalhousie University has the power to self govern its operations and dictate policy that reflects its values. Recognizing the importance of sustainable storm water management in Dalhousie University's Natural Environment Plan (Dalhousie University, 2014), Dalhousie has already set a precedent for further campus based research into mitigating surface runoff. The use of green roofs, permeable surfaces (such as permeable pavements featured in the Hancock and Ocean Sciences Building parking lots), and rain gardens (exemplified by the installation at the corner of Coburg and Oxford roads) are already employed by the campus and have demonstrated their effectiveness in reducing runoff (Dalhousie University, 2014). The pursuit of a spatially delineated analysis of stormwater runoff would provide Dalhousie with the opportunity to recognize and target further opportunities to combat urban water surface runoff. Moreover, the pursuit of sustainable drainage methods would be pursuant to Halifax Regional Municipality legislation, which now prohibits the discharge into sanitary sewers of "stormwater, surface water, ground water, roof runoff, subsurface drainage, cooling water or industrial process waters" (Halifax Regional Municipality, 2008). The use of the proposed methods could further be extended for application to different institutions, given the availability of equivalent spatial data.

The literature surrounding urban hydrology and its dealings with surface water, precipitation management, and urban flooding is largely centered around the consequences of drainage based management systems and the resulting contamination. Scoping of individual publications is based on the regional level, with less attention to the specific geography of urban spaces. Via the examination of the

contained literature, this review illuminates the need for a spatially defined quantification of surface runoff induced by urbanization. The delineation of Dalhousie's Studley campus will provide a detailed examination of the interaction between urban structures and precipitation, providing the literature with a small scale study on the effects of built structures on surface water. Accounting for surface runoff volume with the use of a geographic information system will provide a detailed measure of precipitation infiltration and its destination, be it either ground infiltration or surface runoff. The proposed study should contribute an aspect to the literature by providing an exemplification of applied GIS technology to delineate surface area type, thereby accounting surface runoff as a quantified factor of urbanization.

Chapter 3 – Methodology:

The methods employed for the execution of this project revolve around three integral components: geospatial vector data, elevation raster data, and precipitation data. The geospatial data (sourced from the 2012 HRM Geodatabase and manually updated to 2016 standards) provides the two dimensional surface framework for land use delineation, and is sourced from the HRM geodatabase. Precipitation data (mm rainfall), collected by Environment and Natural Resources Canada in 2016 (www.canada.ca/en/services/environment.html), serves as the third dimension to yield the total volume of precipitation received by the study area. Finally, a digital elevation map (DEM) is employed to approximate the surface hydrology of the campus, based on a bare-earth 1 m LiDAR (Light Detection and Ranging) scan provided by the HRM (Halifax Regional Municipality, 2017). The resulting geospatial model provides indications for high runoff and flood hazard zones, and serves as a tool for future sustainable drainage development of Studley campus.

The study area (delineated in Figure 3) for the project is confined to the bounds of Dalhousie University's Studley campus, which are broadly delineated by the area contained within Coburg Road, Oxford Street, South Street, and Robie Street. Additional features outside this zone such as the Dalplex recreation and fitness facility, its adjacent Dalhousie-maintained landscape, and the raingarden diagonally across from the campus at Oxford and South Street are not included. The University of King's College is included in the study area, given its institutional capacity to govern campus policy and management, and geographic integration into the campus and study area. Temporal bounding of the project extends the duration of the 2016 calendar year, to provide a range of seasonal precipitation data.

Featuring the use of ESRI's ArcGIS software, this study utilizes geospatial vector data to delineate the various surface types found in the study area, such as building footprints, parking lots, sidewalks, roads, green areas, and recreational surfaces. The two dimensional framework generated therein provides proportions of permeable and impermeable surface area. Surface types are assigned a permeability type to

indicate their capacity for precipitation infiltration, either as impermeable (such as conventional concrete structures like parking lots) or permeable (such as the turf grass found within and around University Avenue). Using the DEM as the input, the flow direction ArcMAP tool is employed to determine the flow direction of each pixel in the raster image. In turn, the flow direction serves as the input to derive the surface runoff accumulation via ArcMAP's 'Flow Accumulation' tool (Spatial Analyst Tools > Hydrology > Flow Accumulation), to indicate pixels which have numerous others flowing into them.

