Laboratory Study on the Hydraulic Performance of Bioretention for Stormwater Management in Cold Climates

by

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ABSTRACT

Bioretention has shown effective stormwater peak flow and volume reduction in warm and temperate climates. However, the applicability of bioretention for successful stormwater management in cold and semi-arid regions such as Edmonton is still not well understood. Four large bioretention columns were designed for this study and set up in a temperature-controlled laboratory with the capacity of lowering temperature to – 20 °C. Designed storm events were applied and monitored for 1st summer operation, one winter exposure and 2nd summer operation. Synthetic stormwater was applied weekly in summer conditions to investigate the hydraulic performance of two different soil types, with and without an internal water storage layer.

Column 1 and Column 3, with less porous soil media (50.8% sand, 29.4% silt, and 19.8% clay), were shown to effectively attenuate peak flow for 1:2 year events, with a mean peak flow reduction of 83% and 91% respectively in 1st summer, and 77% and 73% respectively in 2nd summer. Column 2 and Column 4, with more porous soil media (67.2% sand, 19.6% silt, and 13.2% clay), maintained high hydraulic conductivity (9.6 cm/hr and 9.1 cm/hr respectively) after 2nd summer operation. Under winter conditions, columns with more porous soil media retained more volume of water within the columns, took less time for soil thawing and water breakthrough, and ponding vanished faster over frozen soil than columns with less porous soil media. After columns underwent an extreme winter condition of columns frozen at −20 °C air temperature three times, their hydraulic performance was able to rebound quickly. All columns successfully managed 1:2 year events in terms of the infiltration rate, ponding depths and durations. Preliminary results also showed that both less and more porous soil media have the potential to accept and drain the less frequent, large volume events (1:5 and 1:10 year events).

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CHAPTER 1: INTRODUCTION

1.1 Background

Hydrological conditions have been significantly impacted in urban environments due to the increase of impervious surfaces. Urbanization has created impervious surfaces, resulting in increased stormwater peak runoff volume, increased flooding, decreased evapotranspiration, and decreased groundwater recharge. Bioretention is a low impact development (LID) feature in urban environments that have consistently been growing in popularity in recent years (Bratieres et al., 2008; Li & Davis, 2009). Bioretention is an at-source treatment method for stormwater that reduces peak runoff by providing sufficient infiltration and evapotranspiration capacity in order to mimic predevelopment hydrological characteristics (Davis et al., 2009). It also captures or degrades stormwater pollutants by various physical, chemical, and biological processes such as filtration, sedimentation, adsorption, mineralization, biotransformation, and plant uptake.

Bioretention facilities incorporate the natural infiltration capacity of a soil media mixture containing soil, sand, and gravel, along with the evapotranspiration capability of native vegetation. They can directly recharge underlying aquifers or have an impervious base and underdrain leading to existing stormwater catchment systems. Investigations have demonstrated that in warm and temperate regions bioretention can improve hydraulic and water quality in comparison to conventional stormwater management practices (Davis et al., 2009; He & Davis, 2011; Brown & Hunt, 2012). However, there is lack of knowledge and experience on the performance of bioretention in cold and semi-arid regions like Edmonton, Alberta. In cold climates, conditions such as cold temperatures, frozen soils during winter, deep frost lines, repeating freeze-thaw cycles, short growing seasons, and significant snowmelt volume make bioretention application difficult. The challenges of bioretention application result from these characteristics of cold climates include reduced biological processes, reduced soil infiltration, high concentrations of sediment and pollutants during first flush in spring, impact of salt and de-icing agents on vegetation, high runoff volume during snowmelt, ice blocked inlets, and soil compaction. Compare to other bioretention researches in cold climates, winter in Northern Prairies regions such as Edmonton is long and dry, with about 265 to 245 frost days. The average annual precipitation of Edmonton is 477 mm, of which approximately 23% occurs as snow (Environment Canada, 2018). Also, Edmonton experiences intermittent warming periods during the winter, as temperatures temporarily rise above zero for a few days and occur several times every year resulted in multiple freeze-thaw cycles. Few studies have tested the hydraulic response in the presence of an anoxic zone and the performance under multiple freeze-thaw cycles with cold season conditions that reach -20 °C. This research will address these issues with application of bioretention systems in cold climates, and investigate the cold climates impacts on hydraulic performance and function of bioretention cells.

