Spatial and Temporal Analysis of Hydraulic Conductivity, Snow Depth and Soil Properties of a Bioretention System

by

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A thesis submitted in conformity with the requirements
for the degree of Master of Applied Science
Department of Civil and Mineral Engineering
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Abstract

Bioretention Cells (BC) are a Low Impact Development technology that provide distributed storm water management near to its source. Most research envisages BC as a black box with ambiguous processes between the input and the output. This thesis aims to consider BCs as heterogeneous systems with physical processes that vary both spatially and temporally.

For this study, a 5-year-old BC at Kortright Centre for Conservation in Vaughan, Ontario is used as an investigation area. The following results were observed. D_{30} and D_{60} were lower in the central flow path due to sedimentation and suspended solids deposition. Organic content was negatively correlated with bulk density. K_{sat} in the central pathway region and non-central pathway region showed a mild rise during and a mild decrease respectively during warm winter days possibly due to freeze-thaw action. However, after statistical outliers were identified and removed from the K_{sat} data, this effect was not observed.

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Table of Contents

Acknowledgments.....	iii
Table of Contents.....	iv
List of Tables	vii
List of Figures	viii
List of Appendices	xi
1 Introduction.....	1
1.1 Background	1
1.2 Research Objective.....	3
1.3 Thesis Structure.....	4
2 Literature Review.....	5
2.1 Introduction:	5
2.2 Spatial Variability	6
2.2.1 Surficial variability	8
2.2.2 Vertical variability	13
2.3 Temporal Variability:	16
2.3.1 Effect of freeze thaw cycles on natural soil:	16
2.3.2 Effect of freeze thaw cycles on BC media:.....	17
2.3.3 Effect of aging on BC:	18
2.4 Conclusions and Research gaps:	20
3 Methodology	21
3.1 Site Description	21
3.2 Spatial Location Selection.....	25
3.3 Saturated Hydraulic Conductivity (K_{sat})	27
3.3.1 Guelph Permeameter (GP).....	27
3.3.2 K_{sat} calculation	29
3.3.3 Radcliffe et al. (2015) Method.....	29
3.3.4 Elrick and Reynolds (1992) Method.....	31
3.4 Soil Analysis	32
3.4.1 Bulk density, moisture content and organic content.....	32
3.4.2 Soil Particle Distribution.....	34
3.4.3 Particle Density and Porosity.....	36
3.5 Winter Measurements	37

3.5.1	Snow Depth and Density	37
3.5.2	Frost depth	40
3.5.3	Frost tube preparation	41
3.5.4	Surface and subsurface water levels and temperatures	43
3.5.5	Weather data	45
3.6	Data Analysis	46
3.6.1	Statistical & Spatial analysis.....	46
3.6.2	Time Series Analysis	47
3.6.3	Correlation	48
3.6.4	Water level data	48
3.6.5	Required Sample Size	49
4	Results & Discussion	50
4.1	Spatial Variability	50
4.1.1	Saturated Hydraulic Conductivity (K_{sat})	51
4.1.2	Bulk Density, Moisture Content and Organic Content	54
4.1.3	Porosity and Particle Density.....	56
4.1.4	Soil Particle Size Distribution.....	57
4.1.5	Snow Depth and Snow density	60
4.1.6	Correlations	64
4.1.7	Frost Depth.....	66
4.2	Temporal Variability	69
4.2.1	Saturated Hydraulic Conductivity (K_{sat})	69
4.2.2	Water level	75
4.3	Additional Considerations.....	77
4.3.1	Physio-chemical processes.....	77
4.3.2	Uncertainties in the data.....	78
5	Conclusions and Recommendations	79
5.1	Conclusions	79
5.1.1	Objective 1	80
5.1.2	Objective 2	80
5.1.3	Objective 3	80
5.1.4	Objective 4.....	81
5.2	Recommendations for future research.....	81
5.2.1	Saturated Hydraulic Conductivity (K_{sat})	81

5.2.2	Soil parameters.....	81
5.2.3	Snow depth.....	82
5.2.4	Water levels	82
6	Bibliography	83
7	Appendices.....	87
7.1	Contour Map Generation Matlab Code.....	87
7.2	Semi-variogram Generation Matlab Code	87
7.3	Assumptions for Grubbs test.....	87
7.4	Assumptions for Wilcoxon signed-rank test	88
7.5	Figures and Tables	89

List of Tables

Table 2-1: Spatial information available in various papers, the intent and the type of study.....	7
Table 2-2: Models used in the considered papers	7
Table 2-3 Calculated porosity (n) values and Hydraulic Conductivity Slope (HCO) values for sand media with different column depths - Lynn et al. (2018)	13
Table 2-4: Infiltration rates with respect to number of freeze thaw cycles – Baratta (2013)	17
Table 3-1: Points considered for snow depth and soil parameters measurement	26
Table 3-2 Infiltration rate measurement dates, antecedent conditions and conditions during data collection.....	27
Table 3-3: Snow depth and density data collection dates and antecedent conditions	38
Table 3-4: Frost tubes location and lengths	40
Table 3-5: Frost depth measurements dates and antecedent conditions	42
Table 4-1: Summary table for soil parameters, K_{sat} and Snow Depth	51
Table 4-2: Summary table for K_{sat} (cm/s) - Radcliffe method and Elrick & Reynolds method .	52
Table 4-3: Snow depth (cm) statistics with antecedent conditions.....	62
Table 4-4: Snow Density with date, time and antecedent conditions.	62
Table 4-6: Frost depth (cm) from ground surface with dates and locations with antecedent conditions.....	67
Table 4-7: K_{sat} (cm/s)– Radcliffe method – Statistics and Antecedent Conditions	73
Table 4-8: Results of Grubbs test for outliers	74
Table 4-9: Event statistics - Water levels	76
Table 7-1: Ryan Joiner P value for temporal k_{sat} data (normality test).....	87
Table 7-2: Location with their coordinates with the inlet as the origin	89
Table 7-3: K_{sat} data (cm/s) – Radcliffe Method	89
Table 7-4: K_{sat} data (cm/s) – Elrick and Reynolds method	90
Table 7-5: Snow depth data (cm).....	90
Table 7-6: Soil Particle Distribution data by location (Weight in grams).	91
Table 7-7: Soil Properties data by location.	91
Table 7-8: Locations with D_{60} , D_{30} , D_{10} , Cu and Cc.....	92

List of Figures

Figure 1-1 Conceptual diagram with the front view of the BC	2
Figure 2-1: Spatial K_{sat} map of University of Minnesota BC and the parallel excel data used to calculate the correlations - Asleson et al. (2009).....	9
Figure 2-2: Three-dimensional view of the model configuration with 14 sand plugs and the range of K_{sat} values - Chavez et al. (2013).	10
Figure 2-3: BC Zn distribution in comparison to USEPA recommended thresholds, forebay outlined - Johnson et al. (2016).....	12
Figure 2-4: Pb profile in the BC - Li et al. (2008).	15
Figure 2-5: Filter media frost penetration for a range of LID systems Roseen et al. (2009).....	15
Figure 3-1: BC and the catchment area (From Google Maps).....	21
Figure 3-2: BC location - left and Layers & their dimensions in the BC - right (Sustainable Technologies Evaluation Program, 2015).....	22
Figure 3-3: Front view of the BC showing the inlet and the marked locations	22
Figure 3-4: Rubber layer in the BC – Top View - Left and Cross-sectional View – Right (Graham, 2016).	23
Figure 3-5: Map of focal points (shown in numbers) of the pictures shown in Figure 3-5 with their respective angular orientation (Graham, 2016).	23
Figure 3-6: BC construction pictures numbered (Young, 2018).	24
Figure 3-7: Map of points with their locations with respect to the inlet.....	26
Figure 3-8: A GP with its parts labelled (Eijkelpkamp Agrisearch Equipment, 2011).	28
Figure 3-9: GP in the BC (Left) and a 15 cm deep hole for the GP (Right).....	29
Figure 3-10 Eight wet soil samples in porcelain dishes to be dried in the oven (Left) and the oven (right)	33
Figure 3-11: Weighing the soil samples after drying (left), before breaking (middle) and after breaking (right).	34
Figure 3-12: Soil being poured into the fine sieve set (left) and soil retained in sieve no. 16 after shaking (right).	35
Figure 3-13: Sample holder & the Quantachrome Stereopycnometer (left) and the soil sample inside the sample holder (right).	36
Figure 3-14: Snow density sampling using graduated cylinder and trowel (left) and the graduated cylinder being weighed in a weighing machine (right).	39
Figure 3-15: "Do not push snow" sign in the BC.	40
Figure 3-16: Locations of the frost tubes with respect to the inlet (origin).	41
Figure 3-17: An installed frost tube during winter at point O near the inlet of the BC (left) and coloured water being poured into transparent tube to be installed inside the frost tube (right). ..	42
Figure 3-18: Frost tube design (Institute of Northern Engineering, 2011)	43
Figure 3-19: Surface water level logger being pulled out of the well (left) and ice surrounding the logger during winter (right).	44
Figure 3-20: Surface and ground water level loggers with their respective elevations with the perforated pipe as the bench mark	45
Figure 3-21: Ice inside the Geonor Weighing Gauge bucket with anti-freeze (left) and the vibrating wire transducer (right).	46
Figure 4-1: Moisture Content (top) and K_{sat} – Radcliffe Method (bottom).....	53
Figure 4-2: Organic Content (top) and Bulk Density (bottom)	55

Figure 4-3: Porosity (top) and Particle Density (bottom)	56
Figure 4-4: Soil textural triangle classification with BC soil proportions plotted (United States Department of Agriculture, 2018).....	57
Figure 4-5: Cu (top) and Cc (bottom)	58
Figure 4-6: D ₆₀ (top) and D ₃₀ (bottom)	59
Figure 4-7: Snow depth before snow melt spatial map (top) and picture (bottom) on December 22, 2016, before thaw.....	61
Figure 4-8: Snow depth after snow melt spatial map (top) and picture (bottom) on January 19, 2017, after thaw.	63
Figure 4-9: Semi-variogram - Moisture Content.	64
Figure 4-10: Semi-variogram – Cc	65
Figure 4-11: Semi-variogram - K _{sat}	65
Figure 4-12: Frost depths on Feb 5, 2018.	67
Figure 4-13: Frost depths on Jan 8, 2018.....	68
Figure 4-14: Frost depths on Jan 17, 2018.....	68
Figure 4-15: Frost depths on Feb 26, 2018	69
Figure 4-16: Timeline K _{sat} data – Radcliffe method – All locations	71
Figure 4-17: K _{sat} – Elrick and Reynolds method – All locations	72
Figure 4-18: Timeline- K _{sat} – Central Pathway, Radcliffe Method.	72
Figure 4-19: K _{sat} – Non-Central Pathway – Radcliffe Method.....	73
Figure 4-20: K _{sat} before outlier removal (top) and after outlier removal through Grubbs test (bottom).....	74
Figure 4-21: Rain on snow melt event reflected on the water level data (top) and temperature data (bottom).....	75
Figure 7-1: Histogram of Difference in K _{sat} with curve fitting.....	88
Figure 7-2: Soil particle distribution results in % – location M	92
Figure 7-3 Soil particle distribution results in % – location A1	93
Figure 7-4 Soil particle distribution results in % – location S	93
Figure 7-5 Soil particle distribution results in % – location W	94
Figure 7-6 Soil particle distribution results in % – location F.....	94
Figure 7-7 Soil particle distribution results in % – location Y	95
Figure 7-8 Soil particle distribution results in % – location O	95
Figure 7-9 Soil particle distribution results in % – location T.....	96
Figure 7-10 Soil particle distribution results in % – location V	96
Figure 7-11 Soil particle distribution results in % – location R	97
Figure 7-12 Soil particle distribution results in % – location C1	97
Figure 7-13 Soil particle distribution results in % – location N	98
Figure 7-14: Soil particle distribution results in % – location I.....	98
Figure 7-15: Soil particle distribution results in % – location E.....	99
Figure 7-16: Soil particle distribution results in % – location Q	99
Figure 7-17: Soil particle distribution results in % – location B	100
Figure 7-18: Soil particle distribution results in % – location A	100
Figure 7-19: Moisture Content Spatial map - All locations.....	101
Figure 7-20: K _{sat} - Radcliffe Method Spatial map - All locations.....	101
Figure 7-21: Organic Content spatial map – All locations	102
Figure 7-22: Bulk Density spatial map – All locations.....	102

Figure 7-23: Porosity Spatial map - All locations	103
Figure 7-24: Particle Density spatial map – All locations	103
Figure 7-25: Cu spatial map - All locations.....	104
Figure 7-26: Cc Spatial Map - All locations.....	104
Figure 7-27: D ₆₀ Spatial Map – All locations	105
Figure 7-28: D ₃₀ Spatial Map – All locations	105
Figure 7-29: Ksat Elrick and Reynolds method average	106
Figure 7-30: June 5 & 6, 2017 - Ksat Radcliffe method.....	106
Figure 7-31: July 10 & 11, 2017 - Ksat Radcliffe method	107
Figure 7-32: August 15 & 16, 2017 - Ksat Radcliffe method	107
Figure 7-33: September 19 & 20, 2017 - Ksat Radcliffe method.....	108
Figure 7-34: Oct 10 & 11, 2017 - Ksat Radcliffe method	108
Figure 7-35: Oct 24 & 25, 2017 - Ksat Radcliffe method	109
Figure 7-36: February 26 & 27, 2018 - Ksat Radcliffe method.....	109
Figure 7-37: May 16 & 17, 2018 - Ksat Radcliffe method.....	110
Figure 7-38: June 8, 2018 - Ksat Radcliffe method.....	110
Figure 7-39: January 11, 2017 – Snow Depth	111
Figure 7-40: February 1, 2017 – Snow Depth	111
Figure 7-41: February 8, 2017 – Snow Depth	112
Figure 7-42: February 13, 2017 – Snow Depth	112
Figure 7-43: February 15, 2017 – Snow Depth	113
Figure 7-44: January 8, 2018 – Snow Depth	113
Figure 7-45: January 17, 2018 – Snow Depth	114
Figure 7-46: February 5, 2018 – Snow Depth	114
Figure 7-47: Overall Average – Snow Depth	115

List of Appendices

1. Contour Map Generation Matlab Code
2. Semi-variogram Generation Matlab Code
3. Assumptions for Grubbs test
4. Assumptions for Wilcoxon signed-rank test
5. Figures and Tables

1 Introduction

1.1 Background

As cities become denser and their size increases, conventional methods of centralized drainage and stormwater management are no longer feasible. Impervious surfaces within urban centres reduce infiltration and increase both runoff frequency and peak flow rates while contributing to nonpoint-source pollution. Policy makers now promote emulating the natural water cycle as the best and most sustainable way to manage urban stormwater (Credit Valley Conservation, 2010). Low Impact Development (LID) is a stormwater management approach that emphasizes the preservation of the natural water cycle in urban environments to minimize flood risks and beautify cities. Some examples of the LID systems are permeable pavements, bioretention cells (BC), underground stormwater detention chambers, infiltration trenches and green roofs.

BCs are a LID technology developed to provide distributed stormwater quantity and quality control near to its source through infiltration, retention, and evapotranspiration. BCs have been constructed and tested across the globe in many different climatic, geographical and topographical conditions for over 20 years (Prince Georges County, 1999).

Typically, BCs are designed based on the inflow quality, volume and rate and desired outflow quality, volume and rate. Designing a BC requires the catchment area characteristics, IDF curves, downstream release rate and the infiltration rate of the soil under the proposed BC. With these data, the surface area, depth of gravel layer and the depth of BC media layer are calculated. These three boxes used to model any BC are shown in Figure 1-1. Any required chemical amendments for the BC base layer or the necessity of internal water storage layer are determined based on inflow and outflow water quality.

BCs are often treated by designers as homogeneous black boxes with emphasis on the system's inputs and outputs but with limited understanding of the internal chemical and hydraulic processes. They are sometimes designed with terrains that do not make full utilization of the BCs infiltration and treatment potential. This results in a loss of efficiency requiring more media and

area to infiltrate and treat less water. This study aims to unpack the black box approach by investigating the spatial and temporal heterogeneity of various parameters within a monitored BC.

Figure 1-1 Conceptual diagram with the front view of the BC

Designers generally assume that BCs can be analyzed and modelled as lumped one-dimensional systems. However, Asleson et. al. (2009) noted that saturated hydraulic conductivity (K_{sat}) rates in twelve mature (i.e. > 3 years old) BCs were spatially heterogeneous. Johnson and Hunt (2016) also observed spatial heterogeneity in the deposition of heavy metals in a BC in Charlotte, NC with excessive amounts of metals concentrating near the BC inlet. These findings suggest that pollutant accumulation and infiltration rates are spatially heterogeneous within a typical BC. Thus, two or even three-dimensional analysis may be required to accurately describe or simulate the flow and treatment of stormwater as it moves through a BC.

BCs experience temporal changes as the system ages. The accumulation of fines near the surface reduces a BC's capacity to infiltrate stormwater and, after several years of accumulation, this material will clog the system. For BCs located in cold climates, freeze-thaw action may also induce structural changes, within the soil. Denich et. al. (2013) has suggested that the expansion caused by freezing temperatures may increase a BC's soil pore size and thus increase its saturated hydraulic conductivity. Ding (2017 & 2018) also observed that consecutive freeze-thaw cycles

result in larger pores and a higher frequency of small and isolated pores through X-ray tomography imaging. According to Ding, this phenomenon helps to maintain the high infiltration rates required for the proper hydrological functioning of the BCs. Ding has also suggested that freeze-thaw cycle effects on soil structure, hydrology, and nutrient removal observed in the column studies should be evaluated at pilot and full field scales as well as over longer periods. Therefore, more work is needed to confirm these findings, determine cause of this phenomenon and to understand its implications on BC design and performance, particularly through field scale studies.