The application of rainfall depth to the delineated surface area will yield a runoff volume (mL) as a function of the study site's cumulative permeability. This model assumes an equal distribution of precipitation across the study site, and is limited in accuracy by the freeze-thaw effect of snowfall and soils, resulting in solid, impermeable surfaces. Wherein the subzero temperatures experienced by Halifax will freeze snowpack inundated with rainfall, a mass impermeability effect can be experienced by the surface of the study site, heavily affecting surface runoff patterns. However, it is the goal of this study not just to produce a summary runoff volume, but serve as a tool for sustainable drainage development, which will not be affected by the aforementioned limitations. The surface analysis produced by this study provides a guide for future sustainable development of urban water management via the presentation of flood hazard and highly impermeable areas to be addressed.

The use of GIS software for runoff analysis is founded in existing studies in the literature pertaining to natural hydrology, surface runoff, and urban hydrology. Typically used on a regional scale for the purpose of flood hazard analysis and prediction (El Osta & Masoud, 2015; Elkhachy, 2015; Haq et al., 2012), similar methods developed by Mahmoud (2014) exemplify the utility of GIS software in factoring surface permeability in the production of runoff volume estimates. Moreover, discussion and demonstration of GIS applications on a municipal scale demonstrate the capacity of the software to utilize surface structures for runoff and flood analysis (Wolthusen, 2005).

Chapter 4 – Results:

The total surface area of Dalhousie’s Studley campus, delineated by the area enclosed by the surrounding sidewalks, is 327,109 m² (Oxford, South, Robie, and Coburg streets, as displayed in Figure 3). Of that area, 214,078 m² (65% of total surface area) is composed of impermeable surface material, such as roads, sidewalks, parking lots, and buildings (exemplified in Appendix 2). Recreational surfaces notably contribute to campus impermeability, occupying 16,570.40 m² (5%) of Studley’s total surface area (or 7.7% of impermeable surface area) due to the Wickwire field and tennis courts. Accordingly, a total of 65% of Studley campus is sealed with impermeable surfaces, while 35% remains permeable to precipitation (Figure 2).