1.2 Research Objectives

The goal of the research was to investigate the effectiveness of bioretention system for stormwater quantity management in cold climates region. The main objectives of this thesis were:

1. To investigate local soil amendment options for bioretention cells with the purpose of performing well both in summer and winter temperature conditions.
2. To investigate the effect before and after a cold weather exposure on hydraulic performance of bioretention cells, including peak flow reduction, peak delay, ponding, and saturated hydraulic conductivity.
3. To evaluate the hydraulic performance under winter conditions when subjected to freeze-thaw cycles and large flows of spring runoff.
4. To evaluate the hydraulic performance when using a submerged anoxic zone at the bottom of bioretention cells.

5. To use the obtained data to evaluate the potential of bioretention as a stormwater best management practice for small volume, more frequent events and large volume, less frequent events.

1.3 Thesis Layout

This thesis consists of five chapters, each of which will contribute to the overall main objectives of the research. Chapter 2 provides an in-depth literature review on the hydraulic performance of bioretention for stormwater management in cold climates regions. Chapter 3 presents the materials and experimental methods used to conduct laboratory experiments and the analyses. Chapters 4 presents and discusses the results from the laboratory experiments. Lastly, Chapter 5 outlines the major conclusions of the project, and provides recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

Bioretention hydraulic performance will be discussed in four aspects: stormwater peak flow reduction and lag time, volume reduction, factors affecting hydraulic performance in cold climates, and the long-term performance. The section 2.1 to section 2.4 in this chapter were previously published in the Journal of Frontiers of Environmental Science & Engineering in 2017, titled “A critical literature review of bioretention research for stormwater management in cold climate and future research recommendations” (Kratky et al., 2017). I wrote the part of hydraulic performance.

2.1 Peak Flow Reduction and Lag Time

Bioretention systems smooth stormwater runoff hydrographs by reducing peak flow, which reduces erosion, scour, and sediment transport to the receiving stream (Davis, 2008). Bioretention is a buffer to runoff peak flow by: forming ponding water on the surface, retaining water within the media and releasing it slowly, exfiltration and evapotranspiration, or by a combination of the above factors. Different peak flow reduction rates have been reported and range from 44% (Davis, 2008) to 95% (Ping &

Tao, 2011). Bioretention systems also delay the peak flow of runoff and this is often reported in different forms, such as lag time, lag coefficient, peak delay or peak delay ratio (Davis, 2008; Roseen et al., 2009). Lag time, expressed in minutes, is the time from the beginning of inflow into the bioretention cell to when outflow reaches the underdrain and has been observed to range from approximately 60 to 600 min (Khan, 2011; Muthanna et al., 2008). Lag coefficient is the ratio of effluent hydrograph time to effluent hydrograph centroid over influent hydrograph time to influent hydrograph centroid and can range from 1.3 to 2.0 (Roseen et al., 2009). Peak delay ratio is calculated as the elapsed time of outflow peak over the elapsed time of inflow peak, and a target ratio of 6 has been set by some research (Davis, 2008).