1.2 Research Objective

The objective of this thesis is to analyze the spatial and temporal heterogeneity of soil parameters in a BC. The BC monitored for this project is located at the Kortright Centre for Conservation, Vaughan, Ontario. A conceptual diagram with the front view of this BC is shown in Figure 1-1 . This BC has an approximate area of 30 m² and a catchment area of 265 m² consisting of an impervious parking lot constructed with recycled tire-derived rubber composite brick pavers (Eco-flex® Churchill). The BC layers include 7.5 cm of shredded hardwood mulch above 40 cm of filter media (60% sand and 40% silt/clay). A geotextile wrapped 15 cm deep 20 mm clear stone gravel water reservoir is below the filter media bed. A perforated drainage pipe (10 cm diameter) is placed on top of the geotextile and transitions into a solid pipe as it leaves the BC.

The objectives of this research are:

1. To measure K_{sat} spatially in the BC throughout a year, analyze how various locations in the BC behave in terms of K_{sat} before, during and after winter and asses how antecedent weather conditions affect estimated K_{sat} values.
2. To collect spatially referenced soil samples from the BC, conduct laboratory experiments to determine the organic content, bulk density, moisture content, particle density, porosity and particle size distribution and compare them using spatial maps to identify patterns and investigate spatial relations among them and K_{sat} .
3. To measure snow depth and density during snow events and after thaw during winter, observe spatial snow depth distribution and analyze its relationship with the other soil parameters and K_{sat} .

4. To measure surface and subsurface water levels and temperatures, analyze them along with precipitation data and identify water level patterns during rain, snow melt or rain on snow melt conditions.

1.3 Thesis Structure

The thesis consists of six chapters, they are structured as follows:

Chapter 1 - Introduction:

Introduces thesis topic, outlines objectives, and presents the thesis structure.

Chapter 2 - Literature Review:

Presents a literature review on the spatial-temporal heterogeneity within BCs.

Chapter 3 - Methodology:

Outlines the characteristics of the study site, the data collection procedure, the calculation procedure used to calculate the required parameters from the collected data and the data analysis methodology used to analyze and present the data in interpretable format.

Chapter 4 - Results:

Discusses the results of the K_{sat} , soil and snow measurements from a spatial perspective through the use of spatial maps. The temporal data are analyzed and discussed using graphs produced from excel and R.

Chapter 6 - Conclusions and Recommendations:

Presents conclusions of the thesis research and discusses future research directions and recommendations.

2 Literature Review

2.1 Introduction:

Stormwater management practices have been evolving in the past two decades as our understanding of watershed science and management improves. Proper management of stormwater is critical to maintaining the health of our streams, rivers, lakes, fisheries and terrestrial habitats. Precipitation that lands on the ground surface infiltrates into the ground, flows as surface runoff and evaporates or gets consumed by plants. In natural watersheds, only a small part of the rainfall produces runoff due to less impermeable surfaces and more vegetated areas. In built communities, more impermeable surfaces and reduced vegetative cover alter this balance generating significantly more runoff compared to natural watersheds. Additionally, Infiltration rates are reduced in urban watersheds reducing natural recharge to our streams, wetlands and groundwater resources (Stormwater Management Criteria, 2012).

When precipitation does not infiltrate into the ground or drain through the stormwater systems but flows on the ground, it can cause surface water flooding. When runoff water carries pollutants from various parts of the urban catchments including roads, parking lots, etc., it pollutes the downstream waterbodies (London Sustainable Drainage Action Plan, 2015). LID systems like BCs, permeable pavements, underground stormwater detention chambers, infiltration trenches and green roofs are developed to mimic the natural water cycle in urban watersheds by increasing infiltration and evapotranspiration. They also treat stormwater and reduce the concentration of many pollutants carried over by them before releasing them into the natural water bodies.

Extensive research has been completed in the past two decades on BCs. Data on BCs has been collected and analysed resulting in various findings. Based on present literature on BCs and for ease of understanding, the literature review has been divided into two sections i.e., Spatial Variability and Temporal Variability. Section 2.2 discusses the literature on spatial heterogeneity of various physical parameters within the BC and Section 2.3 discusses the literature on temporal changes in the BC with weather conditions and aging.

2.2 Spatial Variability

Much of the published research envisages BCs as black boxes with specific (but undefined) processes occurring inside the box temporally. From this perspective, BCs are treated as deterministic systems with spatially homogeneous processes throughout the BC media. This approach has been historically followed in field, laboratory and computer modelling studies of BCs. Published research that considers BCs as spatially heterogeneous systems is limited. Spatial heterogeneity of Physical and chemical parameters of BC media is often studied independently. There is no comprehensive review of the spatial heterogeneity of various physical or chemical parameters in the BC and there are no studies with comparison among the physical or chemical parameters to uncover the relationships among them.

For this review, forty-nine full text reviews were completed but only four papers explicitly studied spatial heterogeneity within a BC. Spatial information was identified in the remaining papers even if they did not have focused research objectives on spatial heterogeneity. Many papers recorded spatial data for only a part of their study. For example, the objective of Muthanna et al. (2007) is to evaluate the metal retention and fate of chloride in a BC during snowmelt. During their investigation, the authors observed that different plant species uptake metals in different rates and have different concentrations of metals in their biomass leading to spatial variability within the BC media. The authors also observed that the top mulch layer is responsible for most of the metal retention which shows spatial heterogeneity. Therefore, only 17 of the 49 reviewed papers which had either explicitly studied the spatial heterogeneity or happened to have spatially heterogeneous data for a part of their study, are discussed in this literature review.

Table 2-1 summarizes the papers considered and the spatial data each paper contains. The 'Intent of analyzing the spatial data' column shows whether the authors intentionally analyzed spatial heterogeneity, or they had different research questions and the data collected happened to be spatially heterogeneous within the BC. The papers are also classified based on whether the study is field-based, column-based, modelling-based or any combination of the three. It can be observed that out of 17 papers, 11 had a field or column experiment component and 7 had modelling components.

Different models have been used to study the BC. Table 2-2 summarizes all the models used to study BCs when spatial information is involved. The models used vary from well-known and established models to models that the authors have programmed themselves.

Table 2-1: Spatial information available in various papers, the intent and the type of study

Citation	Spatial Parameters available	Intended spatial analysis	Type of study
Asleson et al. (2009)	K_{sat}	Yes	Field study
Chavez et al. (2013)	Filter media K_{sat} heterogeneity	Yes	Modelling
Johnson et al. (2016)	Accumulation and spatial distribution of zinc, copper and phosphorous	Yes	Field study
Jones et al. (2013)	Spatial distribution of accumulated lead, copper, and zinc in the media.	Yes	Field study
LeFevre et al. (2009)	Pool depth	No	Field study
Li et al. (2008)	Depth vs Cu, Pb and Zn at various times.	No	Field & modelling
Li et al. (2008)	Depth vs TSS	No	Field and column
Lynn et al. (2018)	Depth vs several parameters	No	Modelling
Muthanna et al. (2007)	Depth vs Cu, Zn and Pb.	No	Field - controlled
Paus et al. (2013)	Depth vs organic matter, Cu & Zn	No	Field study
Quinn et al. (2014)	Depth vs pressure head and volumetric water	No	Modelling
Roseen et al. (2009)	Frost Depth	No	Field study
Stewart et al. (2017)	Pressure and soil moisture	No	Field & modelling
Thompson et al. (2008)	Depth vs K_{sat}	No	Column Studies
Yergeau et al. (2013)	Soil compaction depth	No	Field study
Zhang et al. (2017)	Ground water table depth	No	Modelling

Table 2-2: Models used in the considered papers

Citation	Model used	Dimensions
Chavez et al (2013)	COMSOL Multiphysics Earth Science Module (2008)	2D
Cheng et al (2015)	Excel model - new	0D
Lynn et al. (2018)	HYDRUS -1D, SWMM	1D
Muthanna et al. (2007)	RECHARGA	0D
Quinn et al. (2014)	KWE and RECHARGE	0D
Stewart et al. (2017)	HYDRUS-2D/3D	2D
Zhang et al. (2017)	VS2DI- 2-dimensional finite difference model	2D

Numerical modelling is generally carried out to reduce the expenses that would be incurred if actual field tests are conducted for the same purpose. Therefore, BCs are numerically modelled by researchers in various levels of accuracy for various purposes.

Table 2-2 shows the number of dimensions considered in each model. 0D denotes a compartment-based approach without any spatial considerations, 1D denotes a unidimensional spatial consideration having cells based on distance from inlet and 2D denotes a two-dimensional model with distinct cells. 3D models have not yet been used to simulate internal processes for a BCs. In this literature review, modelling results are considered alongside results from field tests since the literature on this topic are limited. Furthermore, 2D LID models have not been properly integrated with Storm Water Modelling softwares like SWMM. But there are simple 1D LID modules in SWMM to include LID in the stormwater quantity and quality simulations.

2.2.1 Surficial variability

BC soil parameters that have been spatially analyzed by researchers include saturated K_{sat} , organic content, TSS, Cu, Pb, Zn and P. These parameters are important to overall functionality of a BC in the following ways. K_{sat} governs the hydrologic performance of a BC. Organic content and TSS reflect on the sedimentation in the BC. Cu, Pb and Zn deposition show where most of the inflow stormwater pollutants get deposited. Heterogeneity in P concentration reflects the media P sorption capacity.

Asleson et al. (2009) has collected spatial K_{sat} data from 12 BCs in Minnesota. The Modified Philip-Dunne (MPD) infiltrometer is used to measure all the saturated hydraulic conductivity measurements. The MPD device was chosen because it measures the K_{sat} values in the surface layer where clogging typically occurs. Spatial maps with K_{sat} information are prepared for six of those BCs by the authors. From the maps provided by the authors it is evident that K_{sat} values are higher along the outer edge of the BC and lower along the central flow path.

Figure 2-1: Spatial K_{sat} map of University of Minnesota BC and the parallel excel data used to calculate the correlations - Asleson et al. (2009)

Chavez et al. (2013) assumed that contaminant attenuation would be maximized when there is uniform flow throughout the BC without concentration of flows in specific regions of the BC media. Therefore, the impact of K_{sat} heterogeneity on the flow processes is analyzed. Both field experiments and modelling were carried out. The ratio of the watershed area to the BC surface area considered is 50:1 which is higher than the recommended ratio of 10:1. One hundred and sixty-two samples were collected during the construction of two BCs in Stillwater, Oklahoma. The measured K_{sat} varied between 2.8×10^{-6} and 10^{-4} m/s with a mean of 3.5×10^{-5} m/s.

Through numerical simulations, they modelled a BC with a 0.10 m grid, filter media layer. The K_{sat} values in the model are randomly distributed based on the measured K_{sat} values. The modelled BC system also had sand plugs as shown in Figure 2-2. Using this model, the authors concluded that there is a slight increase in discharge with increased variance of the BC media K_{sat} . Therefore, the authors recommend proper mixing of the BC media before installation. The authors also concluded that reduction in BC media K_{sat} variance during construction had only a miniscule effect on the overall treatment performance of the BC.

Figure 2-2: Three-dimensional view of the model configuration with 14 sand plugs and the range of K_{sat} values - Chavez et al. (2013).

Chavez's modelling results applies to an ideal BC in laboratory conditions with randomly distributed K_{sat} throughout the BC media layer, but it may not represent an aged BC which does not have an ideal random distribution of K . It will have a variation in K_{sat} with respect to topographical, hydraulic, biological and physical parameters of the BC. Hence, more research should be done in real, aged BCs to verify the results of modellers like Chavez et al. (2013).

Jones et al. (2013) observed the flow path in a BC at the University of Maryland by simulating water flow using a portable pump. The sampling locations for this field study were chosen along the flow path. The authors observed that the organic content is lowest near the inlet in a BC and increases with distance away from inlet. The appearance of the organic matter is characterized by a dark colored soil. The authors state that the organic layer appears to have evolved from the original mulch layer augmented by decaying cell vegetation. They suspected that the low organic content near the inlet is due to particle deposition and mobilization of organic layer/mulch by scouring. Scouring occurs near the inlet due to swiftly moving water that enters the BC that dissolves and carries the organic matter away leaving the heavy soil particles to settle down. While particle deposition reduces the organic content by increasing the proportion of inorganic material, they also reduce organic content by inhibiting plant growth. Even though the BC studied Jones et al. (2013) has an unusual length to width ratio of 5:1, it suggests that near the

inlet, due to deposition of heavy metals, the organic content reduces and in other locations where depositions do not occur, organic content remains high.

Muthanna et al. (2007) analyzed plant uptake of heavy metals in BCs and found that the accumulation of metals including Cu in the roots and shoots of the plants varies greatly between species. Metal concentrations of BC plants was measured before and after snow melt. The authors were able to detect clear accumulation of metals in the above ground biomass. Therefore, the metal uptake should have taken place through the roots. This also indicates a good transport of metals from roots to the shoots in the plant. *Vinca minor* had the highest heavy metal absorption rate.

Li et al. (2008) conducted field and laboratory column experiments to investigate TSS deposition patterns in BC media. Inflow water was prepared in a drum with an agitator and a magnetic stirrer. Kaolin was added at a standard rate to simulate the runoff suspension. The authors note that TSS deposition is very high near the inlet and reduces with increased distance from the inlet. The authors suggest that a BC's ability to capture suspended solids is limited by clogging since surface layer clogging stops the entry of suspended solids into the BC media. The effect of breakthrough (preferential flow path) was not observed to be significant with respect to TSS reduction performance. Cake layer formation with suspended solid material is observed in most experiments. Likewise, the study also found that small clay sized deposition causes a much higher reduction of the infiltration rate than deposition of other larger sized particles due to better clogging efficiency.

Johnson et al. (2016) found that a substantial amount of Zn removal occurs within the forebay in BCs. While sampling, Zn concentrations within the forebay area were found to be 157 mg kg⁻¹ compared to a mean concentration of 26 mg kg⁻¹ across the remainder of the BC. In Figure 2-3, near the inlet (forebay region), the Zn concentration is higher than the thresholds suitable for plant growth and soil invertebrate survival. This is because as Zn laden water enters the BC, Zn is deposited near the inlet.

Johnson et al. (2016) and (2013) observed a significant decrease in Zn concentration with respect to distance from the inlet ($p < 0.0001$) and depth below the surface ($p < 0.0001$) as shown in Figure 2-3. This accumulation of Zn in the forebay is suspected to be due to the two removal mechanisms; filtration and sorption. Johnson et al. (2016) also note that higher concentrations of Cu can be found near the inlet, again suggesting the majority of Cu removal occurs near the inlet. Cu concentrations decreased significantly with distance away from the inlet ($p < 0.0001$) and

with depth ($p < 0.0001$). Like Cu, Zn concentrations also decrease with increasing ordinate distance from the inlet.

Figure 2-3: BC Zn distribution in comparison to USEPA recommended thresholds, forebay outlined - Johnson et al. (2016)

Johnson et al. (2016) recorded higher phosphorous concentrations close to the inlet and a strong correlation between Zn and P ($p < 0.0001$ and a Kendall's Tau correlation coefficient of 0.88). Elevated P concentrations in the forebay is observed and a strong correlation was also observed between P and humic matter. This could be because the organic matter and mulch as well as sediment and particulate-bound metal ions are accumulated in the forebay leading to higher humic matter concentrations closer to the inlet. The authors suspect that phosphorus removal is linked to the accumulation of sediment and organic matter in the forebay. Therefore, the authors suggest that maintenance regarding removal of phosphorous rich sediment can be restricted to the BC forebay.

2.2.2 Vertical variability

2.2.2.1 Soil parameters and pollutant removal

Lynn et al. (2018) attempted to improve the accuracy of the EPA SWMM model by developing a unified equation that can approximate flow rates under both saturated and unsaturated conditions with better accuracy. Calibrations for the equation required porosity and hydraulic conductivity slope. Hydraulic conductivity slope is a parameter that characterizes the exponential decrease in K_{sat} with decreasing moisture content. It can be calculated using the following formula:

$$K = K_{sat} \times e^{[-HCO \times (n - MC)]} \quad (1)$$

Where

- K_{sat} is the saturated hydraulic conductivity,
- HCO is the hydraulic conductivity slope,
- n is the porosity and
- MC is the moisture content.

Table 2-3 Calculated porosity (n) values and Hydraulic Conductivity Slope (HCO) values for sand media with different column depths - Lynn et al. (2018)

Depth (cm)	Porosity	Hydraulic Conductivity Slope
30.48	4.7	15
45.72	4.0	13
60.96	3.7	12
76.20	3.5	12
91.44	3.4	11
106.68	3.3	11
121.92	3.2	11

The calibration values for sand media (Table 2-3) show that as soil depth increases n and HCO decrease. The decrease in porosity is attributed to increasing pressure by the above lying soil and reduced biological activity. As evident from Table 2-3, K_{sat} decreases faster in the upper soil layers compared to the lower soil layers and is tied to increasing soil moisture content. It is suggested that this could be because the lower soil layers don't fluctuate as much as the upper soil

layers in terms of their moisture content. Moreover, the lower soil layers are closer to the saturated zone which could limit the K_{sat} change since they are consistently wet compared to the upper soil layers which dry and wet parallel to fluctuating weather conditions.