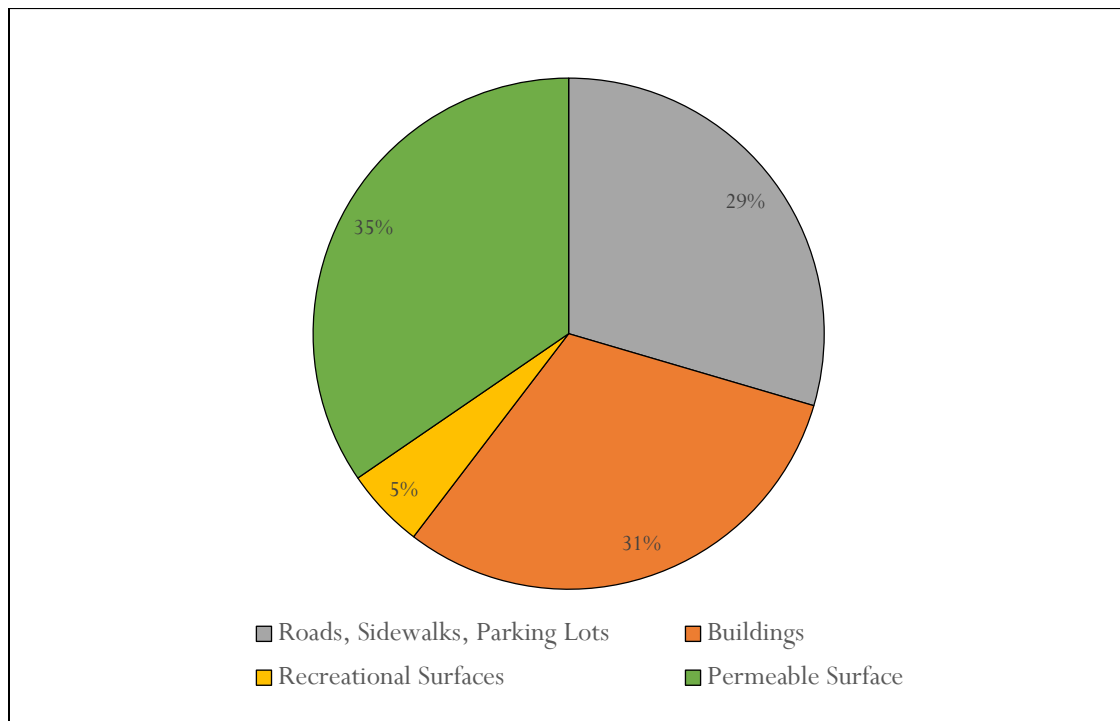


Figure 2: Percent (%) surface area of Dalhousie’s Studley campus covered by impermeable (roads, sidewalks, parking lots, buildings, and recreational sites) and permeable surfaces (turf).

Over the course of the 2016 calendar year, a total of 1219.70 mm (1.2197 m) of precipitation fell on central Halifax. As a consequential product of the impermeable surface area and total annual precipitation, a volume of $2.6111 \times 10^5 \text{ m}^3$ of rainfall was shed off Studley campus's impermeable regions alone. As displayed in Figure 3, the surface types are divided into five relatively large sub-categories, covering substantial areas of landscape with various surface types.