2.2 Stormwater volume reduction

Stormwater volume reduction is a result of bioretention systems' media storage capacity, evapotranspiration, exfiltration, and ponding water depth (He & Davis, 2011). Media porosity has water storage capacity and when the soil is saturated, this capacity is referred to as maximum retentive capacity, which may be reached during a large rainfall event. However, in the long term (e.g. one day after the rain event), once macropores have drained of water, the soil's field capacity is most important for stormwater volume reduction (Nyle & Ray, 2008). The water remaining in the soil's micropores is then reduced via evapotranspiration or infiltration as capillary water. Therefore, the volume of the micropores influences the volume reduction rate. This can partially explain why sandy clay loam (i.e. more micropores) media can have a higher volume reduction rate than loamy sand media (He & Davis, 2011). Deeper bioretention media can also have a higher volume reduction rate due to having more micropores in certain media. For example, bioretention systems with deeper media depths (0.9 m) had significantly more outflow reduction than shallower media (0.6 m) (Brown & Hunt, 2012).

Evapotranspiration (i.e. the combination of evaporation and transpiration) as a stormwater volume reduction mechanism varies between different bioretention systems. Evapotranspiration is influenced by climate and weather, but also by heat supply (i.e.

primarily solar radiation). For example, nighttime evapotranspiration is only about 1.7%–14% of 24 hour evapotranspiration (Malek, 1992). Evapotranspiration is also influenced by the type of soils within and surrounding the system. Therefore, a variety of evapotranspiration rates within bioretention have been reported by various researchers; while evapotranspiration accounted for only 3% of total volume reduction in one study (Brown & Hunt, 2012), it has also been observed to release 50% of the inflow as evapotranspiration in a different study (Sharkey & Hunt, 2005). Evapotranspiration is a slow process and could take 30 days to regain 1 inch of field capacity (Palhegyi, 2010). However, compared to percolation, it functions anytime there is heat and the total effect might be significant.

Exfiltration is influenced by the native soil's texture and moisture that surrounds bioretention cells. Bioretention systems surrounded by soil with high conductivity (e.g. sandy clay loam) will encourage lower outflow in the underdrains (He & Davis, 2011). Depending on the native soil type, only 25% of inflow might be exfiltrated (Sharkey & Hunt, 2005) or it may be predominantly exfiltrated out the bottom compared to the sides (He & Davis, 2011). Volume reduction efficiency of bioretention not only depends on the system's design, which affects the above mechanisms, but also on rainfall event intensity. In Trowsdale and Simcock's (2011) research in Auckland, New Zealand, the average ratio of outflow to inflow was 41%, and the smallest volume reduction efficiencies corresponded to the largest rainfall events. In Khan et al.'s (2012a) research in Calgary, Canada, for events less than 32 mm, bioretention captured 100% of the runoff, but for events with long return periods, the removal rate decreased to 91.5%. Stormwater volume reduction relies heavily on both the hydrological conditions and hydraulic performance of bioretention.

2.3 Factors Affecting Hydraulic Performance in Cold Climates

The hydraulic performance of bioretention can be evaluated by several indicators including, peak flow reduction, lag time, the time delay of the flow rate, and stormwater volume reduction, which can all be quite variable based on bioretention design and rainfall event. These factors are impacted even more under cold climate conditions and when subjected to snowmelt, as infiltration and transpiration are limited and spring runoff consists of significantly higher volumes of water to treat. Cold climates impact stormwater volume reduction efficiencies by causing significantly lower evapotranspiration rates, dormancy in plants and therefore low water uptake (Geheniau et al., 2015; Muthanna, 2007; Paus et al., 2014), and decreased soil pore volume due to freezing water creating channelized flows (Muthanna, 2007). To counteract this decrease in hydraulic performance, bioretention cells designed for cold climates should employ a smaller catchment area relative to its surface area compared to facilities designed for warm climates.