Similarly, Paus et al. (2013) observed organic content is highest in the first few centimeters of depth and reduces considerably as the depth increases for six BCs in Minneapolis, USA. The authors also noted that the rate of increase of metal sorption capacity with respect to increasing organic content is higher in older media compared to newer media signifying that the organic content in older media has a higher metal sorption capacity. It is suggested that this could be because the weathering and microbial transformation reactions are likely to increase the number of oxygenated functional groups over time that in turn increases the metal sorption capacity.

Li et al. (2008) conducted field and laboratory column experiments with BC media and found that most suspended solids do not penetrate through 5 – 20 cm of the BC media. Jones et al. (2013) and Paus et al. (2013) found that a majority of Zn is retained in the first 5 cm of the BC media. Johnson et al. (2016) also observed that Zn and Cu concentrations decreased with increasing depth from 5 cm to 20 cm ($p < 0.0001$). However, Li et al. (2008) conducted similar experiments for two consecutive years (2004 and 2005) and found mixed results. It is observed that in the set of measurements collected during 2005, the Cu concentrations decreased with increasing depth. However, Cu concentrations increased with increasing depth during 2004. Li et al. (2008) also confirmed the release of Cu from the media. The authors therefore, suggest that since Cu tends to associate with soil organic matter, it is more likely than Pb and Zn to be dissolved into highly-organic water and get released from the media. Paus et al. (2013) also identified that for Zn and Cd, the amount of sorption increased with increasing organic content in the media. However, no correlation was observed for Cu sorption with respect to organic content.

Like Cu and Zn, Pb also gets deposited in the top layer of the soil according to Li et al. (2008) as shown in Figure 2-4. Muthanna et al. (2007) found that the 5 cm thick top mulch layer retained approximately 74% of the Zn, 66% of the Cu and 13% of the Pb by mass that was retained overall in the BC system.

Figure 2-4: Pb profile in the BC - Li et al. (2008).

2.2.2.2 Frost Depth

Roseen et al. (2009) monitored filter media frost penetration throughout winter months on both weekly and rainfall-runoff event basis (before and after events). Frost penetration was monitored using a method developed by the U.S. Army Cold Regions Research (CRREL). Frost penetration was then compared to rainfall-runoff characteristics to evaluate hydraulic efficiency.

Figure 2-5: Filter media frost penetration for a range of LID systems Roseen et al. (2009)

The authors observed the frost penetration did not affect overall hydraulic performance. A predictable frost penetration cycle which includes frost penetration into a filter media before a rain

and snowmelt event, followed by thaw and frost penetration again during subsequent below-freezing days is observed as shown in Figure 2-5.

Roseen et al. (2009) also acknowledges that a system could thaw slowly and result in failure to properly attenuate a storm. However, this phenomenon was not observed during their study. The authors also mention that frost penetration does not necessarily equate to zero filter media permeability as frozen media may still have significant porosity and permeability.

2.3 Temporal Variability:

The physical processes in BCs vary temporally among seasons and as the system ages. Antecedent dry conditions have been observed to produce higher infiltration rates and freeze-thaw cycles during winter are observed cause structural changes in the BC media (Denich et al., 2013; Barrett et. al., 2013). With aging, clogging due to suspended solids deposition and excessive metal deposition near the inlet are observed (Johnson et. al., 2016; Jones et. al., 2013; Paus et. al., 2014; Li et al., 2008). These phenomena will be reviewed from the literature, in the following sections.

2.3.1 Effect of freeze thaw cycles on natural soil:

Konrad et al. (2000) conducted laboratory experiments to investigate changes in K_{sat} resulting from freeze thaw cycles for various soil types. The authors found clay content, plasticity, initial void ratio and water content to be significant parameters that affect the freeze-thaw behavior of soils. A higher increase in K_{sat} was observed during freeze thaw for samples with lower clay content (clay content varied from 25% to 50%) and lower void ratio. A systematic increase in K_{sat} was noticed for all samples that had gone through one freeze-thaw cycle, with a decrease in void ratio.

Xie et al. (2015) studied the freeze-thaw cycle form soil samples collected in the Qinghai-Tibet Plateau. Seven soil samples after different number of freeze-thaw cycles were tested in room temperature of 15°C. Volume deformation is also observed during the freezing phase due to frost heaving. Soil porosity is observed to be affected. Porosity increased significantly from 23% to 32% during the 15 freeze-thaw cycles. Porosity increase rates were the highest during the first six freeze-thaw cycles.

2.3.2 Effect of freeze thaw cycles on BC media:

Denich et al. (2013) has observed that the soil volumes increased during freezing of the BC mesocosms and did not return to their original level beneath the container's top edge after the soil matrix thawed. Two identical BC mesocosms were constructed based on standard bioretention design guidelines. A synthetic winter runoff was used to simulate winter runoff from roads in Guelph, Ontario. Ten applications were assumed per year based on the analysis of winter runoff and de-icer application data from roads in the City of Guelph. The mesocosms were constructed outdoors during summer to facilitate plant establishment. The initial infiltration capacity of each mesocosm is measured. During winter, the mesocosms were moved to an unheated, indoor space and the above specified synthetic urban runoff equivalent to 2 years loading was applied. The mesocosms were then moved outdoor and allowed to naturally thaw. The infiltration rates were measured again. An increase in infiltration rate is observed after the winter cycle. This increase could be attributed to the freeze-thaw action which increases the soil porosity and thus resulting in elevated infiltration rates.

Baratta (2013) tested the effects of freeze-thaw cycles on three different BC soil mixtures on laboratory conditions by measuring the infiltration rates after a series of freeze thaw cycles aiming to quantify the long-term changes in BC infiltration rates in cold climates. Unlike other studies, the author observed a steady decrease in infiltration rates after freeze thaw cycles as shown in Table 2-4. Infiltration rates were observed to decrease with increasing number of freeze thaw cycles.

Table 2-4: Infiltration rates with respect to number of freeze thaw cycles – Baratta (2013)

Freeze-Thaw Column Infiltration Rates (cm/hr)						
Column Number	Column Soil Composition	Number of Freeze-Thaw Cycles				
		0	5	10	15	20
1	80% Sand & 20% Compost	104.9	80.3	54.6	44.5	52.4
2	60% Sand & 40% Compost	131.8	92.7	70.1	57.9	48.7
3	1/3 Sand: 1/3 Compost: 1/3 Topsoil	57.0	27.6	11.2	6.8	4.4
3a	1/3 Sand: 1/3 Compost: 1/3 Topsoil + 1.5 grams Sediment	60.1	25.4	8.8	5.8	4.6
3b	1/3 Sand: 1/3 Compost: 1/3 Topsoil + 3.0 grams Loess	82.9	20.8	9.7	7.0	4.9

Ding et al. (2017) used 50 cm deep BC soil cores in the laboratory to simulate freeze – thaw action. Freeze thaw action is simulated by controlling the temperature of the air above the core and wrapping the soil core with an electric heater. To simulate freezing conditions, the chamber air is dropped to below 0°C and the soil freezes downwards from the surface. Approximately, 5 cm of snow is also added above the soil at the start of freezing simulation. To simulate thaw, the chamber air temperature is raised above 0°C. During experiments, the air temperature is changed gradually to avoid abrupt temperature drop. The electric heater wrapped around the soil core is used to maintain the Ontario groundwater temperature which is approximately 8 °C. It is observed that freeze thaw action caused a slight increase in the drainage rate.

Serpi (2015) assessed the variation of K_{sat} over time due to cyclic freezing of soil. Clayey silt soil with inorganic medium is used in the laboratory tests. The author observed permanent fractures whose size is linked to the number of freeze thaw cycles and soil compaction effort. A direct method, using a flexible wall permeameter and an indirect method, using oedometric test results to determine the K_{sat} of the soil. A positive correlation is observed between the number of freezing-thawing cycles and the K_{sat} value. As expected, a negative correlation is observed between the effective stress and K_{sat} value. The author also suspects that the size effects of the laboratory samples and the axial stress-free condition maintained during the freezing process could have contributed positively to the soil fracture formation.

Furthermore, most research on freeze-thaw action in BC media has been completed in controlled laboratory scale mesocosms. Therefore, when all these studies with conflicting results are considered, it seems to be important that the K_{sat} values of BC media are analyzed through field studies to find out the effect of freeze-thaw cycles on BC media.

2.3.3 Effect of aging on BC:

Although BCs have a predicted design life of 25 years, most field studies have been completed on BCs that are less than 2 years old. Aging can affect the performance of the BC both in terms of water quantity performance and water quality performance. Therefore, it becomes important to understand the literature on the long-term performance of BC.

2.3.3.1 Water Quantity – Stormwater control capacity

Jenkins et. al. (2010) studied a BC for a period of nine years. The soil textural profile of the BC is characterized prior to allowing the storm water to drain through (2001) and after aging (2006 and 2009). For the storms between 2003 and 2008, the mean and median inflow TSS values were 171 and 74 mg/L and the mean and median outflow TSS values were 17 and 4 mg/L. Accumulation of fines smaller than 0.1 mm was observed in the BC. Infiltration rate in BCs were observed to drop immediately after installation and then level off at a sustainable level. The authors observed no significant difference between infiltration rates measured on 2006 and 2009. Therefore, they recommend no maintenance in the short term. However, they noted that the variability of the infiltration rates in 2006 is lower than the variability observed in 2009 indicating that structural changes were occurring in the BC media.

Barrett et. al. (2013) conducted column experiments with BC media outdoors in Austin, Texas. An initial rapid decrease in K_{sat} in all column experiments is observed which then stabilized. A slight increase in K_{sat} is also observed during summer after prior stabilization which could be because of lower soil moisture content during summer. Paus et. al. (2014) also observed a slow increase in K_{sat} measured at the soil surface as the BC ages in a field study.

Coustumer et. al. (2008) conducted K_{sat} measurements in 125 BC columns at Australia over a 72-week period. Initial K_{sat} measurements were within Australian Guidelines (50 – 200 mm/h) but after 1.5 years of operation, the K_{sat} values dropped 27% of the initial value (median of 51 mm/h). Therefore, it is clear that K_{sat} value is in its peak just after the construction of the BC, reduces quickly till it reaches a steady state and then increases marginally with aging. Variability in K_{sat} values within the BC also increases with age.

2.3.3.2 Water Quality – Pollutant removal capacity

Deposition of metals (Zn, Cu, Fe and Pb) has been observed in aging BCs by Johnson et. al. (2016), Jones et. al. (2013), Paus et. al. (2014) and Li et al (2008). However, no reduction in metal retention capacity has been observed. Most of the metal deposition took place near the inlet and the remaining parts of the aged BCs have significantly less metal concentrations compared to the inlet.

2.4 Conclusions and Research gaps:

Through the systemic literature review on the spatial heterogeneity of various parameters inside the BC and the literature review on the effect of freeze thaw action in a BC, the following inferences can be made.

1. K_{sat} varies spatially within a BC. K_{sat} increases with increasing of the location to the central flow path. K_{sat} is lower near the inlet (Asleson et al., 2009).
2. TSS, Zn, Cu, Pb and P have high values near the inlet suggesting heavy sediment, metal and pollutant deposition in the forebay area/ area near the inlet. They also have high values in the top soil layer i.e., near the surface (Johnson et al., 2016; Jones et al., 2013; Li et al., 2008; Muthanna et al., 2007; Paus et al., 2013; Li et al., 2008).
3. Organic content is low near the inlet as expected due to the high sediment and metal deposition. Organic content also decreases with increasing depth under the soil surface due to lesser biological activity in the lower soil layers (Paus et al., 2013).
4. There is seasonal variation in the K_{sat} values of the BC media, particularly in cold climate regions. Researchers have suggested that freeze thaw action could increase K_{sat} values by causing cracks in soil due to freezing of soil moisture based on observations (Denich et al., 2013; Ding et al., 2017; Serpi., 2015; Konrad et al., 2000; Xie et al., 2015). However, opposing observations (reduction in infiltration rate due to freeze thaw action) have also been made in laboratory experiments by some researchers (Baratta., 2013).
5. K_{sat} of the BC media is high right after installation and stabilizes to a steady state value. Even though the average K_{sat} of the BC media does not vary significantly as the system ages, the variability among the K_{sat} measurements within the BC increases as the system ages indicating the formation of preferential flow paths and soil cracks (Jenkins et. al., 2010; Barrett et. al., 2013; Coustumer et. al., 2008). There was no observation of reduction in metal retention functionality of the BC. Leaching of nutrients out of the BC is also observed particularly in BCs with compost amendments (Logsdon, 2017; Hurley, 2017).

On this account, we can reasonably conclude that there is significant spatial and temporal heterogeneity within BCs and important internal processes may be overlooked when BCs are treated as black boxes by designers.

3 Methodology

3.1 Site Description

A five-year-old Bioretention Cell (BC) located at the Kortright Centre for Conservation in Vaughan, Ontario, Canada (Figure 3-2 - left) is used as an investigation area for this study. This BC has an approximate area of 30 m² and a catchment area of 265 m² (Figure 3-1) comprised of an impervious parking lot constructed with recycled tire-derived rubber composite brick pavers (Eco-flex® Churchill).

Legend

- Bioretention Cell
- Catchment Area

Figure 3-1: BC and the catchment area (From Google Maps)

Figure 3-2: BC location - left and Layers & their dimensions in the BC - right (Sustainable Technologies Evaluation Program, 2015).

The BC layers include 7.5 cm of shredded hardwood mulch, 40 cm of filter media (60% sand and 40% silt/clay), 15 cm of 20 mm clear stone gravel and a geotextile (Figure 3-2). A perforated drainage pipe (10 cm diameter) is placed on top of the geotextile and transitions into a solid pipe as it leaves the BC. The inlet into the BC consists of a 2 m² concrete pad overlaid by a geotextile and river stone. Concrete collars were installed in the BC sub-base gravel perpendicular to the flow path to retain water and prevent uncontrolled release of water through the outlet. The BC drains to a monitoring hut where pipes are elevated to a level just below its base (Sustainable Technologies Evaluation Program, 2015).

Figure 3-3: Front view of the BC showing the inlet and the marked locations

Figure 3-4: Rubber layer in the BC – Top View - Left and Cross-sectional View – Right (Graham, 2016).

Figure 3-5: Map of focal points (shown in numbers) of the pictures shown in Figure 3-5 with their respective angular orientation (Graham, 2016).

Figure 3-3 shows the front view of the BC with the inlet. The BC varies spatially in surface slope, plant density, shading, proximity to the inlet and proximity to the saturated zone. The lower half of the BC side slopes are lined with rubber sheets to prevent lateral seepage of water to the adjacent parking lot gravel sub base. The top view and cross-sectional view of the rubber layer are shown in Figure 3-4.

Figure 3-6: BC construction pictures numbered (Young, 2018).

The BC has been operational since 2013. Water quantity and quality performance of the BC is measured during the first two years of its operation by Toronto and Region Conservation Authority (TRCA) staff (Sustainable Technologies Evaluation Program, 2015). Basic maintenance including pruning, replacing of the mulch layer and planting of dead plants is conducted annually.

The pictures taken during BC construction are shown in Figure 3-6. A map of the focal points of the pictures are shown along with the angular orientation to facilitate easy visualization in Figure 3-5. Pictures numbered 1, 2 and 7 in Figure 3-6 shows the rubber sheets installed to prevent lateral seepage. Picture numbered 8 in Figure 3-6 shows the BC media being poured into the site and picture numbered 4 in Figure 3-6 shows the BC media after it has been poured. Picture numbered 3 in Figure 3-6 shows the part of the BC central pathway without the rubber sheet. Pictures numbered 5 and 6 in Figure 3-6 shows the gravel sub-base layer before the geotextile is folded to separate the BC media from the gravel sub-base layer. Pictures numbered 1, 2 and 7 in Figure 3-6 shows the geotextile after it has been folded over the gravel sub-base layer.

3.2 Spatial Location Selection

Thirty points were selected throughout the BC as shown in Figure 3-7. Locations were selected to ensure that spatially diverse physical conditions (i.e. surface slope, plant density, whether it is in the water flow path or in the hills, and the distance from the inlet) were included. Points were marked with drive way markers and labelled (A – Z, A1- D1). The location of each point with respect to the origin (i.e. Inlet) was measured with tapes manually. The soil parameters were measured in seventeen points only as summarized in Table 3-1. Snow depths were measured in all the thirty points. Table 3-1 describes each monitoring point and measurements that were collected.

Figure 3-7: Map of points with their locations with respect to the inlet

Table 3-1: Points considered for snow depth and soil parameters measurement

Spatial parameter	Points considered for snow depth	Points considered for soil parameters
Central pathway	M,J,G,D,O,X,Y,S,I	M,O,Y,S,I
On slope	W,V,R,Q,A1,E,C,K	W,V,R,Q,A1,E
On hills	N,T,C1,B1,C1,L,D1,A,C	N,C1,A,T
Near inlet	D,O,G,Q	O,Q
High plant density	L,R,D1,F,U,C,N	R,F,N
Near the outline of the BC	H,F,Z,B,C1,A,D1	F,B,C1,A

3.3 Saturated Hydraulic Conductivity (K_{sat})

3.3.1 Guelph Permeameter (GP)

Infiltration rates were measured on nine different dates with a GP throughout 2017/2018 (Table 3-2). When possible, measurements were collected in two consecutive days with similar weather conditions. Figure 3-8 shows a GP with its parts labelled. Table 3-2 lists the various dates at which the GP measurements were taken.