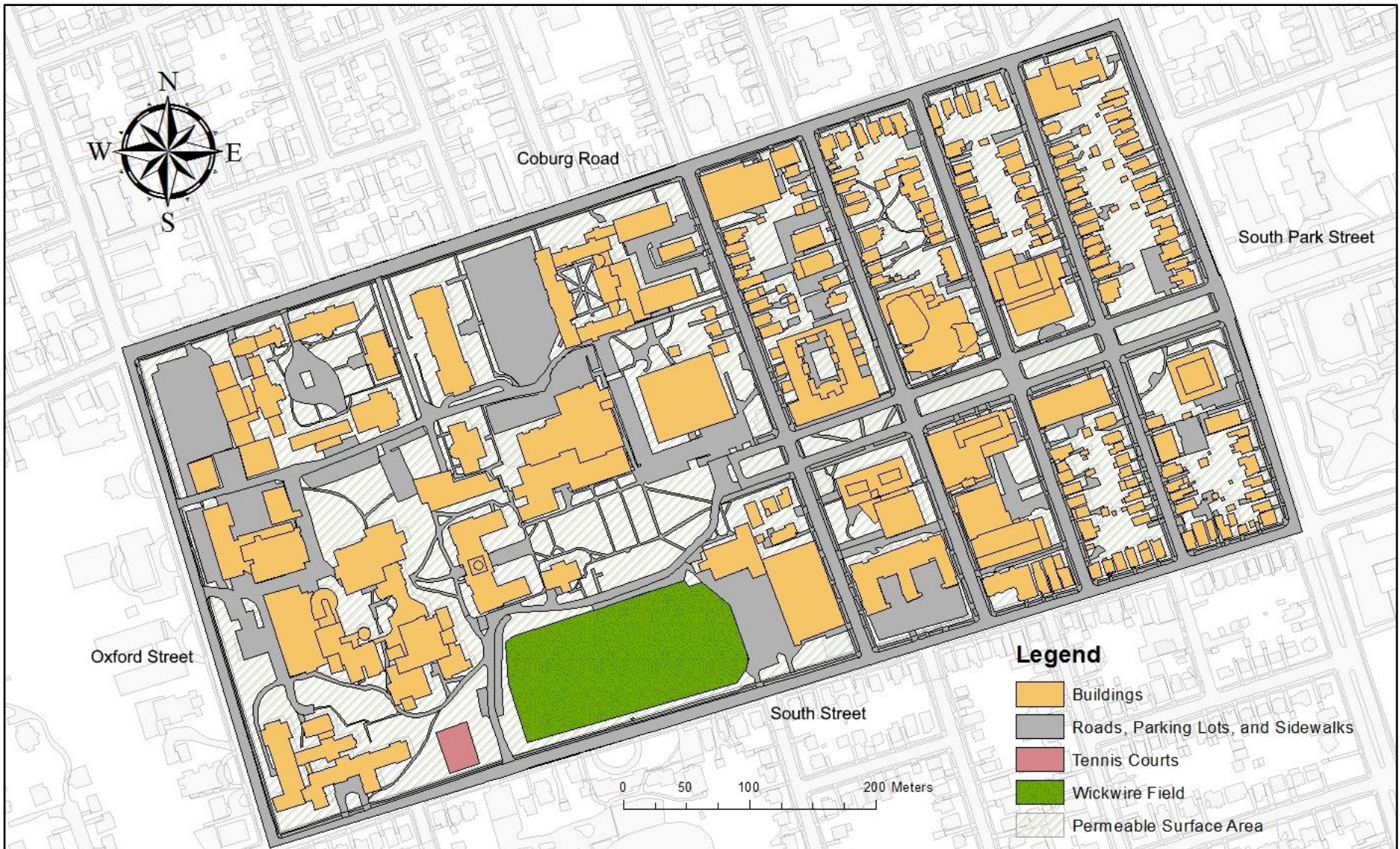


Figure 3: Surface area types of Dalhousie's Studley campus. Note: the perimeter roads and exterior region are not included in surface area calculations.

With the local water management infrastructure being entirely composed of combined wastewater and runoff lines on Studley campus (displayed in Figure 3), all surface runoff yielded by the campus is a direct input to the Halifax water management and treatment system. Moreover, with a notable lack of catch basins –which serve as collection points for the combined system– across the western portion of the campus, there is potential for a high degree of surface runoff given the corresponding impermeability of the campus. Below, Figure 3 displays the disposition of runoff accumulation across the campus, and potential, undeveloped sites adjacent to critical accumulation regions that could be converted into runoff management features. While the amount of accumulation is derived independently from surface type, a visual assessment of the map indicates a notable occurrence of surface runoff accumulation with large regions of impermeability. Moreover, the absence of catch basins in high accumulation regions through south-western and central-north areas presents the opportunity for flood events.

Given the position of Studley campus on a slight gradient, the formation and accumulation of runoff streams was anticipated. The model for such is displayed in Figure 4, and yields large accumulation zones in sloped regions. Moreover, these sloped regions occur atop already impermeable surfaces, enabling the generation of considerable at risk zones during large precipitation events. However, the error associated with the DEM used to generate the surface hydrology has an associated error margin of ± 15 cm, or a potential range of 30 cm.