A study conducted in North Carolina supports the conclusion of bioretention having poor hydraulic performance in cold climate as the ratio of stormwater in outflow to inflow was 0.07 in summer and 0.54 in winter (i.e. significantly more was retained in summer) which was possibly due to the lower evapotranspiration rate and exfiltration rate in the winter (Hunt et al., 2006). Reduced hydraulic bioretention performance in cold climate has also been observed in other studies; for example, total volume reduction decreased from 25% in August to 13% in April (Muthanna et al., 2007b) and total volume reduction declined from 59.7% ± 3.3% to 35.0% ± 11.6% from the warm to cold season, respectively (Geheniau et al., 2015). Winter conditions also decreased average peak flow reductions from 42% in summer to 27% in winter and the hydraulic detention time decreased with temperature and snowmelt events generally decreased hydraulic performance (Muthanna et al., 2008). If snow storage is included in the bioretention design, issues such as snow depth (not to exceed 2 m) (Muthanna et al., 2007c) and soil compaction are of concern because they may significantly reduce hydraulic performance as well.

In cold climate, the moisture in the soil can freeze, block soil pores, and reduce infiltration rates. The frost formed within the soil can be concrete, granular, or porous: concrete frost forms in saturated soils and permits little water movement due to formation of an ice lens (Muthanna, 2007); granular frost forms in unsaturated soils and maintains high permeability (LeFevre et al., 2009); porous frost is the most permeable type

(LeFevre et al., 2009). Interestingly, the hydraulic conductivity of soil with granular or porous frost can be greater than unfrozen soils due to the presence of preferential flow paths (LeFevre et al., 2009; Stoeckeler & Weitzman, 1960). LeFevre et al. (2009) tested hydraulic conductivity of bioretention in cold climate and concluded that the most important design parameter is the ability of the media to drain efficiently such that granular or porous frost forms rather than concrete. Concrete frost formation in the surface can restrict water movement and impact the application of bioretention in cold climates. Freeze-thaw cycles, however, have been observed to have a beneficial effect on increasing infiltration by generating greater pore volumes during freezing through expansion of the water in the soil, which do not return to their original volume when the water thaws (Denich et al., 2013). A study in New Hampshire (Roseen et al., 2009) illustrated the same trend of increased infiltration rates in winter. Another explanation of greater hydraulic conductivity in winter is that the organic matter has a macropore structure that helps maintain infiltration even in partially frozen soils (Dietz, 2007).

Many bioretention studies in cold climate have selected coarse materials as the filter media (Blecken et al., 2011; Denich et al., 2013; Geheniau et al., 2015; LeFevre et al., 2009; Muthanna et al., 2007a; Muthanna et al., 2007b; Muthanna et al., 2008; Søberg et al., 2017) to avoid ice blockage but also to prevent the higher TSS concentrations in snowmelt from blocking pore spaces. For instance, several studies in Norway selected low clay content and a high sand (90%) content soils for bioretention units to improve winter infiltration (Muthanna et al., 2007a; Muthanna et al., 2007b; Muthanna et al., 2008). Moghadas et al. (2016) conducted a laboratory scale study on infiltration of water into two frozen engineered bioretention soils (one with coarse soil and one with fine soil). It was found that finer, more compacted soils reduced porosity, extended water breakthrough times, and steadied percolation rates. Fine solids entering the bioretention facility also must be controlled by pre-treatment (Moghadas et al., 2016). One concern of using coarse media (sand) and less clay content in cold climates is that heavy metals and TSS removal may be impaired. Blecken et al. (2011) used coarse filter media in a 10-week laboratory bioretention column study. This media consisted of two 400 mm layers: an upper sand layer (< 4% silt and 14% fine gravel (2–4 mm), D50 = 620 μm) and lower fine to medium sand layer (D50 = 280 μm) with 100 mm of topsoil on the surface to enhance sorption capacity. Heavy metals were effectively removed and most retained dissolved metals were captured by the thin layer of topsoil, even at low temperatures (2 °C). It is recommended that topsoil or mulch on the surface be used to increase sorption in the media. Similarity, Søberg et al. (2014) also found that large grain sizes and therefore pore sizes do not seem to have a negative impact on bioretention performance as similar TSS and metal removal efficiencies are seen in finer bioretention media subjected to warmer conditions.