Table 3-2 Infiltration rate measurement dates, antecedent conditions and conditions during data collection

No	Dates	Antecedent conditions	Conditions during data collection
1	6/5/2017 and 6/6/2017	Wet	Light rain
2	7/10/2017 and 7/11/2017	Wet	Sprinkles
3	8/15/2017 and 8/16/2017	Wet	Dry
4	9/19/2017 and 9/20/2017 *9/29/2017	Dry	Dry *Rain
5	10/10/2017 and 10/11/2017	Wet	Light rain
6	10/24/2017 and 10/25/2017	Wet	Light rain
7	2/26/2018 and 2/27/2018	Freezing	Dry
8	5/16/2018 and 5/17/2018	Wet	Dry
9	6/8/2018	Dry	Dry
* denotes that some measurements are found to be erroneous and are measured again later			

All measurements were completed at a depth of 15 cm below the surface. For each location, two measurements were completed, one with a 5 cm hydraulic head and another with a 10 cm hydraulic head. Infiltration rates from both measurements are used to arrive at the K_{sat} as per Soilmoisture Corporation recommendations (Eijkelkamp Agrisearch Equipment, 2011).

Figure 3-8: A GP with its parts labelled (Eijkelkamp Agrisearch Equipment, 2011).

During the first four data sets infiltration measurements were repeated in the the same bore hole. This practice was discontinued after 9/19/2017 because it was suspected that preferential flow paths were forming below the GP. This phenomenon is suspected to have caused excessive infiltration rates observed at locations N and F on 9/19/2017 and 9/20/2017. Consequently, measurements were repeated at these locations again on 9/29/2017. The antecedent conditions were the same in all the three dates mentioned. After this observation of preferential flow paths, the holes made already were closed and a new hole was augured for every measurement during the remaining data collection period. Figure 3-9 shows the GP in the BC at location N on the left and a 15 cm deep hole made in the BC on the right.

Figure 3-9: GP in the BC (Left) and a 15 cm deep hole for the GP (Right).

3.3.2 K_{sat} calculation

Infiltration rates can be used to estimate a soil's K_{sat} . Methods generally assume a bore hole of specific diameter and depth, soil type and require a with an observed steady state infiltration rate t . Two methods i.e., Elrick & Reynolds (1992) and Radcliffe & West (2015) are used to calculate K_{sat} from the observed steady state infiltration rate.

3.3.3 Radcliffe et al. (2015) Method

The equations from *SOILMOISTURE Ksat Calculator* was used to estimate the K_{sat} . In all calculations, the BC media was considered to be Sandy Clay Loam. *SOILMOISTURE Ksat Calculator* uses the Radcliffe et al. (2015) method to calculate the K_{sat} . This method was formulated to eliminate the necessity of two infiltration measurements with different heads to calculate K_{sat} and to improve the accuracy of the resultant K_{sat} by including the effect of gravity and capillarity on water flow (Radcliffe et al., 2015). The equations used are as shown below and they are only for unstructured medium sands, fine sands and loams.

$$Q_1 = \bar{I}_1 \times 35.22 \quad [5 \text{ cm depth}] \quad (2)$$

$$Q_2 = \bar{I}_2 \times 35.22 \quad [10 \text{ cm depth}] \quad (3)$$

$$G_1 = \frac{1}{2\pi} \times \left[0.083 + 0.514 \times \frac{H_1}{R} - 0.053 \times \left[\frac{H_1}{R} \right]^2 + 0.002 \times \left[\frac{H_1}{R} \right]^3 \right] \quad (4)$$

$$K_{sat} \text{ for } H_1 = \frac{Q_1}{\pi a^2 \left[1 + \frac{H_1(\lambda + H_1)}{G_1 \times \pi R^2} \right]} \quad (5)$$

$$G_2 = \frac{1}{2\pi} \times \left[0.083 + 0.514 \times \frac{H_2}{R} - 0.053 \times \left[\frac{H_2}{R} \right]^2 + 0.002 \times \left[\frac{H_2}{R} \right]^3 \right] \quad (6)$$

$$K_{sat} \text{ for } H_2 = \frac{Q_2}{\pi a^2 \left[1 + \frac{H_2(\lambda + H_2)}{G_2 \times \pi R^2} \right]} \quad (7)$$

$$\text{Overall } K_{sat} = \frac{K_{sat} \text{ for } H_1 + K_{sat} \text{ for } H_2}{2} \quad (8)$$

Where,

- G_1 and G_2 are geometric factors that depend on the ratio of H/R .
- H_1 and H_2 are 5 cm and 10 cm respectively. These are the two water depths at which the experiment is replicated at every location.
- I_1 and I_2 are the steady state infiltration rates in cm/min for water depths H_1 and H_2 respectively.
- Q_1 and Q_2 are the steady state infiltration rates in cm^3/min for water depths H_1 and H_2 respectively.
- R is the radius of the borehole which is on average 3 cm.

$$\lambda = 8.3 \text{ (for unstructured medium sands, fine sands and loams)}$$

Radcliffe method is able to calculate K_{sat} with one steady-state infiltration rate. However, since infiltration rates were measured using both depths for Elrick and Reynolds method, the both K_{sat} values are averaged in the Radcliffe method calculations for better accuracy.

3.3.4 Elrick and Reynolds (1992) Method

This method improved upon several older methods of K_{sat} calculation by partitioning the flow into its field-saturated and unsaturated components (Elrick and Reynolds, 1992). The two head combined reservoir method used to determine the K_{sat} .

$$G_3 = \frac{H_2 C_1}{\pi (2H_1 H_2 (H_2 - H_1) + R^2 (H_1 C_2 - H_2 C_1))} \quad (9)$$

$$G_4 = \frac{H_1 C_2}{\pi (2H_1 H_2 (H_2 - H_1) + R^2 (H_1 C_2 - H_2 C_1))} \quad (10)$$

$$C_1 = \left[\frac{\frac{H_1}{R}}{2.074 + \frac{0.093 \times H_1}{R}} \right]^{0.754} \quad (11)$$

$$C_2 = \left[\frac{\frac{H_2}{R}}{2.074 + \frac{0.093 \times H_1}{R}} \right]^{0.754} \quad (12)$$

$$K_{sat} = G_4 Q_2 - G_3 Q_1 \quad (13)$$

Where,

- C_1 and C_2 are shape factors.
- G_3 and G_4 are geometric factors. All other parameters are the same as outlined for Equation 2 – 8.

If the calculated K_{sat} is negative, it is because, I_1 with 5 cm head is higher than I_2 with 10 cm water depth. If that is the case, a sub-optimal solution is to find K_{sat} separately without combining 5 cm and 10 cm depth measurements and averaging them to get the overall K_{sat} . In this case the following formulae applies.

$$K_{sat} \text{ for } H_1 = \frac{C_1 \times Q_1}{2\pi H_1^2 + \pi a^2 C_1 + 2\pi \left(\frac{H_1}{a^*} \right)} \quad (14)$$

$$K_{sat} \text{ for } H_2 = \frac{C_2 \times Q_2}{2\pi H_2^2 + \pi a^2 C_2 + 2\pi \left(\frac{H_2}{a^*} \right)} \quad (15)$$

Where,

- a^* is the macroscopic capillary length parameter, 0.12 for unsaturated medium and fine sands.

3.4 Soil Analysis

Two soil samples were collected from the 17 points on Oct 25th, 2017. First, a bulk density measuring kit was used to collect undisturbed samples at 15 to 20 cm depth below the BC surface. Rubber caps were used to close both sides of the cylinder to ensure that the soil inside is not disturbed and to make it a closed system. Following, disturbed samples were collected manually. The wooden mulch at the top was removed manually so that the soil was visible. The top 10 to 15 cm of soil was removed using a spade. The soil below was collected in zipper bags using the spade. Samples were analyzed at University of Toronto labs...

3.4.1 Bulk density, moisture content and organic content

Standard ASTM tests were completed to determine bulk density, moisture content and organic content of soil samples (ASTM C29/C29M – 17a, 2017 and ASTM D2974 – 14, 2014).

Samples were weighed, and the bulk densities were calculated using the formulae below.

$$BD = \frac{W_s}{V_s} \times \frac{1000000}{1000} \quad (16)$$

Where,

- BD = Bulk density (Kg/m^3)
- W_s = Weight of the soil (g)
- V_s = Volume of the soil (cm^3)

$$W_s = W_t - W_c - W_r \quad (17)$$

Where,

- W_t = Total weight of the cylinder with the soil (g)
- W_c = Weight of the cylinder (g)
- W_r = Weight of the rubber caps on both ends of the cylinder (g).

Figure 3-10 Eight wet soil samples in porcelain dishes to be dried in the oven (Left) and the oven (right)

After weighing for bulk density, the soil samples were transferred to individual washed porcelain dishes. The soil samples were then dried at 115 °C in an oven for a minimum of 24 hours (Figure 3-11). The dried samples are taken and weighed again. The percent moisture content is calculated using the following formulae.

$$MC = \frac{W_m}{W_{w+p}} \times 100 \% \quad (18)$$

$$W_m = W_{w+p} - W_{d+p} \quad (19)$$

Where,

- MC = Moisture content (%)
- W_m = Weight of moisture in the soil sample (g)
- W_{w+p} = Weight of wet soil sample including the porcelain dish (g)
- W_{d+p} = Weight of soil sample after being oven dried including the porcelain dish (g)

After being oven dried, the sample is then maintained at 450 °C in a Muffle furnace overnight to burn away the organic matter. The sample is then weighed again to find out the

inorganic weight of the soil. The percent organic matter of the soil is calculated using the following formulae.

$$OC = \frac{W_o}{W_{d+p}} \times 100 \% \quad (20)$$

$$W_o = W_{d+p} - W_{i+p} \quad (20)$$

Where,

- OC = Organic content (%)
- W_o = Weight of the organic matter in the soil (g)
- W_{d+p} = Weight of the soil with organic matter and porcelain dish (g) = Weight of soil sample after being oven dried including the porcelain dish (g)
- W_{i+p} = Weight of inorganic soil and porcelain dish (g)

3.4.2 Soil Particle Distribution

Standard ASTM tests were completed to determine the soil particle distribution (ASTM D4513 – 11, 2017) with the collected disturbed samples. Soil was sieved with No. 1-1/2, 3/4, 3/8, 4, 10, 16, 30, 50, 100 and 200 sieves.

Standard ASTM procedures are followed. However, the soil had many lumps. Therefore, after the sample is dried, it is broken down using mortar and pestle iron so that no visible lumps of particles are observed as shown in Figure 3-11.

Figure 3-11: Weighing the soil samples after drying (left), before breaking (middle) and after breaking (right).

Moreover, All the pre-cleaned individual sieves are taken and coated with antistatic spray. Antistatic coating is performed before every experiment run to ensure that there are no soil particles smaller than any mesh size sticking in the mesh due to magnetic forces (sieve shaker has an electric motor and that might cause magnetic induction). Soil being poured into the fine sieve set and soil retained in sieve no. 16 after shaking are shown in Figure 3-12 left and right respectively.

Figure 3-12: Soil being poured into the fine sieve set (left) and soil retained in sieve no. 16 after shaking (right).

Tables are produced as shown in Table 7-6, using the data collected from the sieve analysis experiments. The following formula is used to calculate the percentage of overall weight retained in each individual sieve.

$$\% \text{ Weight Retained} = \frac{\text{Weight of soil in a particular sieve}}{\text{Sum of weights of soils in all sieves}} \quad (22)$$

The weight of soil that is above a particular sieve size can be calculated by arranging the weights in the descending order of mesh sizes and cumulatively adding the weight retained at each mesh with all the weights retained in all the other bigger meshes. This cumulative % weight retained in each sieve is then plotted in a log normal graph with the mesh sizes along the x axis (log) and the % cumulative weight retained on the y axis (cartesian) as shown from Figure 7-2 to Figure 7-18. D_{60} , the grain diameter of 60% passing at a specific location is calculated by measuring the corresponding mesh size for 60% cumulative soil weight as shown from Figure 7-2

to Figure 7-18. Similarly, D_{30} and D_{10} are also calculated. The coefficient of uniformity, C_u is a natural shape parameter and is calculated using the following equation.

$$C_u = \frac{D_{60}}{D_{10}} \quad (23)$$

The coefficient of curvature, C_c is also a shape parameter and is calculated using the following equation.

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} \quad (24)$$

3.4.3 Particle Density and Porosity

Particle densities were measured using the Quantachrome Stereopycnometer. Soil samples were dried by heating in an oven at 115 °C overnight. Following 10g of soil was broken down using a mortar and pestle iron to facilitate access to all soil pores by nitrogen gas within the Quantachrome Stereopycnometer.

and the prepared samples were placed inside the Quantachrome Stereopycnometer as shown in Figure 3-13 and nitrogen gas is allowed to accumulate in the soil container and the pressure is measured. Using the volume of gas required to attain the pressure, the volume of soil already present in the container is determined.

Figure 3-13: Sample holder & the Quantachrome Stereopycnometer (left) and the soil sample inside the sample holder (right).

The weight of the sample soil is measured before measuring the volume. The volume of particles in the selected sample is calculated using the formula provided below.

$$V_p = V_c + \frac{V_a}{\left(1 - \frac{P_2}{P_3}\right)} \quad (25)$$

Where,

- V_p = Volume of soil (cc).
- V_c = Volume of sample cell holder (cc).
- V_a = Added volume of nitrogen gas.
- P_2 = Pressure reading after pressurizing cell.
- P_3 = Pressure reading after adding V_a .

It should be noted that V_c and V_a are calibration values and they might change as the equipment ages. Hence, they are measured again during June 2018 by the lab manager.

The particle density of the soil is calculated using the following formula.

$$PD = \frac{W_{sp}}{V_p} \quad (26)$$

Where,

- W_{sp} = Weight of soil sample taken for particle density measurement.
- PD = Particle density of the soil.

The porosity of the soil is calculated using the following formula.

$$Pt = 1 - \frac{BD}{PD} \quad (27)$$

Where,

- Pt = Porosity of the soil.

3.5 Winter Measurements

3.5.1 Snow Depth and Density

Snow depth and density was measured in all thirty points on nine different dates manually with a ruler. Table 3-3 summarizes the measurement dates and antecedent conditions. Snow density measurements were completed with a 500 ml glass jar. is the jar was inverted and thrust through the undisturbed snow layer in the ground. A trowel was then used to remove the snow

adjacent to the measuring jar till the lower end of the jar can be seen. Then the trowel is pierced into the snow right beneath the jar such as it closes the mouth of the jar. The jar is then removed and the volume of snow in the jar is arrived at using the graduations in the measuring jar.

Table 3-3: Snow depth and density data collection dates and antecedent conditions

No	Date	Antecedent Conditions
1	12/22/2016	Snow
2	1/11/2017	Rain on snow melt
3	1/19/2017	Rain on snow melt
4	2/1/2017	Snow
5	2/8/2017	Rain on snow melt
6	2/13/2017	Snow
7	2/15/2017	Snow
8	1/8/2018	Snow
9	1/17/2018	Snow
10	2/5/2018	Snow
11	2/26/2018	Rain on snow melt

In most of the measurements, the snow did not fill the jar completely. So, it is not possible to measure the snow volume since the jar does not have graduations at the top and the graduations start from the bottom. The jar is twirled rapidly so that the snow settles near the bottom of the cylinder before measuring the snow volume. The weight of the jar is also measured before and after collecting snow. Snow density is then calculated using the following formula.

$$SD = \frac{WJ_a - WJ_b}{V_s} \quad (28)$$

Where,

- SD = Snow density,
- WJ_a = Weight of jar after collecting snow
- WJ_b = Weight of jar before collecting snow
- V_s = Volume of snow.

Before the availability of a weighing scale, the snow is allowed to melt near a space heater and the snow water equivalent is measured. In this case, the snow density is calculated using the following formula.

$$SD = \frac{V_w}{V_s} \times 1000 \text{ kg/m}^3 \quad (29)$$

Where,

- V_w = Snow water equivalent i.e., volume of melted water.

Figure 3-14 shows the sampling method explained above on the left and the cylinder being weighed in the weighing machine on the right.

Figure 3-14: Snow density sampling using graduated cylinder and trowel (left) and the graduated cylinder being weighed in a weighing machine (right).

It should be noted that while measuring snow depths near the inlet, due to river stone riprap, snow was accumulated over them but there was space underneath that had air. Therefore, only the snow depth above the stones were considered for data analysis. Moreover, since this BC is beside a parking lot, during winter snow is pushed by the shovelling equipment into the BC. Signage is placed during winter 2017 to reduce artificial accumulation of snow in the BC as shown in Figure 3-15.

Figure 3-15: "Do not push snow" sign in the BC.

3.5.2 Frost depth

Frost depth was measured using seven frost tubes during winter 2018. Six of them were installed inside the BC. The remaining one is installed outside as a reference point. The locations were selected based on terrain but four of them were installed in the central water flow pathway since that is the most hydrologically active area.

Table 3-4: Frost tubes location and lengths

Point	Locations inside the BC	Length of frost tube (cm)
1	Near T (Tree)– In the hill	200
2	S – In the central pathway	150
3	Between I & Y – In the central pathway	150
4	Near O – In the central pathway	150
5	Near M – In the central pathway	150
6	Between W & V – On slope	200
7	External location	300

Figure 3-16: Locations of the frost tubes with respect to the inlet (origin).

The frost tube depths beneath the ground surface were selected based on the anticipated maximum frost depth and the depth of the gravel layer in the BC. Frost tube locations and the length of the frost tube are given in Table 3-4. Figure 3-16 has a map of the frost tube locations with respect to the inlet of the BC.