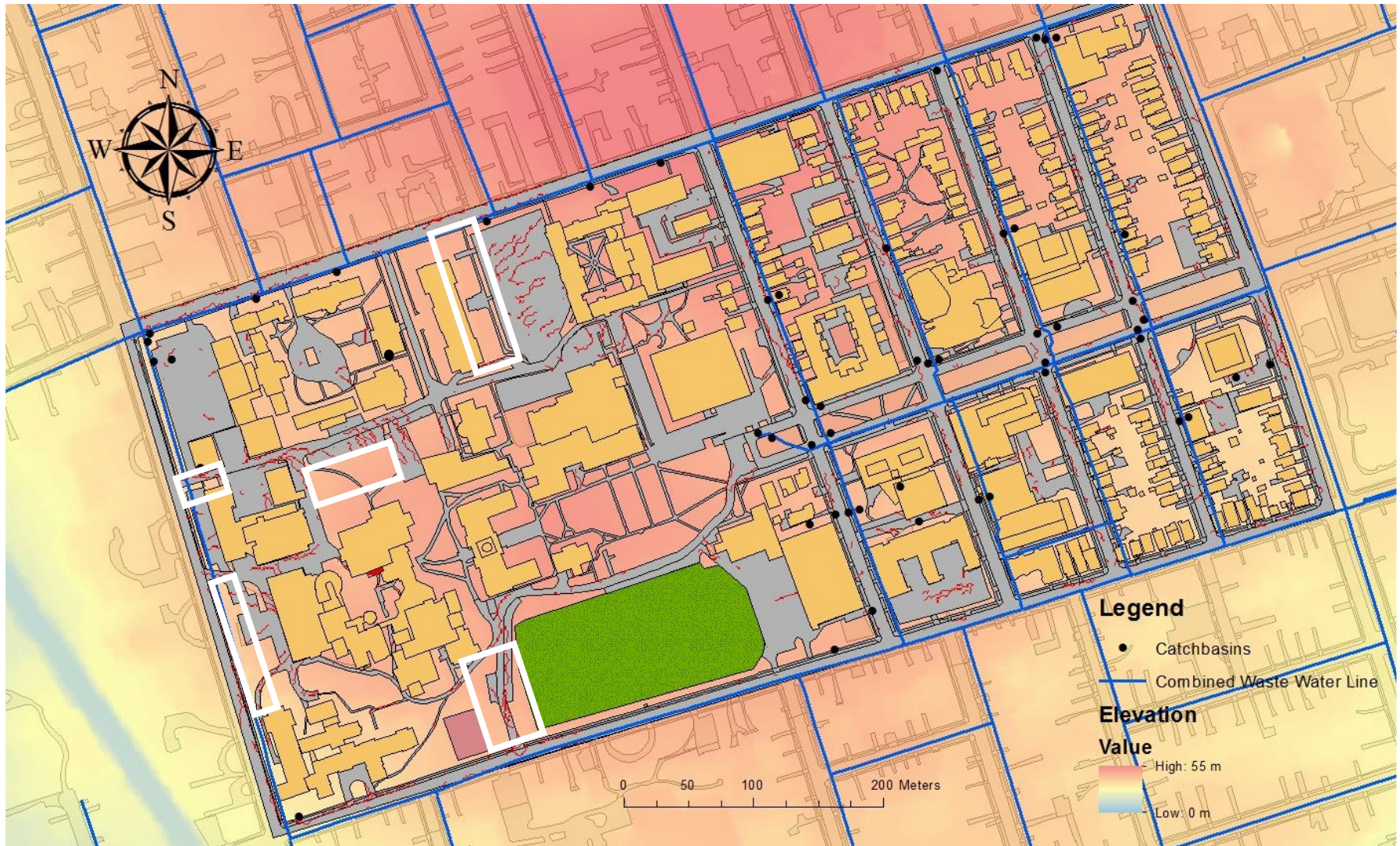


Figure 4: Topography, with ground elevation represented on a faded gradient from red (high), to orange (intermediate), to blue (low), surface hydrology (with flow accumulation represented by bold red), and municipal water management infrastructure. White boxes indicate regions adjacent to high surface flow that could be considered for sustainable drainage measures (such as SuDS). Remaining map items same as Figure 3.

Chapter 5 – Discussion:

Analysis of Studley campus surface types and area yields a large amount of impermeable surface area, equal to 65% of the campus, leaving the remaining 35% permeable to precipitation. Moreover, surface runoff accumulation occurs consistently with large regions of impermeable surface, while the modelling of each is entirely separate. Following a precipitation depth for 2016 of 1.2197 m, a total volume of $2.6111 \times 10^5 \text{ m}^3$ of surface runoff was produced by the impermeable proportion of campus. However, this volume remains only moderately constrained, due to buffering of runoff by permeable surfaces during small precipitation events, and enhanced runoff bolstered by permeability surfaces that are inundated with water during large precipitation events.