Designing bioretention for cold climates is especially challenging due to the inherent contradiction between designing for stormwater quantity while still maintaining sufficient water quality improvement. By utilizing coarser media, water quality improvement may be sacrificed and by using fine media to improve contaminant removal, concrete frost would form in cold climate and the system's hydraulic performance would be inadequate. The goal of research on bioretention in cold climate is to strike a balance between these two vital aspects of stormwater runoff treatment. It is also critical to analyze the specific goals the system is being designed to achieve as most sites have diverse characteristics and treatment requirements. For example, perhaps flooding is the major concern in a region; therefore, peak flow and volume reduction are the most important design objectives and water quality improvement might not be a priority.

A study of field and column experiments in Calgary, Canada, demonstrated good hydraulic performance in both summer and winter conditions, with the average peak flow reduction of 96.2% in summer and 93.5% in winter (Khan et al., 2012b). In this study, cold conditions had a significant effect on hydraulic performance (i.e. lower volume reduction, lower peak flow reduction, and longer lag times) during intense rainfall events. An analysis of soil moisture in this study showed that the frozen surface soil can change the water path through the bioretention cell so that the water moves laterally until finding a preferential pathway vertically (Khan et al., 2012b). This causes less soil volume wetting and, therefore, higher effluent peak flow rates, less water volume retention, and decreased permeability causing longer peak delays. However, these impacts were only seen up to a certain media depth; the sensors in Khan's study (2012b) showed no variation between warm and cold weather at 300 mm and 500 mm depths meaning that the bioretention media in cold climate is not the issue, but rather, the surface boundary effects caused by frozen media. This is a common phenomenon in prairie regions under freeze-thaw cycles. Local conditions need to be considered when designing a bioretention system.

2.4 Long Term Performance (Hydraulic Conductivity)

The main concern for long-term peak flow reduction and hydraulic performance in bioretention is reduced hydraulic conductivity due to compaction and clogging in the media (Khan et al., 2012b; Le Coustumer et al., 2012). However, vegetation growth could help to maintain the soil structure and enhance infiltration without requiring much maintenance (Stephens et al., 2012). Various studies have reported a diminishing trend in hydraulic conductivity over a period of operation (Hatt et al., 2008; Khan et al., 2012b; Le Coustumer et al., 2007; Le Coustumer et al., 2012). A large-scale column study in Australia observed clogging over 72 weeks causing the hydraulic conductivity to decrease by an average of 73% (Le Coustumer et al., 2012). This research also evaluated the impact of plant species and system catchment size on hydraulic performance and concluded that plants with thick roots tend to maintain the conductivity and that small systems are more prone to clogging than large systems due to their high loading rate. Interestingly, hydraulic conductivity has been seen to initially decrease for a period and then recover to an average value (Hatt et al., 2008; Le Coustumer et al., 2012; Li & Davis, 2008). The initial decline of hydraulic conductivity results from compaction of bioretention media under hydraulic loading. After this decline, the vegetation growth and root systems improve the porosity of the media and create new pathways for water movement (Khan et al., 2012b).

However, an increase in saturated hydraulic conductivity (K_{sat}) was observed in a bioretention system in Minnesota, United States, over four-years of operation (from 2006 to 2010), and there was a positive relationship between K_{sat} and service time, with a slope of 10.2 ± 2.4 $\text{cm}\cdot\text{h}^{-1}$ per year (Paus et al., 2013). This relationship is likely attributed to 1) reduced bulk density, 2) increasing organic matter, 3) development of macropores by earthworm activities and plant roots, and 4) freeze-thaw cycles (Paus et al., 2013).