3.5.3 Frost tube preparation

Frost tubes were prepared based on the model provided in (Institute of Northern Engineering, 2011). However, due to non-availability of the pipe sizes recommended in the document, different pipe sizes were used to device the frost tube. A half inch radiant heat tube is cut in the appropriate length. The length of the frost tube in each location is given in Table 3-4. Tubes were extended 1 m above the ground for easy identification during snow accumulation. Half inch PVC pipe was cut longitudinally in half to 'sandwich' around the radiant heat tube and taped together using a Gorilla Duct Tape. The bottom of the frost tube was sealed with epoxy putty. A 7/16 inch outside diameter clear tubing was cut to the same length as the PVC and radiant tubing and filled with a mixture of water and food colouring. Tube ends were heat sealed. Graduations were added to clear tubing to facilitate quick measurement. The clear tubing is then inserted into

the PVC-radiant heat tube. Figure 3-18 shows the frost tube sketch and Figure 3-17 (right) shows the coloured water being poured into the clear tubing in the frost tube during preparation phase.

Figure 3-17: An installed frost tube during winter at point O near the inlet of the BC (left) and coloured water being poured into transparent tube to be installed inside the frost tube (right).

On site soil was augured till the appropriate depth and the frost tubes were installed. The remaining gap in the drilled hole was then filled with the excavated soil. A gas auger was used for holes deeper than 50 cm. A cap is installed in the top of the frost tube to prevent precipitation from entering the tubing. Figure 3-17 (left) shows an installed frost tube during winter in the BC.

Table 3-5: Frost depth measurements dates and antecedent conditions

No	Date	Antecedent Conditions
1	1/8/2018	Snow
2	1/17/2018	Snow
3	2/5/2018	Snow
4	2/26/2018	Rain on snow melt

Figure 3-18: Frost tube design (Institute of Northern Engineering, 2011)

The installation locations were chosen to cover the central pathway clearly and to have one representative measurement in the hills and one in the slope inside the bioretention. One reference measurement is also taken outside the bioretention in natural soil. During 2018 winter, four frost depth measurements were taken. The date and the antecedent weather condition associated with the measurements are given in Table 3-5.

3.5.4 Surface and subsurface water levels and temperatures

Surface water ponding and subsurface water levels and temperatures were measured every two minutes by Diver loggers. To compensate for atmospheric pressure variation, a barometric Diver logger is also installed on site. The barometric logger also measures the on-site air temperature.

During extremely low temperatures, the surface water level logger froze and produced erroneous high temperature and pressure values as shown in Figure 3-19 (right). However, since this phenomenon is irregular, it was not possible to find out a threshold temperature below which this happens. Moreover, no ice formation was observed in the subsurface water level logger. Figure 3-19 (left) shows the surface water level logger being pulled out of the surface water well during winter. The surface water logger failed to start on 1/15/2018 and was replaced with a HOBO logger.

Compensation for barometric pressure variation is done by subtracting the pressure measured in the surface water logger and the ground water logger at every time step by the atmospheric pressure at those time steps. This atmospheric pressure correction is done using the diver office software provided by Van Essen Instruments for the diver loggers. For the period during which the surface water level is measured using the HOBO logger, this compensation is done manually in Excel. For relating the water depths i.e., the surface ponding and the saturated zone with the K_{sat} measurements, elevation differences were measured manually (Figure 3-20) and used for the respective calculations.

Figure 3-19: Surface water level logger being pulled out of the well (left) and ice surrounding the logger during winter (right).

Figure 3-20: Surface and ground water level loggers with their respective elevations with the perforated pipe as the bench mark

3.5.5 Weather data

Precipitation during non-winter conditions and snow water equivalent during winter conditions was measured with a Geonor Weighing Precipitation Gauge located on site. The gauge has a 12 L bucket suspended by three chains from the gauge frame. A vibrating wire transducer is placed replacing one of the chains as shown in Figure 3-21 (right). The vibrating wire transducer returns the frequency it measures in Hertz (Hz). That frequency is then used to arrive at the water quantity in the bucket through the following empirical equation.

$$P = A(f - f_0) + B(f - f_0)^2 \quad (30)$$

Where

P = Precipitation in cm

A = given calibration constant

B = given calibration constant

f = frequency reading from the datalogger at any time step (Hz)

f_0 = frequency of empty bucket at calibration (Hz)

The frequency was logged every five minutes by a Sutron Logger. During the winter, to prevent the water inside the rain gauge bucket from freezing, anti-freeze solution is added as recommended by the Geonor Weighing Precipitation Gauge manual (Campbell Scientific (Canada)Corp., 2011) however, even after adding anti-freeze solution, mild icing was occasionally observed (Figure 3-21).

Figure 3-21: Ice inside the Geonor Weighing Gauge bucket with anti-freeze (left) and the vibrating wire transducer (right).

3.6 Data Analysis

3.6.1 Statistical & Spatial analysis

General statistics (range, mean median, standard deviation, skewness) were calculated for all measured soil parameters. Contour maps were generated using MATLAB's contour function. This function uses a linear interpolation method to generate contours. The relative x and y axis distance from the inlet is used as the location information of each point to generate the contour maps. The MATLAB code used to generate the contour maps is provided in the Appendix 7.1.

The MATLAB code uses the MATLAB function “meshgrid” to generate a mesh between the cartesian coordinates (-5, -4) to (8,10). The mesh grid size is 0.005 m x 0.005 m. Following this step, the “griddata” function takes in the soil parameter data and interpolates it so that each grid in the mesh has an individual soil parameter value. The interpolation method used is linear interpolation. “Contourf” function then plots a contour map by connecting the grids that have the same soil parameter value. The colour scheme is then adjusted to clearly portray the important parts of the spatial map.

3.6.2 Time Series Analysis

A summary table is prepared for the temporal snow depth data as shown in Table 4-3. The summary table contains range, mean, median, standard deviation, coefficient of variation and antecedent conditions. Snow depth spatial maps are generated using MATLAB’s contour function. Two snow depth maps are provided to compare before and after thaw conditions (Figure 4-7 – top and Figure 4-8 – top). The remaining snow depth spatial maps are provided in the appendix (Figure 7-39 to Figure 7-46). An overall average snow depth spatial map is also provided in the appendix (Figure 7-47).

All analysis on K_{sat} are carried out using K_{sat} generated from infiltration rates through Radcliffe method. A summary table is prepared for the temporal K_{sat} data as shown in Table 4-6. The summary table contains range, mean, median, standard deviation, coefficient of variation and antecedent conditions. An average K_{sat} spatial map generated using MATLAB’s contour function is given in Figure 4-1 (bottom). K_{sat} spatial maps are generated for temporal data and are given in the appendix (Figure 7-30 to Figure 7-38).

K_{sat} measurements are also plotted in timeline box-whisker plots to study the temporal variability as shown in Figure 4-16. The K_{sat} measurements are also grouped into central pathway and non-central pathway locations and the timeline box-whisker plots are prepared for both categories as shown in Figure 4-18 and Figure 4-19 respectively. Since outliers are suspected to distort the incarnate K_{sat} trend, after checking for normality using Ryan – Joiner normality test, Grubbs test is used to check for outliers. Both above mentioned statistical tests are carried out using Minitab. The outliers are removed, and a temporal graph is prepared with average K_{sat} before outlier removal (all, central pathway and non-central pathway locations) and after outlier removal (all, central pathway and non-central pathway locations) as shown in Figure 4-20.

K_{sat} is also calculated using Elrick and Reynolds method. A temporal box whisker plot and an average spatial map are prepared as shown in Figure 4-17 and Figure 7-29. A Wilcoxon signed rank test is also conducted using Minitab to verify the statistical difference between the K_{sat} values calculated by the two methods.

3.6.3 Correlation

Semi-variograms are prepared using MATLAB and the code used to generate the semi-variogram graphs are given in Appendix 7.2. The Semi-variogram depicts the spatial autocorrelation of the measured sample points. The Experimental (Semi-) Variogram tool is downloaded from the MATLAB file exchange. The tool is then imported into MATLAB and used to generate the semi-variograms.

Spatial autocorrelation (Moran's I test) has not been performed since carrying it out in MATLAB required the usage of certain functions and was more complicated. Therefore, spatial correlation was discussed in light of the semi-variograms without utilizing Moran's I value.

3.6.4 Water level data

Water level data and temperature data collected by the loggers are observed. An example rain on snow melt event is plotted to show the temporal surface water level, ground water level, precipitation events, surface water temperature, ground water temperature and air temperature. The datum used for water levels is the axis of the perforated pipe shown in Figure 3-20. The relative elevation of the tops of the wells from the datum are measured. The measured lengths are shown in Figure 3-20. They are used to calculate the water levels with respect to the datum.

Events are generated based on the surface water level data using PCSWMM software. The criteria used for event classification is as follows.

1. Minimum interevent time = 1 hr,
2. Event threshold = 15 cm,
3. Extend events by 1 hr following and 1 hr preceding and
4. Events with maximum surface water level more than 100 cm are discarded.

3.6.5 Required Sample Size

The required sample size has been calculated using the following equation.

$$SS = \frac{Z^2 \times (sd) \times (1 - sd)}{C^2} \quad (30)$$

Where,

SS = required sample size

Z = Z score

sd = standard deviation

C = acceptable margin of error.

The z score for 95% and 90% confidence is 1.96 and 1.645 respectively. The margin of error for 95% and 90% confidence is 0.05 and 0.1 respectively.

4 Results & Discussion

This chapter presents the spatial and temporal analysis results from the field experiments and data collection carried out between Fall 2016 and Summer 2018. It includes

1. a discussion of the spatial variability of K_{sat} , moisture content, bulk density, organic content, particle density, porosity, D_{60} , D_{30} , C_c , C_u , Snow depth & density and frost depth.
2. an analysis on the temporal variability of K_{sat} .

Weather conditions and anecdotal observations were taken into consideration for the analysis to facilitate better interpretation of the above-mentioned soil parameters, snow depth & density and K_{sat} data. Spatial maps were prepared to analyze the heterogeneity and box-whisker plots are prepared to analyze the temporal changes.

4.1 Spatial Variability

In the following sections, soil data from location Q has been removed from the dataset. First iteration maps that included Q (Figure 7-19 to Figure 7-28 in the Appendix) consistently identified Q as an outlier with distinctly different soil characteristics than neighboring samples. This outlier identification is done by visual examination of the spatial maps. All soil samples are collected between 15 cm to 20 cm underground within the top soil layer, but the top soil layer was comparatively narrow (<15 cm thick) at Q. This resulted in samples being collected from under the BC media / topsoil in the native soil which has considerably distinct soil properties.

Therefore, all statistical analysis and summaries were completed without Q. However, the snow depth maps have 30 points including Q. A summary of all the measured soil parameters, K_{sat} and Snow Depth is given in Table 4-1. The table also shows distinct summaries for the locations in the central flow path and the non-central flow path regions. The differences between these two groups of locations as shown in the spatial maps in sections 4.1.1 to 4.1.5 can be numerically observed in this summary.

Table 4-1: Summary table for soil parameters, K_{sat} and Snow Depth

					Overall						
	BD	MC	OC	PD	Porosity	D60	D30	Cu	Cc	K _{sat}	SD
Number	16	16	16	16	16	16	16	16	16	16	16
Max	1895	26	8	5153	80	1.4	0.4	10.6	1.0	0.006	20
Min	610	14	5	2750	31	0.5	0.2	3.1	0.6	0.000	6
Range	1285	12	3	2403	49	0.9	0.2	7.5	0.4	0.005	14
Mean	1590	20	6	3230	50	0.7	0.3	6.0	0.8	0.002	12
Median	1794	19	6	3126	45	0.6	0.2	5.7	0.8	0.002	12
StdDev	468	4	1	554	16	0.3	0.1	2.2	0.1	0.002	3
COV	29	19	19	17	31	36	21	37	16	77	26
				Central Flow Path							
	BD	MC	OC	PD	Porosity	D60	D30	Cu	Cc	K _{sat}	SD
Number	6	6	6	6	6	6	6	6	6	6	6
Max	1825	26	6	3396	46	0.8	0.3	8.2	1.0	0.003	15
Min	1793	18	5	2842	37	0.5	0.2	3.3	0.8	0.000	10
Range	32	8	1	553	10	0.3	0.1	4.9	0.2	0.003	5
Mean	1806	23	5	3174	43	0.6	0.2	5.7	0.9	0.001	12
Median	1801	24	5	3185	43	0.5	0.2	5.7	0.9	0.001	12
StdDev	13	3	1	196	4	0.1	0.0	1.6	0.1	0.001	2
COV	1	14	11	6	8	19	12	29	10	113	15
				Non-Central Flow Path							
	BD	MC	OC	PD	Porosity	D60	D30	Cu	Cc	K _{sat}	SD
Number	10	10	10	10	10	10	10	10	10	10	10
Max	1895	21	8	5153	80	1.4	0.4	10.6	0.9	0.006	20
Min	610	14	5	2750	31	0.5	0.2	3.1	0.6	0.001	6
Range	1285	6	3	2403	49	0.9	0.2	7.5	0.3	0.004	14
Mean	1461	18	6	3264	55	0.8	0.3	6.2	0.8	0.003	13
Median	1747	18	6	3091	47	0.7	0.3	5.7	0.8	0.003	12
StdDev	562	2	1	698	18	0.3	0.1	2.6	0.1	0.002	4
COV	38	13	19	21	34	37	23	41	15	53	31
				Legend							
BD (Kg/m³)	Bulk Density			D60 (mm)	60% passing mesh size			K _{sat} (cm/s)		Saturated hydraulic conductivity	
MC (%)	Moisture Content			D30 (mm)	30% passing mesh size						
OC (%)	Organic Content			Cu (no unit)	Coeff. of uniformity			SD (cm)		Snow Depth	
PD (Kg/m³)	Particle Density			Cc (no unit)	Coeff. of curvature			COV (%)		Coeff. of Variation	

4.1.1 Saturated Hydraulic Conductivity (K_{sat})

On the day of soil samples collection i.e., Oct 25th, 2017, the moisture content was high in the central water flow pathway as shown in Figure 4-1 (top). In the low-lying central path soil

moisture ranged from 26 – 18% while for locations at higher elevation moisture ranged from 14 – 21%.

It should be noted that between the two methods used for K_{sat} calculation i.e., Radcliffe Method and Elrick & Reynolds method, Elrick & Reynolds method is derived from Glover's equation (Elrick & Reynolds, 1992). Glover's equation has been identified to work well in coarse textured soils where the capillary effect is minimal and initial water content in the soil is near the field capacity (Jabro & Evans, 2006). Glover's equation also ignores the effect of gravity and capillary water flow (Radcliffe & West, 2015). On the contrary, Radcliffe method has been formulated to include the effect of gravity and capillary water flow (Radcliffe & West, 2015). Both these phenomena are understood to be prominent and enhanced near the ground surface, particularly in a BC. Therefore, Radcliffe method is the primary method used for analysis. Furthermore, Elrick & Reynold method results are shown and discussed briefly since it is the primary method provided in the online Guelph Permeameter K_{sat} excel calculator provided by the Soilmoisture Equipment Corporation.

Table 4-2: Summary table for Ksat (cm/s) - Radcliffe method and Elrick & Reynolds method

	Elrick and Reynolds Method								
Date	05-Jun-17	10-Jul-17	15-Aug-17	19-Sep-17	10-Oct-17	24-Oct-17	26-Feb-18	16-May-18	8-Jun-2018
Number	16	16	16	16	16	16	16	16	16
Range	0.0053	0.0372	0.0593	0.0661	0.0155	0.0465	0.0318	0.0513	0.0135
Mean	0.0016	0.0071	0.0068	0.0140	0.0053	0.0092	0.0090	0.0071	0.0037
Median	0.0014	0.0021	0.0011	0.0091	0.0059	0.0033	0.0051	0.0051	0.0014
StDev	0.0014	0.0119	0.0147	0.0168	0.0045	0.0134	0.0116	0.0123	0.0047
COV (%)	91	167	217	120	85	145	129	174	129
	Radcliffe Method								
Date	05-Jun-17	10-Jul-17	15-Aug-17	19-Sep-17	10-Oct-17	24-Oct-17	26-Feb-18	16-May-18	8-Jun-2018
Number	16	16	16	16	16	16	16	16	16
Mean	0.0011	0.0020	0.0018	0.0041	0.0022	0.0026	0.0026	0.0020	0.0013
Range	0.0054	0.0078	0.0120	0.0189	0.0066	0.0116	0.0139	0.0110	0.0050
Median	0.0004	0.0010	0.0003	0.0027	0.0019	0.0013	0.0015	0.0011	0.0008
StDev	0.0014	0.0025	0.0032	0.0048	0.0021	0.0031	0.0035	0.0030	0.0015
COV (%)	129	129	178	115	92	119	134	148	120

K_{sat} data is summarized in Table 4-1 & Table 4-2 and average K_{sat} values are mapped in Figure 4-1 (bottom). K_{sat} values were lowest in the central pathway. The average K_{sat} in the central flow path was 0.33 times that of the average K_{sat} at the remaining locations. The central flow path

being the hydrologically active area in a BC, measuring infiltration rates outside this area might not provide representative measurements indicating the BC performance.

Figure 4-1: Moisture Content (top) and K_{sat} – Radcliffe Method (bottom)

Overall the BC has acceptable infiltration rates and met recommended minimum infiltration rates for BC, i.e. 15 mm/hr (Toronto and Region Conservation Authority, 2012). There were significantly fewer plants located in the central flow path compared to BC hills. Plants sustain infiltration processes through several mechanisms. Root structures maintaining soil structure,

mitigate erosion, and create macro-structure within the subsurface (Valtanen et. al., 2016; Le Coustumer et. al., 2012). Additionally, plants absorb moisture content from the soil and evapotranspire water, leaving the soil with lesser moisture. Therefore, BCs should have a diverse terrain (for plant growth in hills and infiltration/stagnation in the flow path) with more than one flow path facilitating infiltration, seepage and snow melt.