Given the size of storm water management features, such as curbs, that direct water flow being within a range of 30 cm, conclusions derived from the DEM are potentially inaccurate. With the size of management features being beyond the spatial resolution of the DEM, water management could effectively be taking place without the model taking notice. However, high surface flow regions, indicated in Figure 4, nonetheless provide an insight into critical campus areas for runoff management. The highlighted regions (indicated by white outlines in Figure 4) present opportune sites for the installation of SuDS and LID runoff management. Where both strategies rely on permeable urban surfaces or green infrastructure to enable runoff infiltration, Dalhousie University could develop further raingardens to mediate the infiltration of campus runoff, or direct current runoff flows over existing permeable surfaces.

Although the delineation of campus surface areas has allowed for the generation of a runoff volume stemming from the impermeable portion of campus, the value does not consider any

buffering from permeable regions. While the water being shed off the impermeable surface types does not make it directly into the soil, runoff into adjacent permeable regions could serve as water management features and input sites for groundwater. As such, permeable campus spaces could already be serving as the SuDS suggested by Jones & Macdonald (2007), agreeing with further literature arguing the wide scale acknowledgment of urban green spaces in regulating surface runoff (Demuzere et al., 2014; Sørensen et al., 2016; Spatari et al., 2011). Conversely, during periods of intense precipitation, those same permeable regions could become saturated with water, and in effect become impermeable, rejecting further precipitating past a certain point. The latter notion is consistent with the effect of frozen soil or ice pack serving as an impermeable barrier to precipitation, despite the surface being spatially catalogued as permeable.

Due to the constraints posed by soil type and infiltration capability, further research is required to more accurately constrain the effect of runoff buffering and the saturation volume of soils on total surface water runoff to give a more accurate approximation. Analysis of the infiltration rates and buffering capacities of soil profiles local to the study area, along with hourly precipitation data, could provide a means to quantify a highly resolved picture of surface runoff.

Despite further research being required to constrain a volumetric approximation of campus runoff, this research provides a basis from which to begin implementing sustainable and low impact drainage methods at targeted locations. Moreover, it contributes to filling a knowledge gap regarding runoff assessment, while serving as a precedent and template for future research on campus runoff management at Dalhousie and other university institutions seeking to implement sustainable campus initiatives.

Conclusion:

Urban areas have been identified as vulnerable to flooding due to the conversion of natural, permeable landscapes to developed, impermeable ones, with additional detrimental environmental and infrastructural consequences. Dalhousie University's Studley campus is similarly at risk from the large extent urban surfaces have sealed the campus. Geospatially assessing the surface area composition of the campus with ArcGIS, a map of surface area type and distribution, along with additional identification of high surface runoff accumulation areas, was generated. In conjunction with precipitation data for 2016, a volume approximating total surface runoff from impermeable campus surface area was presented. Potential areas for the introduction of sustainable and low impact water management systems are suggested.

Due to an impermeable surface area of 214,078 m² with an annual rainfall of 1.2197 m, an estimated volume of 2.6111×10^5 m³ of precipitation was shed off as surface runoff. Moreover, the research presented herein agrees with the postulated hypothesis that the majority of Studley campus is impermeable, from the resulting spatial analysis producing an impermeable proportion of 65%. The foremost suggestion following the conclusion of this research is the implementation of permeable green spaces (as SuDS) to buffer the effect of surface runoff and relieve stress from the water management and treatment infrastructure, at least during periods when the weather allows (such as spring, summer, and fall). In contrast, the practical viability of SuDS are limited during winter months when the majority of all interfaces across the campus are effectively impermeable.