Sediment accumulation over time could be of concern as it will lead to clogging in bioretention cells. Khan et al. (2012b) used column experiments to mimic 20 years of equivalent TSS loading to analyze long-term performance; K_{sat} decreased in the first period of sediment accumulation but ultimately remained constant. This indicates that bioretention cells could maintain constant hydraulic conductivity after long-term operation without any maintenance and that surface filtration (top 20 cm of these columns) is the primary function of sediment capture (Khan et al., 2012b). Considering field experiments have better plant maturity and larger catchment sizes, acceptable and stable hydraulic performance can be expected for long-term operation. A bioretention cell located in Oslo, Norway, reported that after 7-years of operation, 98% of runoff infiltrated the cell, and it maintained sufficient K_{sat} of 45 ± 15.3 $\text{cm}\cdot\text{h}^{-1}$ (Paus et al., 2016). Even in cold regions, although vegetation becomes dormant and therefore pore reopening by root growth is diminished, the freeze-thaw cycle can counteract this adverse effect (Paus et al., 2013).

Additional organic matter in the media has generally been observed as beneficial for physical properties and the slowing of media compaction, which ultimately maintains hydraulic performance. However, in some long-term operation studies (Le Coustumer et al., 2012; Paus et al., 2016), bioretention cells with organic matter have poor performance compared to cells without it. This may be because the media with compost tends to be more non-uniform and has an increased bulk density due to compaction. Additionally, high compost content in the media could lead to phosphorus leaching (Bratieres et al., 2008; Fletcher et al., 2007b) and needs further investigation.

2.5 Intermittent warming periods in Edmonton's winter

Edmonton has a continental climate characterized by cold, dry and long winter with the daily average temperature of -10.4 °C for January from 1971-2010 (Environment Canada, 2018). Edmonton also gets warm winter days during the winter time, which brings temperatures above freezing for a few days and occurs several times every winter. This phenomenon results in frequent freeze-thaw cycles that lead to snowmelt events several times during the winter. APPENDIX A provides historical temperature data for Edmonton's winter (from mid-November to next year's mid-March) from 2005 to 2015. The days with the daily maximum temperatures above 0 °C were defined as warm winter days and are bolded in APPENDIX A. Table 1 summarizes how often the warming periods appeared and how long the duration was in Edmonton's winter during this period. From 2005 to 2015 there were about 30-53 days in winter in which the daily maximum temperature is above freezing. The frequency of warming periods is 8-17 times per winter. The duration of warming periods is from 1-16 days with a typical length of 1-3 days. Bioretention designs in cold climate should be derived from both melt patterns and snow storage requirements, rather than just account for a large amount of snowmelt at the end of the winter (Khan, 2011).

Table 1: Frequency and duration of daily max temperatures above 0 °C for Edmonton’s winter (mid-November to mid-March)

Warming period duration (day)	**Frequency**									
	2014 to 2015	2013 to 2014	2012 to 2013	2011 to 2012	2010 to 2011	2009 to 2010	2008 to 2009	2007 to 2008	2006 to 2007	2005 to 2006
1	4	5	5	3	2	4	1	3	6	2
2	3	4	3	4	-	-	3	4	1	2
3	3	1	2	3	3	-	4	2	3	2
4	-	1	5	1	1	1	1	2	2	1
5	2	1	1	1	-	1	1	1	1	1
6	-	-	-	1	1	1	-	-	2	1
7	-	2	-	-	-	-	1	-	1	1
8	-	-	-	2	-	2	-	1	-	1
9	-	-	-	1	1	-	-	-	-	-
10	-	-	-	-	-	-	-	-	-	-
11	1	-	-	1	-	-	1	1	-	-
12	-	-	-	-	-	-	-	-	-	1
13	1	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	1	-	-	-	-
Number of warm winter days[1]	53	39	42	71	30	51	46	49	49	54
Number of frequency[2]	14	14	16	17	8	10	12	14	16	12

[1] For column 2014 to 2015, 53 days (number of warm winter days) = 1 day × 4 + 2 days × 3 + 3 days × 3 +5 days×2 + 11 days×1 + 13 days × 1