For moisture content, the required sample size for 90% and 95% confidence interval are 4 and 12 respectively. For K_{sat} averaged, the required sample size for 90% and 95% confidence interval are 5 and 14 respectively. Since, 16 measurements have been taken (excluding Q), the number of samples required to confidently estimate moisture content and K_{sat} are met in this study. However, the number of K_{sat} measurements required to estimate the K_{sat} within the central flow path with statistical certainty could not be calculated with the available data. For the central flow path K_{sat} , the number of samples formula (Equation 30) returned a negative sample size because the standard deviation to mean ratio in the central flow path is greater than one.

4.1.2 Bulk Density, Moisture Content and Organic Content.

Organic content is lower in the central pathway and higher in the hills (Figure 4-2 - top). The average organic content in the central flow path and non-central flow path are 5 % and 6 % respectively at 15 to 20 cm depth below the surface. The difference in average organic content is however very low and this could be due to some locations in non-central pathway regions having lower organic content. But in general, the central pathway having a lower organic content can be clearly seen in Figure 4-2 (top). There is anecdotal evidence that the number of plants is lower in the central pathway compared to the number of plants in the hills. As organic content is a direct consequence of plants, it is not surprising that lower organic content lower due to the lower plant density. Moreover, incoming stormwater likely deposits mineral-based sediments within the central pathway thus increasing the proportion of inorganic materials observed in collected soil samples.

It can be observed from Figure 4-2 (bottom) that bulk density is lower along the outline of the BC, particularly the points B, E and C1 has very low bulk density. Based on observations, it is suspected that a very loose soil has caused the low bulk density in E. Loose soil and mulch are suspected to have caused low bulk density and high organic content in B and C1. Moreover, the average bulk density in the central flow path and non – central flow path regions are 1806 Kg/m^3

and 1461 Kg/m^3 respectively. The higher bulk density in the central flow path could be due to higher moisture content and sedimentation.

Figure 4-2: Organic Content (top) and Bulk Density (bottom)

For organic content, the required sample size for 90% and 95% confidence interval are 4 and 12 respectively. For bulk density, the required sample size for 90% and 95% confidence interval are 6 and 16 respectively. Since, 16 measurements have been taken (excluding Q), the

number of samples required to confidently estimate organic content and bulk density are met in this study.

4.1.3 Porosity and Particle Density

There was no clear distinction between central pathway and hill regions for porosity. Porosity is calculated from particle density and bulk density as shown in Equation 24. Since, both of these parameters are measured from soil samples collected through different methods, there could be some dissonance between the two data sets. This uncertainty is discussed in section 4.5.

Figure 4-3: Porosity (top) and Particle Density (bottom)

From Figure 4-3 (bottom), particle density is higher in the central pathway regions compared to the hill region. However, this effect is particularly high in the central pathway arm near the inlet. Therefore, the sedimentation could be higher in the central pathway arm near the inlet compared to the other arm. The particle density near V is very high and it is considered as an outlier.

For porosity, the required sample size for 90% and 95% confidence interval are 6 and 16 respectively. For particle density, the required sample size for 90% and 95% confidence interval are 4 and 11 respectively. Since, 16 measurements have been taken (excluding Q), the number of samples required to confidently estimate porosity and particle density are met in this study

4.1.4 Soil Particle Size Distribution

The soil is classified as sand, silt or clay using the soil textural triangle shown in Figure 4-4. Collected BC samples had an average proportion of Sand - 91.51% and Silt & Clay - 8.49 % classifying the media is Sandy Soil. Coefficient of uniformity (Cu) and Coefficient of curvature (Cc) describe the grading quality of the soil. According to the ASTM standard D2487 – 17, well graded sandy soil has (Cu greater than 4 and Cc between 1 and 3).

Figure 4-4: Soil textural triangle classification with BC soil proportions plotted (United States Department of Agriculture, 2018).

For sand to be classified as well graded, C_u should be greater than or equal to 6 and C_c should be between 1 and 3. A classification of well graded does not necessarily mean that the soil is ideal for BC functionality (high infiltration rate and high plant growth support). The ideal BC media installed initially might not have been well graded. For the media to be well graded now, the particle sizes that are not represented enough should have been brought by sediment deposition or native soil erosion/mixing so in this context, well graded soil may not be preferable for BC functionality.

Figure 4-5: C_u (top) and C_c (bottom)

For Cu, the required sample size for 90% and 95% confidence interval are 6 and 18 respectively. For Cc, the required sample size for 90% and 95% confidence interval are 4 and 10 respectively. Since, 16 measurements have been taken (excluding Q), the number of samples required to confidently estimate Cc (90 & 95% CI) and Cu (only 90% CI) are met in this study. However, since Cu requires 18 samples for 95% confidence interval (>16), Cu cannot be estimated with 95% confidence interval.

Figure 4-6: D_{60} (top) and D_{30} (bottom)

From Figure 4-5 (top), it can be recognized that the soil is well graded in most of the regions except near T. From Figure 4-5 (bottom), it can be recognized that in the central pathway is well graded. Therefore, based on both C_c and C_u , the soil is well graded in the central pathway particularly in the arm further from the inlet. This could be because, sediment deposition takes place in the central pathway, which is filled with the BC media. Sediment deposition causes the soil to be well graded because, the installed BC media is predominantly sandy. Sediments that are deposited are either silt or clay (smaller than sand particles). Therefore, the BC media in regions with sedimentation becomes well graded (a mix of sand, silt and clay).

The BC soil D_{60} and D_{30} i.e., the sieve size at which 60% and 30% of the soil is retained, is low in the central pathway and near the inlet (Figure 4-6) suggests sediment deposition may have occurred in these areas. Moreover, majority of the suspended solids are below the D_{30} size and therefore they are settled near the inlet showing smaller sizes near the inlet. They are also settled in the central flow path throughout the BC. The average D_{60} in the central pathway and non-central pathway region are 0.6 mm and 0.8 mm respectively. The average D_{30} in the central pathway and non-central pathway region are 0.2 mm and 0.3 mm respectively. This proportional difference also confirms that there is clogging through fines deposition in the central pathway.

For D_{60} , the required sample size for 90% and 95% confidence interval are 6 and 18 respectively. For D_{30} , the required sample size for 90% and 95% confidence interval are 5 and 13 respectively. Since, 16 measurements have been taken (excluding Q), the number of samples required to confidently estimate D_{30} (90 & 95% CI) and D_{60} (only 90% CI) are met in this study. However, since D_{60} requires 18 samples for 95% confidence interval (>16), D_{60} cannot be estimated with 95% confidence interval.

4.1.5 Snow Depth and Snow density

Snow depth and snow densities were measured during 10 instances between 2016 and 2018 during winter. Shown in Table 4-3 the covariances of the snow depths are very high during events after or during rain on snow melt. A coefficient of variation (CV) is a statistical measure of the dispersion of data points in a data series around the mean. This shows that snow melts in heterogeneous rates throughout the BC. Because, just after snow before snow melt, the CV is comparatively low suggesting uniformity in the deposited snow depth. Since standard deviation is a quantity calculated to indicate the extent of deviation for a set of data, it increases when the mean

increases and decreases when the mean decreases. Therefore, standard deviation cannot be used as a reliable measure in this situation to measure heterogeneity in snow depth.

Figure 4-7: Snow depth before snow melt spatial map (top) and picture (bottom) on December 22, 2016, before thaw.

Example spatial snow depth data sets are presented to show the increase in heterogeneity in snow depths during snow melt. Figure 4-7 (top and bottom) are the spatial map from the snow depth data collected and picture taken on December 22, 2016 just after a snow event. Figure 4-8

(top and bottom) are the spatial map from the snow depth data collected and picture taken on January 19, 2017 four days of snow melt after a snow event. On Dec 22nd, the snow depth was mostly homogeneous throughout the BC except for the peak near the top right corner. This was determined to be due to snow being pushed from the parking lot by snow ploughs. On Jan 19th, after four days of warm weather (daily temperature highs > 0°C), snow varied with location and reflected different rates of snow melt. The homogeneity and heterogeneity in snow depths are visible in pictures collected from the site on Dec 22nd and Jan 19th as shown in Figure 4-7 (bottom) and Figure 4-8 (bottom) respectively.

Table 4-3: Snow depth (cm) statistics with antecedent conditions

Date	Range (cm)	Mean (cm)	Median (cm)	StDev (cm)	COV (%)	Antecedent Conditions
12/22/2016	29.50	23.80	22.25	5.25	22.05	Snow
1/11/2017	32.50	14.04	13.75	6.36	45.29	Rain on snow melt
1/19/2017	24.00	6.30	6.00	5.45	86.48	Rain on snow melt
2/1/2017	10.50	4.40	4.00	1.98	45.00	Snow
2/8/2017	12.00	2.13	1.75	2.42	113.48	Rain on snow melt
2/13/2017	14.00	16.62	16.50	2.53	15.21	Snow
2/15/2017	8.00	8.29	8.00	1.73	20.82	Snow
1/8/2018	22.00	21.18	20.25	5.21	24.58	Snow
1/17/2018	18.50	9.65	9.50	4.16	43.07	Snow
2/5/2018	25.50	12.35	11.25	5.22	42.28	Snow

Table 4-4: Snow Density with date, time and antecedent conditions.

Date and Time	Snow Density (Kg/m ³)	Antecedent Conditions
12/22/2016 12.00 pm	209.3	Snow
1/11/2017 9.25 pm	366.2	Rain on snow melt
1/19/2017 10.05 pm	490	Rain on snow melt
2/1/2017 9.45 am	137.5	Snow
2/8/2017 12.30 pm	507.5	Rain on snow melt
2/13/2017 9.00 am	169.8	Snow
2/15/2017	287.1	Snow

From Table 4-4, it can be observed that snow density is significantly higher after rain on snow melt. The average snow density with antecedent snow conditions is 200 Kg/m³, whereas the average snow density with antecedent rain on snow melt conditions is 455 Kg/m³. This 128% increase could be because during snow fall, snow gets deposited, but it does not get compressed. However, during rain on snow melt, even though a significant proportion of snow melts away, the remaining snow gets consolidated due to the kinetic force of rain droplets or the weight of water

over them. Moreover, snow once melted, if freezes again, becomes like ice thereby increasing the snow density significantly. During snow density measurements, it is also observed that there are layers of snow with the lower layers are denser than the upper layers due to repeated snow before complete thaw.

Figure 4-8: Snow depth after snow melt spatial map (top) and picture (bottom) on January 19, 2017, after thaw.

Based on the observations discussed above, parameters that were observed to have an effect in the thaw rates included:

1. Surface slope: the snow melts and slides down into the central flow path during thaw resulting in low snow depth in the slope between the hills and the flow path.

2. Whether or not the location is in the hills or the flow path: any snow melt results in liquid water that flows to the flow path. Hence, this water melts any snow left in the flow path resulting in faster thaw rates in the flow path compared to the hills.
3. The direction where the slope is facing: if the slope is facing south, it receives significantly higher exposure to sunlight compared to north facing slopes. This results in higher thaw rates in South facing slopes and lower thaw rates in North facing slopes.

For Snow Depth, the required sample size for 90% and 95% confidence interval are 5 and 15 respectively. Since, 30 measurements have been taken, the number of samples required to confidently estimate Snow Depth (90 & 95% CI) are met in this study.

4.1.6 Correlations

The semi-variograms generated using MATLAB for all measured parameters are examined for positive trend (increasing variance with increasing distance). A parameter has high spatial correlation if its semi-variogram exhibits a positive trend. Moisture content, K_{sat} and C_c have semi-variograms with positive trends as shown in Figure 4-9, Figure 4-10 and Figure 4-11.

Figure 4-9: Semi-variogram - Moisture Content.

Figure 4-10: Semi-variogram – Cc

Figure 4-11: Semi-variogram - Ksat.

Moisture content and Ksat could have better spatial autocorrelation because, closer points in the central pathway have high moisture content / low Ksat and closer points in the hills have low moisture content / high Ksat except for the outliers. Therefore, the further two points are, the lesser chances are they have a similar moisture content / Ksat. However, it should be noted that near the slopes, this condition doesn't exist i.e., two close points, one in the central pathway and one in the slope could have very different moisture content / Ksat. Both these parameters are also highly negatively correlated.

4.1.7 Frost Depth

It can be observed from Table 4-5 and from Figure 4-15 that there is almost no frost depth on the day with rain on snow melt i.e., February 26th. This is the day when a set of Guelph Permeameter measurements are carried out to test the effect of winter on K_{sat}. The locations in Table 4-5 can be referenced from Figure 3-16. T is the location at the top of the hill near the tree. The lengths of the frost tubes in each location are given in Table 3-4.

For better visualization of the data, figures have been produced for each individual set of data (Figure 4-12 to Figure 4-15). It should be noted that these figures are not engineering drawings. From Table 4-5, location T corresponds to the frost tube labelled 'Hill' in the figures, location W & V corresponds to the frost tube labelled 'Slope' in the figures, 'reference' corresponds to the location 'External reference' and the 'Central pathway average' is the average frost depths of S, I&Y, O and M.

As expected, the measured frost depth is higher in the hill, because the effect of warmer saturated zone is lesser in the hills. In location between W & V, which is in a slope, the frost depth is lower than the frost depth in the hill but higher than the frost depth in the central pathway locations. This could also be due to the proximity to the warmer saturated zone. The reference location is located in natural soil and it has higher frost depth. All locations that are in the central pathway have relatively similar frost depth in the order of 10 cm (Figure 3-16 and Table 4-5). This could be because the gravel layer is at 40 cm depth, the warm saturated layer is close, and the snow melt from any location in the BC is going to flow towards and accumulate in the central pathway.

Table 4-5: Frost depth (cm) from ground surface with dates and locations with antecedent conditions

	T	S	I Y &	O	M	W &V	Reference	Antecedent Conditions
2/5/2018	33.5	12	10	9.5	7	19	12	Snow
1/8/2018	31.5	9.5	9	11.5	9	14	30+ 10 *	Snow
1/17/2018	26	15	7.75	6.5	6.4	8	10	Snow
2/26/2018	0+11 *	0	0	0	0	0	0	Rain on snow melt
* - instances where two patches of frozen layers are identified								

The two data points with two numbers indicated by a * are instances when two patches of frozen layers are identified. The 11 cm patch in Feb 26th was between 21 cm to 32 cm under the ground surface and the 9 cm patch on 8th January was between 23 cm to 33 cm under the ground surface. These phenomena could have happened either because the frozen water inside the frost tube did not defreeze properly or because there is a frozen layer under the soil surface below a non-frozen layer.

Figure 4-12: Frost depths on Feb 5, 2018.

Figure 4-13: Frost depths on Jan 8, 2018

Figure 4-14: Frost depths on Jan 17, 2018

Figure 4-15: Frost depths on Feb 26, 2018

Custom made frost tubes have also been used in BCs by other researchers to measure frost depth (LeFevre et. al., 2009). It should also be noted that while this is an attempt to develop an approach to measure frost depth in BCs and it did show some promise, there were some erroneous issues as well. Also, It was not possible to get the right pipe dimensions recommended in the guidance (Institute of Northern Engineering, 2011). Furthermore, during February 26, 2018, since it was warm, ice was observed to be moving inside the tube due to melting of water along the circumference of the pipe. Therefore, this experimental set up to check the frost depths in BCs need to be further explored to produce reliable results.

4.2 Temporal Variability

4.2.1 Saturated Hydraulic Conductivity (K_{sat})

From Figure 4-17, it can be observed that K_{sat} calculated using the older Elrick and Reynolds method follows the same pattern observed in Figure 4-16. However, the K_{sat} values are significantly higher when calculated using the Elrick and Reynolds method. When compared with K_{sat} values measured using Mini Disk Infiltrometer measurements by Ding (2017), which should be theoretically higher than Guelph Permeameter measurements, Elrick and Reynolds method of

calculation produced K_{sat} values lower than the K_{sat} values produced by Mini Disk Infiltrometer measurements. However, the K_{sat} values arrived at using the newer Radcliffe method produced satisfactory values.

A Wilcoxon signed rank test was run on the K_{sat} data by Radcliffe method and Elrick & Reynolds method to determine whether there is a statistically significant median difference in K_{sat} values between the two methods. The assumptions of Wilcoxon signed test (independence, continuity and symmetrical distribution of the differences between the two related groups) are met and the assumption test results are shown in Section 7.4. K_{sat} calculated through Radcliffe method (0.00219 ± 0.00089 cm/s) was lower than the K_{sat} calculated through Elrick & Reynolds method (0.00708 ± 0.00354 cm/s). A statistically significant median difference of 0.0050247 cm/s was identified, $W = 45.00$, $p = 0.009$. Q was not included in this analysis as discussed earlier. However, the statistical outliers in individual K_{sat} data sets as provided in Table 4-7 were not removed. Since Radcliffe method produced more realistic values of K_{sat} compared to Elrick and Reynolds method, the former used for all discussion purposes and the latter is used just to be compared with the former. The Guelph Permeameter manual has shown the calculation method in the Guelph-Permeamter-Calculator.xls file which can be downloaded from Soilmoisture website. The calculator file has Elrick and Reynolds method (both 1 head and 2 head). For this research, the two head method is used for better accuracy. It should be noted that, Radcliffe method is not the default method of K_{sat} calculation from Guelph Permeameter measurements.