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Appendix 1: Summary Statistics

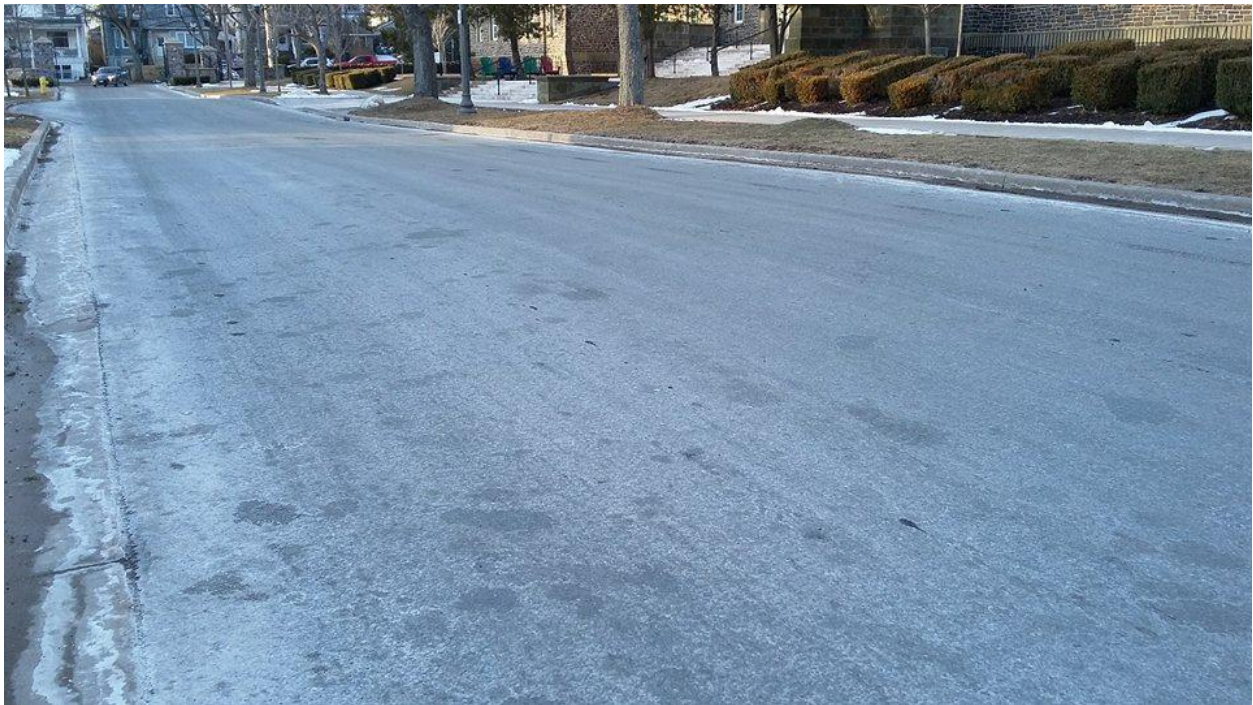
Surface Areas		
Specific Breakdown	Area (m²)	Percent Cover (%)
Study Region	327109	100
Roads, Sidewalks, Parking Lots	96657.6821	29.5490745
Buildings	100849.8347	30.83065117
Recreational Surfaces	16570.399	5.065711735
Permeable Surface	113031.0842	34.55456259
<i>Impermeable Surface Area</i>	214077.9158	65.44543741
<i>Permeable Surface Area</i>	113031.0842	34.55456259
Rainfall Depth		
	depth (mm)	depth (m)
2016 Shearwater Data	1219.70	1.2197
Runoff Volume		
Surface Area (m²)	Rainfall (m)	Volume (m³)
214077.9158	1.2197	261110.834

Appendix 2: Surface Area Types and Features

Surface Type Classification: Sidewalks



Surface Type Classification: Roadways



Surface Type Classification: Parking Lots



Surface Type Classification: Wickwire Field



Surface Type Classification: Tennis Courts



Surface Type Classification: Buildings



Surface Type Classification: Turf (Permeable Surface)



Surface Feature: Catch Basin