[2] For column 2014 to 2015, 14 times (number of frequency) = 4 + 3 + 3 + 2 + 1 + 1

CHAPTER 3: MATERIALS AND EXPERIMENTAL METHODS

3.1 Growth Media Characteristics

A topsoil equivalent to class B topsoil (Edmonton's Landscaping Design and Construction standard) was obtained from IWG Soil Products and was modified with different soil amendments for this study. The texture classification of this topsoil was analyzed by Exova laboratory, Edmonton, Canada, and the testing results indicate that the texture of the topsoil is silty clay loam. The particle-size analysis of the topsoil on a mass basis was determined using the hydrometer method. United States Department of Agriculture (USDA, 2014) has developed a system of soil texture classification to define various types of soils. The classification of a typical soil sample is defined by the mass percentage of sand (particle size>50 μm), silt (particle size=2-50 μm), and clay (particle size< 2 μm). Figure 1 shows the soil textural triangle.

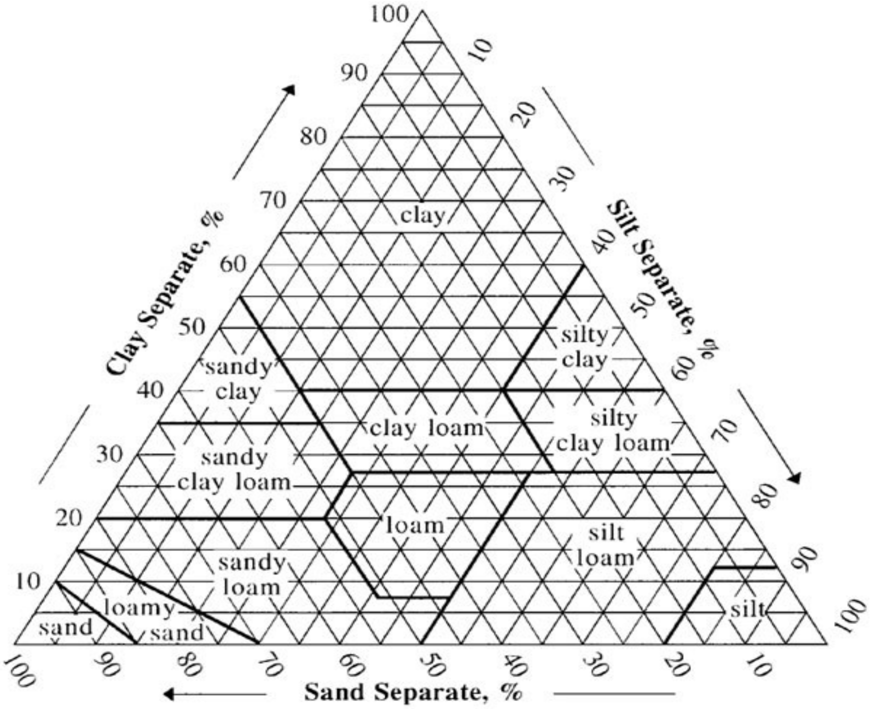


Figure 1: Soil textural triangle (USDA, 2014)

In general, soils in Edmonton area mainly belong to silt loam and silty clay loam. Table 2 provides the typical hydraulic conductivity for different soils. The values in Table 2 are for general guidance only, as the hydraulic conductivity can vary widely with local soil conditions. The hydraulic conductivity of local soils is substantially lower than the City of Edmonton required hydraulic conductivity of 2.5 cm/hr (CoE 2014). To achieve the hydraulic conductivity requirement of 2.5 cm/hr for LID facility, the topsoil was modified with play sand (Sil 8 sand, $d_{50} = 0.7$ mm, Edmonton Sil Industrial Minerals) by a mass ratio of 40% sand/ 60% topsoil (henceforth referred to as **soil media A**) and 60% sand/ 40% topsoil (henceforth referred to as **soil media B**). The texture classification of these two soil media is shown in Table 3. Soil media A (Figure 2a) represents a less porous soil media which is typically used in landscaping in Edmonton area. Soil media B (Figure 2b) represents a more porous soil media for achieve the high infiltration rate for cold climates. The particle size distribution of these two types of soil was analyzed by the wet sieve method and measured by Exova laboratory, Edmonton, Canada (Figure 3).