While the accuracy of Elrick and Reynolds method in natural soil is out of the scope of this thesis, for BC media, it is recommended to use Radcliffe method of calculation as discussed in section 3.3.3. Using Elrick and Reynolds method as by consultants and regulators causes over prediction of BC media K_{sat} as discussed above. It should be noted that the overall mean K_{sat} (0.002 cm/s), central pathway mean K_{sat} (0.001 cm/s) and non – central pathway mean K_{sat} (0.003 cm/s) all meet the TRCA guideline i.e., infiltration rate - 15 mm/hr or 0.00042 cm/s (Toronto and Region Conservation Authority, 2012). The average K_{sat} values for all points, central pathway and non – central pathway points also fall within the K_{sat} values provided for fine sandy loam / sandy loam or sandy soil (United States Department of Agriculture, 2018). Moreover, fluctuations in mean K_{sat} were attributed to isolated outlier measurements that produced a single point of notably higher K_{sat} . Individual spatial maps of K_{sat} values are provided from Figure 7-30 to Figure 7-38 in the

appendix. A spatial map with average K_{sat} calculated from Reynolds method is provided in Figure 4-1 (bottom).

Figure 4-16: Timeline K_{sat} data – Radcliffe method – All locations

In some instances, temporal variability was strong suspected to be due to measurement error and not due of naturally changes in in-situ soil conditions. For example, on September 20th, 2017, the mean K_{sat} is particularly higher compared to the mean K_{sat} in all other days (Table 4-6). The high infiltration rates were attributed to the formation of preferential flow paths. For the first four sets of K_{sat} measurements, the same augured holes were used repeatedly to place the Guelph Permeameters after cleaning. The locations for each measurement was shifted slightly following this measurement date and mean and variability of infiltration rates decreased significantly. The next is that the antecedent dry conditions might have caused a low moisture content media that soaked more water (Gray & Norum, 1967). Therefore, it is suspected by the authors that the repeated infiltration measurements combined with dry antecedent conditions created localized preferential flow paths.

Figure 4-17: K_{sat} – Elrick and Reynolds method – All locations

The occurrence of outlying measurements with high infiltration appeared to occur randomly but were confined to measurement locations outside of the BC central flow path. Therefore, it is important to focus on the central flow areas for infiltration measurements since it reduces the risk of outliers and provides better estimates of infiltration rates in the hydrologically active area of the BC.

Figure 4-18: Timeline- K_{sat} – Central Pathway, Radcliffe Method.

From Figure 4-18, it can be seen that there is a marginal rise in K_{sat} in the central pathway locations during a warm day (26 Feb, 2018) in winter and there is a marginal decrease in K_{sat} in the non-central pathway locations in the same day. Though this seems to provide evidence for freeze-thaw action, the increase in K_{sat} in the central pathway is primarily driven by a peak value. And based on the observation of the box whisker plot, the K_{sat} in other locations are comparatively low. From Figure 7-33, it can be observed that the outlier is slightly left to the central flow path. This point, A1, is in the slope close to the central flow path but not in the central flow path like other locations in the central flow path. Ironically, there is no outlier among the locations in the non-central pathway regions as observed from Figure 7-36.

Figure 4-19: K_{sat} – Non-Central Pathway – Radcliffe Method

Table 4-6: K_{sat} (cm/s)– Radcliffe method – Statistics and Antecedent Conditions

Date	Range	Mean	Median	StDev	CV	Antecedent Conditions
5-Jun-17	0.005	0.001	0.000	0.001	129	Wet
10-Jul-17	0.008	0.002	0.001	0.003	129	Wet
15-Aug-17	0.012	0.002	0.000	0.003	178	Wet
19-Sep-17	0.019	0.004	0.003	0.005	115	Dry
10-Oct-17	0.007	0.002	0.002	0.002	92	Wet
24-Oct-17	0.012	0.003	0.001	0.003	119	Wet
26-Feb-18	0.014	0.003	0.001	0.003	134	Freezing
16-May-18	0.011	0.002	0.001	0.003	148	Wet
8-Jun-2018	0.005	0.001	0.001	0.002	120	Wet

Table 4-7: Results of Grubbs test for outliers

Date	Outliers	Significance Level	G value	P value
05-Jun-17	N	0.05	3.04	0.002
10-Jul-17	-	0.05	2.3	0.188
15-Aug-17	A	0.05	3.22	0.000
19-Sep-17	R	0.05	3.1	0.001
10-Oct-17	-	0.05	2.12	0.361
24-Oct-17	A	0.05	2.94	0.005
26-Feb-18	A1	0.05	3.24	0.000
16-May-18	V	0.05	3.05	0.002
8-Jun-18	-	0.05	2.44	0.100

Figure 4-20: Ksat before outlier removal (top) and after outlier removal through Grubbs test (bottom).

Due to outliers distorting the overall mean of the temporal K_{sat} data, the Grubbs test is performed individually to each temporal data set to spot the outliers. The results of the Grubbs test for outliers are given in Table 4-7. The assumption of normality is checked through the Ryan Joiner test. The results of that test are shown in section 7.3. After the statistical outliers are removed, the average temporal K_{sat} calculated through Radcliffe method is plotted. The central pathway, non-central pathway and all locations, before and after outlier removal through Grubbs test are shown in Figure 4-20 top and bottom respectively. It can be observed that increasing K_{sat} during winter observed in the central pathway in Figure 4-18 is not observed in Figure 4-20 (bottom). To clearly understand if there are seasonal changes in K_{sat} , we would need more data during the spring and multiple years of data collection.

4.2.2 Water level

One series of snow events with a rain on snow melt event at the end is shown in Figure 4-21 (top and bottom). It should be noted that when the Baro – temperature (air temperature) is close to or higher than zero, the precipitation is likely to be rainfall and when it is clearly lesser than zero, the precipitation is likely to be snowfall.

Figure 4-21: Rain on snow melt event reflected on the water level data (top) and temperature data (bottom).

From January 6th, 2017 to January 8th, 2017, there were snow events and the air temperature is below zero. When the air temperature comes closer to zero, on January 9th, during a precipitation event, there is an increase in surface water temperature and a peak in surface water level which suggests rain on snow melt. Two days later, the peak can be observed in the saturated zone levels and a clear temperature drop is also observed in the saturated zone temperature suggesting transfer of surface water into sub-surface water. The datum used to graph surface water level data and saturated zone data is the axis of the perforated pipe in the BC.

Table 4-8: Event statistics - Water levels

Event	Start Time	Duration (h)	Avg. SZL	Avg. SWL	Max. SZL	Max. SWL
1	2017-01-07 05:55	4.67	0.71	41.03	1.44	57.61
2	2017-01-07 19:30	16.17	-0.5	47.57	0.52	58.82
3	2017-01-08 15:00	18.67	-0.66	70.19	0.83	134.9
4	2017-01-12 00:40	2.17	-0.4	33.491	0.54	39.01
5	2017-01-14 23:20	11.92	-0.72	56.19	0.07	77.99
6	2017-01-15 19:55	40.08	-1.78	80.15	-0.41	243
7	2017-02-03 22:10	14.25	0.44	43.39	1.11	48.67
8	2017-02-09 06:25	8.33	-0.07	43.22	0.9	58.81
9	2017-02-09 16:50	19.75	-0.21	55.97	0.91	65.43
10	2017-02-15 08:25	2.33	-0.97	28.97	-0.13	52.76
11	2017-03-05 03:20	5.83	0.94	38.61	1.45	48.58
12	2017-05-18 04:15	2	0.72	25.726	1.16	40.9
13	2017-06-17 13:50	3.08	6.6	36.87	19.03	51.17
14	2017-06-18 07:45	2.25	1.77	32.269	4.27	43.38
15	2017-06-23 02:10	3.67	2.41	35.55	4.07	41.35
16	2017-06-23 06:05	3	3.94	37.77	12.93	55.65
17	2017-06-28 20:50	2	2.07	27.539	2.59	42.38
18	2017-06-29 19:00	2.08	1.29	32.922	1.82	40.15
19	2017-07-07 18:10	2.67	1.83	35.54	3.47	47.13
20	2017-07-12 15:25	3.17	2.16	36.88	2.78	48.07
21	2017-07-12 21:10	2.42	2.51	37.42	3.36	45.42
22	2017-07-20 10:10	2.67	2.86	33.561	5.97	46.45
23	2017-08-04 16:30	2	2.23	34.79	2.74	38.86
24	2017-09-02 13:40	2	0.25	26.138	1.02	41.45
25	2017-09-04 17:45	2.33	2.18	33.288	2.86	41.86
26	2018-01-08 14:35	19.17	0.69	39.03	1.43	41.83
27	2018-01-09 14:35	9.5	0.79	38.55	1.44	38.87
28	2018-01-10 00:30	3	0.95	38.23	1.83	38.59
29	2018-01-10 14:55	2.33	0.87	38.41	1.25	38.72
30	2018-01-10 16:50	2.17	0.64	38.26	1.08	38.66
31	2018-01-12 04:05	2	0.49	37.79	1.01	39.37
32	2018-01-12 06:45	9.67	1.28	38.8	2.12	39.51
Legend						
SZL	Saturated Zone Level	SWL	Surface Water Level			

Table 4-8 shows the event statistics for the water level data. It should be noted that the perforated pipe axis is used as the datum for these calculations. Since, the saturated zone logger is

beneath the perforated pipe axis, for some events, the saturated zone water levels are negative. The criteria used for events generation is given in section 3.6.4. It should be noted that the surface water ponding did not exceed 48 hours for any event which shows that the BC is functioning well.

4.3 Additional Considerations

4.3.1 Physio-chemical processes

Physio-chemical processes are suspected to cause structural changes in the soil by causing flocculation of aggregates according to literature (Kakuturu & Clark, 2015). No chemical analysis has been carried out as part of this study, but salt concentrations are assumed to be higher in the central flow pathway. Based on the physical data presented above, it can be speculated that

1. Higher salt concentrations in the central pathway could cause flocculation of aggregates in the central pathway resulting in a lower K_{sat} as shown in Figure 4-1 (bottom). Higher salt concentrations in the central pathway could cause unfavorable conditions for plants to thrive resulting in lower organic content (Figure 4-2– top) and lower K_{sat} (Figure 4-1 – bottom). Lower organic content could be a direct result of lower plant density as observed through anecdotal evidence. Lower K_{sat} could be due to lower number of roots causing preferential flow paths due to lower plant density.
2. It can be observed from Figure 4-2 (bottom) that bulk density is lower along the outline of the BC, particularly the points B, E and C1 has very low bulk density. Based on observations, it is suspected that a very loose soil has caused the low bulk density in E. Loose soil and mulch are suspected to have caused low bulk density and high organic content in B and C1. Moreover, the average bulk density in the central flow path and non – central flow path regions are 1806 Kg/m^3 and 1461 Kg/m^3 respectively. The higher bulk density in the central flow path could be due to higher moisture content and sedimentation.

For organic content, the required sample size for 90% and 95% confidence interval are 4 and 12 respectively. For bulk density, the required sample size for 90% and 95% confidence interval are 6 and 16 respectively. Since, 16 measurements have been taken (excluding Q), the number of samples required to confidently estimate organic content and bulk density are met in this study.

4.3.2 Uncertainties in the data

One of the uncertainties in the data collected is due to the immiscibility of the soil properties data collected using the two different methods. On this account, it should be noted there that porosity is calculated from bulk density and particle density. Bulk density is measured using the bulk density measuring kit and particle density is measured using Quantachrome Stereopycnometer. The samples for both measurements are collected using different methods. The former is collected using the bulk density measuring kit whereas the latter is collected using spade. Measures were taken to make sure that there is no mulch in the soil samples collected using spade. However, the soil samples collected using the bulk density had some mulch particles in them which could not be avoided. This might have caused a lower than actual bulk density measurement which could have resulted in a higher than actual porosity (Figure 4-2- bottom and Figure 4-3 – top).

5 Conclusions and Recommendations

5.1 Conclusions

This study highlights the temporal and spatial heterogeneity that is present in BCs. For simplicity, designers often treat BCs as black-boxes ignoring heterogeneous internal processes. In this study, the physical soil properties were distinct within the central flow pathway and all other locations surveyed in the BC. The central flow pathway is where the majority of stormwater will collect and infiltrate, hence it is important to better understand the spatial and temporal processes that influence parameters such as K_{sat} in this region of the BC. The role of snow pack, freeze-thaw action and winter pollutants on long-term and seasonal BC processes is still poorly understood. While there was some evidence that freeze-thaw action may temporarily increase K_{sat} (in theory due to increasing pore sizes and preferential flow paths) the effect was limited to the central flow path.

In the introduction, the research objectives provided were

1. To measure K_{sat} spatially in the BC throughout a year, analyze how various locations in the BC behave in terms of K_{sat} before, during and after winter and also study how antecedent weather conditions affect BC K_{sat} value.
2. To collect spatially referenced soil samples from the BC, conduct laboratory experiments to determine the organic content, bulk density, moisture content, particle density, porosity and particle size distribution and compare them using spatial maps to identify patterns and establish spatial relations among them and K_{sat} .
3. To measure snow depth and density during snow events and after thaw during winter, observe spatial snow depth distribution and analyze its relationship with the other soil parameters and K_{sat} .
4. To measure surface & ground water levels and surface water, ground water & air temperatures, analyze them along with precipitation data and identify water level patterns during rain, snow melt or rain on snow melt conditions.

5.1.1 Objective 1

Infiltration rates has been spatially measured at 17 locations in the BC throughout the year using Guelph Permeameters and the K_{sat} values are arrived at through Radcliffe method and Elrick & Reynolds method. The data is analyzed for specific spatial patterns by plotting contour maps. The specific spatial and temporal patterns identified are

- 1 K_{sat} is lower in the central pathway and higher in the hills or slopes due to relative distance from the saturated zone and differences in moisture content.
- 2 K_{sat} remains stable without fluctuations overall. Any minor shift from the mean is due to antecedent dry conditions or preferential flow paths.
- 3 K_{sat} in the central pathway shows a mild rise during warm winter days and K_{sat} in the non-central pathway shows a mild decrease during winter.

5.1.2 Objective 2

- 1 Moisture content is negatively correlated with K_{sat} .
- 2 Organic content is negatively correlated with bulk density.
- 3 Moisture content is higher in the central flow path compared to the hill regions due to proximity to the saturated zone and inflow runoff.
- 4 D_{30} and D_{60} are lower in the central flow path due to sediment and suspended solids deposition.

5.1.3 Objective 3

Snow depth is measured manually inside the BC and spatial maps have been prepared using the collected data. Snow density is also measured manually. Using these information, the following inferences were deduced.

- 1 After every snow event, snow deposition is predominantly homogeneous.
- 2 Snow is pushed into the BC from the parking lots on the sides using mechanical shovels.
- 3 Snow melts at heterogeneous rates inside the BC i.e., faster in the central flow path and slopes and slower in the hills. Snow also melts faster in locations facing the south.

- 4 Snow density after rain on snow melt is 128 % higher than the snow density just after snow before snow melt.

5.1.4 Objective 4

Water level in the BC has been measured using a surface water and a ground water logger. A barometric logger is used for varying air pressure correction. A rain on snow melt event is pinned down and analyzed. The following processes were determined using the above-mentioned data.

1. Surface water level peaks during rain on snow melt events.
2. The surface water level peak is transferred to the ground water with a lag time of roughly two days during rain on snow melt events.

5.2 Recommendations for future research

5.2.1 Saturated Hydraulic Conductivity (K_{sat})

The equipment used for the K_{sat} measurement in this research is Guelph Permeameter which can measure at a minimum depth of 15 cm or higher. Therefore, this caused a limitation in terms of measuring the spatial K_{sat} values in the top 5 cm layer where the clogging could have been identified with much more certainty. However, using other equipments like the Mini Disk Infiltrometer or the Modified Philip – Dunne Infiltrometer has associated problems like the shredded wood mulch layer on the top 10 cm which has to be removed as well. Furthermore, while removing the mulch, based on observation there are always wooden particles sticking into the first 5 cm of the BC media layer which has to be removed as well. Therefore, even methods that does not require a depth of 15 cm might not be able to measure the undisturbed K_{sat} value in the BC media surface.

5.2.2 Soil parameters

As mentioned above, the K_{sat} values are measured at 15 cm depth and to be consistent all soil samples are measured at 15 to 20 cm depth as well. However, measuring soil samples at the

top 5 cm could have provided a clearer look on the soil parameters to substantiate the presence of sediments and the occurrence of clogging.

It is also recommended to auger/take more than one soil sample in the same location and mix them to get a representative sample for the location to eliminate the effects of outliers and variability.

One of the other major limitations of this study is that no chemical tests are carried out to produce a spatial data of salt concentrations. This data could have helped analyze any potential physio-chemical processes (e.g. salt loading) that could lead to structural changes in soil.

5.2.3 Snow depth

Even though snow depth has been measured at several instances and the identified patterns has been discussed, there is no temporal snow melt observations of the snow pack to substantiate the contention. Therefore, dynamic image capture cameras or laser snow depth sensors could provide with better data to verify the assertions in this research with certainty.

5.2.4 Water levels

Even though water levels have been measured continuously for about a two-year period, they have not been much useful in terms of research output other than identifying rain on snow melt water lag time because the inflow and outflow are not monitored during winter. There has been research on cold weather flow monitoring with flumes. There are also flumes with embedded heat, but they might modify the winter flow characteristics. Therefore, measuring inflow and outflow during winter will facilitate winter water balance studies.

6 Bibliography

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7 Appendices

7.1 Contour Map Generation Matlab Code

```
S = xlsread('S');
a = S(:,1);
b = S(:,2);
c = S(:,14);
[xi,yi] = meshgrid(-5:0.005:8,-4:0.005:10);
zi = griddata(a,b,c,xi,yi);
[m,n] = contourf(xi,yi,zi,100);
clabel(m, n);
```

7.2 Semi-variogram Generation Matlab Code

```
S = xlsread('F');
a = S(1:17,1:2);
b = S(:,13);
d = variogram (a,b, 'plotit',true,'nrbins',17,'anisotropy',false);
```

7.3 Assumptions for Grubbs test

Table 7-1: Ryan Joiner P value for temporal k_{sat} data (normality test)

	Ryan Joiner P Value for K_{sat}
05-Jun-17	0.01
10-Jul-17	0.01
15-Aug-17	0.01
19-Sep-17	0.01
10-Oct-17	0.074
24-Oct-17	0.01
26-Feb-18	0.01
16-May-18	0.01
8-Jun-2018	0.01

7.4 Assumptions for Wilcoxon signed-rank test

1. Independence: The K_{sat} values through Elrick & Reynolds method and Radcliffe method are independent because the infiltration rate data which is used to calculate these K_{sat} values are collected in random days with diverse weather conditions.
2. Continuity: Both the dependent variable (Radcliffe method K_{sat} for the purpose of the statistical test) is continuous data.
3. The distribution of the differences between the two related groups are symmetrical in shape: This assumption is also met, and it is verified by calculating the differences between those two values and plotting it in a histogram as shown in Figure 7-1.

Figure 7-1: Histogram of Difference in K_{sat} with curve fitting

7.5 Figures and Tables

Table 7-2: Location with their coordinates with the inlet as the origin

Point	X (m)	Y (m)
A	1.77	8.67
B	-3.69	8.53
C	-0.94	9.05
D	0.5	2.26
E	0.4	8.77
F	-3.85	-1.03
G	1.54	2.22
H	-2.3	-3.28
I	0.28	7.33
J	2.28	2.84
K	1.14	6.33
L	3.71	3.9
M	3.65	2.77
N	-3.05	5.39
O	0.85	3.05
P	1.56	3.88
Q	-0.29	2.76
R	2.38	3.64
S	-1.9	8.08
T	-3.2	3.09
U	-1.63	-0.87
V	4.97	3.43
W	5.15	2.06
X	0.66	4.23
Y	0.52	5.26
Z	-5.66	5.6
A1	-0.75	6.52
B1	3.06	1.48
C1	7.35	2.55
D1	2.52	4.85

Table 7-3: Ksat data (cm/s) – Radcliffe Method

Date	5-Jun-17	10-Jul-17	15-Aug-17	19-Sep-17	10-Oct-17	24-Oct-17	26-Feb-18	16-May-18	8-Jun-18
A	0.0024	0.0362	0.0593	0.0662	0.0113	0.0466	0.0273	0.0062	0.0007
A1	0.0014	0.0011	0.0067	0.0319	0.0030	0.0021	0.0317	0.0051	0.0034
B	0.0003	0.0016	0.0011	0.0072	0.0062	0.0034	0.0061	0.0070	0.0014
C1	0.0003	0.0066	0.0007	0.0029	0.0025	0.0033	0.0170	0.0072	0.0109
E	0.0014	0.0104	0.0074	0.0154	0.0073	0.0076	0.0012	0.0116	0.0135
F	0.0002	0.0017	0.0028	0.0172	0.0155	0.0042	0.0016	0.0004	0.0027
I	0.0006	0.0002	0.0001	0.0090	0.0006	0.0144	0.0041	0.0065	0.0007
M	0.0021	0.0002	0.0001	0.0003	0.0006	0.0012	0.0000	0.0000	0.0006
N	0.0053	0.0054	0.0134	0.0195	0.0059	0.0030	0.0118	0.0033	0.0135
O	0.0018	0.0009	0.0001	0.0022	0.0001	0.0001	0.0004	0.0002	0.0008
Q	0.0001	0.0049	0.0036	0.0020	0.0274	0.0026	0.0002	0.0038	0.0024
R	0.0044	0.0014	0.0009	0.0197	0.0059	0.0316	0.0318	0.0044	0.0010
S	0.0013	0.0003	0.0003	0.0012	0.0010	0.0022	0.0001	0.0009	0.0001
T	0.0014	0.0375	0.0121	0.0091	0.0062	0.0236	0.0054	0.0513	0.0034

V	0.0000	0.0021	0.0026	0.0014	0.0114	0.0027	0.0001	0.0086	0.0052
W	0.0012	0.0025	0.0003	0.0202	0.0066	0.0012	0.0051	0.0003	0.0004
Y	0.0016	0.0058	0.0001	0.0000	0.0014	0.0004	0.0001	0.0002	0.0001

Table 7-4: Ksat data (cm/s) – Elrick and Reynolds method

Date	5-Jun-17	10-Jul-17	15-Aug-17	19-Sep-17	10-Oct-17	24-Oct-17	26-Feb-18	16-May-18	8-Jun-18
A	0.0024	0.0362	0.0593	0.0662	0.0113	0.0466	0.0273	0.0062	0.0007
A1	0.0014	0.0011	0.0067	0.0319	0.0030	0.0021	0.0317	0.0051	0.0034
B	0.0003	0.0016	0.0011	0.0072	0.0062	0.0034	0.0061	0.0070	0.0014
C1	0.0003	0.0066	0.0007	0.0029	0.0025	0.0033	0.0170	0.0072	0.0109
E	0.0014	0.0104	0.0074	0.0154	0.0073	0.0076	0.0012	0.0116	0.0135
F	0.0002	0.0017	0.0028	0.0172	0.0155	0.0042	0.0016	0.0004	0.0027
I	0.0006	0.0002	0.0001	0.0090	0.0006	0.0144	0.0041	0.0065	0.0007
M	0.0021	0.0002	0.0001	0.0003	0.0006	0.0012	0.0000	0.0000	0.0006
N	0.0053	0.0054	0.0134	0.0195	0.0059	0.0030	0.0118	0.0033	0.0135
O	0.0018	0.0009	0.0001	0.0022	0.0001	0.0001	0.0004	0.0002	0.0008
Q	0.0001	0.0049	0.0036	0.0020	0.0274	0.0026	0.0002	0.0038	0.0024
R	0.0044	0.0014	0.0009	0.0197	0.0059	0.0316	0.0318	0.0044	0.0010
S	0.0013	0.0003	0.0003	0.0012	0.0010	0.0022	0.0001	0.0009	0.0001
T	0.0014	0.0375	0.0121	0.0091	0.0062	0.0236	0.0054	0.0513	0.0034
V	0.0000	0.0021	0.0026	0.0014	0.0114	0.0027	0.0001	0.0086	0.0052
W	0.0012	0.0025	0.0003	0.0202	0.0066	0.0012	0.0051	0.0003	0.0004
Y	0.0016	0.0058	0.0001	0.0000	0.0014	0.0004	0.0001	0.0002	0.0001

Table 7-5: Snow depth data (cm)

Year	2016			2017				2018		
Date	12/22	11/1	1/19	1/2	8/2	2/13	2/15	8/1	1/17	5/2
A	46.0	32.5	24.0	12.5	12.0	26.0	13.0	16.0	4.0	9.5
B	25.0	14.8	5.0	4.0	5.0	18.5	10.0	16.0	8.0	4.5
C	22.0	8.8	0.0	4.0	0.0	17.5	8.0	20.0	9.0	8.5
D	19.5	20.0	14.0	8.5	6.0	15.0	8.0	27.0	9.0	14.5
E	31.0	29.0	16.0	3.3	1.5	17.0	8.0	29.0	22.5	13.5
F	23.5	19.5	12.0	5.0	0.0	17.5	8.0	19.5	7.5	11.0
G	22.0	13.5	7.0	7.0	0.0	21.5	11.5	21.5	7.0	13.0
H	23.5	15.8	9.0	3.8	1.0	16.0	7.0	17.5	9.5	11.0
I	22.0	14.5	6.0	3.6	2.5	14.0	7.5	18.5	12.0	11.5
J	21.0	13.5	7.0	4.5	3.5	14.5	7.5	23.0	10.5	12.5
K	26.0	7.5	0.5	2.5	1.5	16.5	7.0	27.0	12.0	12.0
L	23.0	12.0	0.0	3.5	0.0	15.5	6.0	21.5	9.5	14.0
M	21.5	19.5	1.5	4.2	2.5	18.0	10.3	30.5	14.5	30.0
N	22.0	11.3	5.0	3.0	2.0	15.0	9.0	13.0	6.5	11.0
O	21.5	16.5	8.0	4.0	3.0	16.5	7.0	22.0	11.5	13.0
P	24.0	12.5	6.0	4.5	0.0	16.5	7.5	20.5	11.0	9.5
Q	21.0	5.0	1.0	4.5	2.0	14.0	8.0	18.5	7.0	8.5
R	22.0	13.3	5.0	3.0	0.0	15.0	6.0	19.0	8.0	7.5
S	24.0	14.5	10.0	4.5	3.5	17.0	11.0	19.5	9.5	11.5
T	16.5	0.0	0.0	2.0	0.0	12.0	5.0	13.0	5.0	5.0
U	29.5	18.9	11.0	5.0	3.0	16.0	9.0	20.5	13.5	19.0

V	22.5	15.0	8.0	4.5	0.0	16.0	7.0	35.0	20.0	22.0
W	28.0	14.0	6.0	3.5	2.0	17.5	9.5	27.0	10.0	17.0
X	21.0	15.0	6.0	4.5	3.5	17.0	7.5	25.5	11.0	12.5
Y	19.0	9.5	3.0	4.5	2.5	14.0	7.5	25.0	10.5	21.0
Z	19.0	6.4	1.0	2.5	1.0	18.0	10.0	15.0	10.0	9.5
A1	24.0	11.8	3.0	4.0	1.5	17.0	8.5	15.5	5.0	8.0
B1	25.0	12.0	3.0	4.5	1.0	18.5	9.5	19.0	4.0	10.0
C1	28.0	15.5	10.0	3.0	1.5	15.0	7.5	21.5	5.0	10.0
D1	21.0	9.2	1.0	4.0	2.0	16.0	7.5	19.0	7.0	10.0

Table 7-6: Soil Particle Distribution data by location (Weight in grams).

	1- 1/2	3/4	3/8	4	10	Pan	10	16	30	50	100	200	Pan
A	0.3	0.3	7.7	38.2	74.8	301.7	0.6	39.0	62.4	91.6	97.5	4.9	6.1
A1	0.0	0.0	1.9	19.5	62.0	335.5	0.4	31.4	48.0	89.2	108.3	29.4	29.9
B	0.0	0.0	3.8	12.0	0.0	325.8	0.5	30.7	56.2	91.3	86.6	13.0	22.0
C1	0.0	0.0	4.3	25.7	83.1	280.2	1.4	82.4	68.5	60.2	58.7	28.0	16.3
E	0.0	0.0	1.6	16.7	40.5	334.3	0.7	26.5	46.9	145.9	120.8	11.8	14.7
F	0.0	0.1	6.1	13.0	64.3	336.4	0.9	45.0	53.9	69.7	84.2	68.0	16.3
I	0.0	0.1	1.7	16.5	45.4	326.0	0.4	26.5	46.6	125.8	98.6	15.2	12.5
M	0.0	0.0	1.2	19.6	63.9	271.7	0.5	31.6	42.7	68.6	77.6	23.8	27.5
N	0.0	0.0	0.9	13.4	37.9	319.9	0.4	32.1	60.4	111.1	85.8	14.2	14.9
O	0.0	0.2	0.9	14.1	50.1	348.4	0.8	32.9	45.1	87.3	107.7	54.6	21.9
Q	0.1	0.1	1.0	25.2	117.7	293.3	1.1	61.8	69.4	52.3	106.7	3.8	0.0
R	0.0	0.0	4.1	24.7	65.2	336.9	0.9	64.7	57.7	104.6	98.1	24.6	22.3
S	0.0	0.0	3.5	8.0	25.0	303.9	0.4	22.3	46.8	84.3	101.2	24.2	26.3
T	0.0	0.0	8.9	5.2	52.7	363.7	1.3	90.9	70.9	72.3	81.9	43.2	38.4
V	0.0	0.0	3.1	12.2	50.7	354.9	1.0	67.2	57.7	96.6	108.8	36.7	21.3
W	0.0	0.1	6.8	15.0	48.6	324.1	0.5	36.0	49.1	76.5	91.0	42.7	29.8
Y	0.0	0.1	0.7	19.2	43.1	327.1	0.8	29.6	48.1	89.5	99.1	28.7	34.4

Table 7-7: Soil Properties data by location.

Point	Bulk Density	Moisture Content	Organic Content	Particle Density	Porosity
Unit	Kg/m3	%	%	Kg/m3	%
A	1892.59	14.90	6.10	2749.87	31.18
A1	1799.87	17.83	6.07	3206.13	43.86
B	643.01	19.54	4.95	2771.09	76.80
C1	707.03	16.00	6.62	3302.09	78.59
E	609.89	14.42	5.25	3010.02	79.74
F	1788.83	18.65	8.14	2891.51	38.14
I	1818.63	23.25	4.71	3163.95	42.52
M	1825.26	26.26	5.61	3395.56	46.25
N	1698.31	20.69	7.91	3107.89	45.35
O	1794.35	25.39	4.72	3333.91	46.18
Q	1941.16	19.06	2.11	2797.07	30.60
R	1767.86	15.72	6.22	3432.56	48.50
S	1793.24	24.33	4.70	3101.31	42.18
T	1725.91	17.62	6.81	3074.32	43.86
V	1878.24	18.41	4.74	5152.62	63.55

W	1894.80	20.08	5.40	3144.17	39.74
Y	1802.08	20.93	5.44	2842.12	36.59

Table 7-8: Locations with D_{60} , D_{30} , D_{10} , C_u and C_c .

Location	D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	C_u	C_c
A	1.10	0.34	0.19	5.95	0.57
A1	0.58	0.23	0.10	6.11	0.96
B	0.50	0.24	0.13	4.00	0.88
C1	1.40	0.40	0.14	10.00	0.82
E	0.51	0.27	0.17	3.09	0.87
F	0.70	0.21	0.10	7.37	0.63
I	0.54	0.28	0.17	3.27	0.88
M	0.78	0.24	0.10	8.21	0.78
N	0.59	0.30	0.17	3.47	0.87
O	0.50	0.20	0.10	5.26	0.84
Q	1.60	0.40	0.20	8.21	0.50
R	0.85	0.30	0.16	5.31	0.64
S	0.48	0.21	0.10	5.00	0.98
T	0.90	0.25	0.09	10.59	0.78
V	0.68	0.24	0.13	5.44	0.68
W	0.60	0.21	0.09	6.67	0.78
Y	0.55	0.22	0.09	6.29	1.01

Figure 7-2: Soil particle distribution results in % – location M

Figure 7-3 Soil particle distribution results in % – location A1

Figure 7-4 Soil particle distribution results in % – location S

Figure 7-5 Soil particle distribution results in % – location W

Figure 7-6 Soil particle distribution results in % – location F

Figure 7-7 Soil particle distribution results in % – location Y

Figure 7-8 Soil particle distribution results in % – location O

Figure 7-9 Soil particle distribution results in % – location T

Figure 7-10 Soil particle distribution results in % – location V

Figure 7-11 Soil particle distribution results in % – location R

Figure 7-12 Soil particle distribution results in % – location C1

Figure 7-13 Soil particle distribution results in % – location N

Figure 7-14: Soil particle distribution results in % – location I

Figure 7-15: Soil particle distribution results in % – location E

Figure 7-16: Soil particle distribution results in % – location Q

Figure 7-17: Soil particle distribution results in % – location B

Figure 7-18: Soil particle distribution results in % – location A

Figure 7-19: Moisture Content Spatial map - All locations

Figure 7-20: Ksat - Radcliffe Method Spatial map - All locations

Figure 7-21: Organic Content spatial map – All locations

Figure 7-22: Bulk Density spatial map – All locations

Figure 7-23: Porosity Spatial map - All locations

Figure 7-24: Particle Density spatial map – All locations

Figure 7-25: Cu spatial map - All locations

Figure 7-26: Cc Spatial Map - All locations

Figure 7-27: D_{60} Spatial Map – All locations

Figure 7-28: D_{30} Spatial Map – All locations

Figure 7-29: Ksat Elrick and Reynolds method average

Figure 7-30: June 5 & 6, 2017 - Ksat Radcliffe method

Figure 7-31: July 10 & 11, 2017 - Ksat Radcliffe method

Figure 7-32: August 15 & 16, 2017 - Ksat Radcliffe method

Figure 7-33: September 19 & 20, 2017 - Ksat Radcliffe method

Figure 7-34: Oct 10 & 11, 2017 - Ksat Radcliffe method

Figure 7-35: Oct 24 & 25, 2017 - Ksat Radcliffe method

Figure 7-36: February 26 & 27, 2018 - Ksat Radcliffe method

Figure 7-37: May 16 & 17, 2018 - Ksat Radcliffe method

Figure 7-38: June 8, 2018 - Ksat Radcliffe method

Figure 7-39: January 11, 2017 – Snow Depth

Figure 7-40: February 1, 2017 – Snow Depth

Figure 7-41: February 8, 2017 – Snow Depth

Figure 7-42: February 13, 2017 – Snow Depth

Figure 7-43: February 15, 2017 – Snow Depth

Figure 7-44: January 8, 2018 – Snow Depth

Figure 7-45: January 17, 2018 – Snow Depth

Figure 7-46: February 5, 2018 – Snow Depth

Figure 7-47: Overall Average – Snow Depth