Table 2: Soil Textural classes and related saturated hydraulic conductivity (K_{sat}) (USDA, 2014)

Texture	Textural Class	K_{sat} (cm/hr)
Coarse sand	Coarse	> 50.8
Sands **Loamy sands**	Coarse	15.2-50.8
Sandy loam **Fine sandy loam**	Moderate coarse	5.1-15.2

Very fine sandy loam **Loam** **Silt loam** **Silt**	Medium	1.5-5.1
Clay loam **Sandy clay loam** **Silty clay loam**	Moderate fine	0.5-1.5
Sandy clay **Silty clay** **Clay**	Fine and very fine	0.2-0.5

a) Soil media A

b) Soil media B

Figure 2: Pictures of soil media

Table 3: Bioretention soil media texture

Media	% Sand (>50 µm)	% Silt (2-50 µm)	% Clay (<2 µm)	Texture
Soil media A	50.8	29.4	19.8	Loam
Soil media B	67.2	19.6	13.2	Sandy Loam

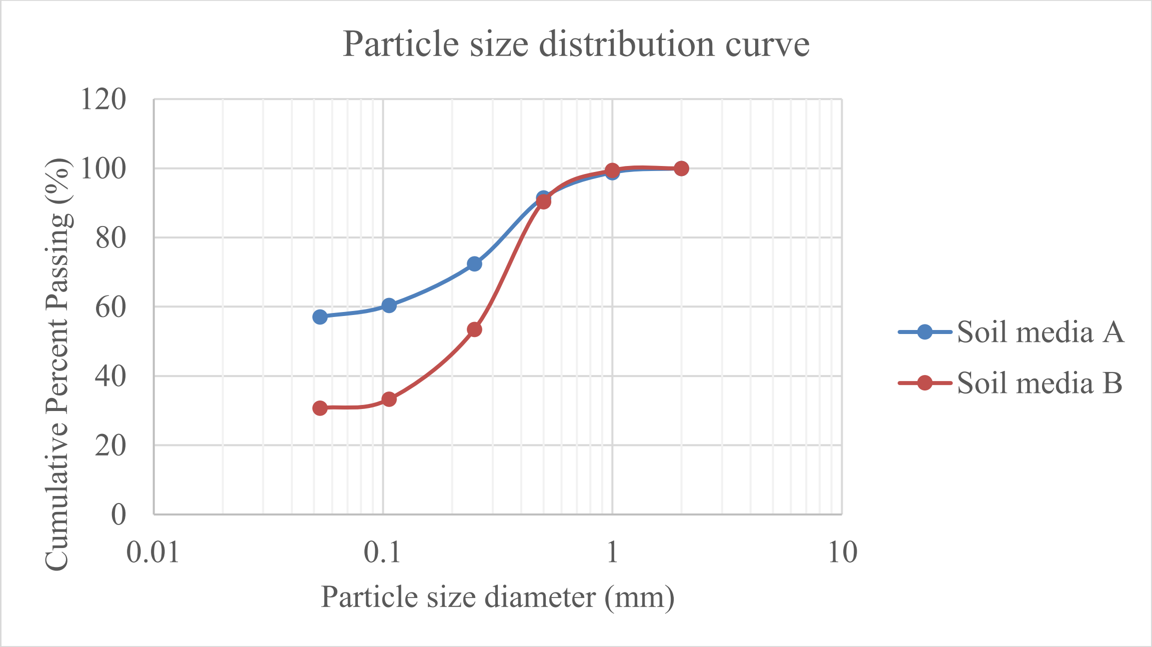
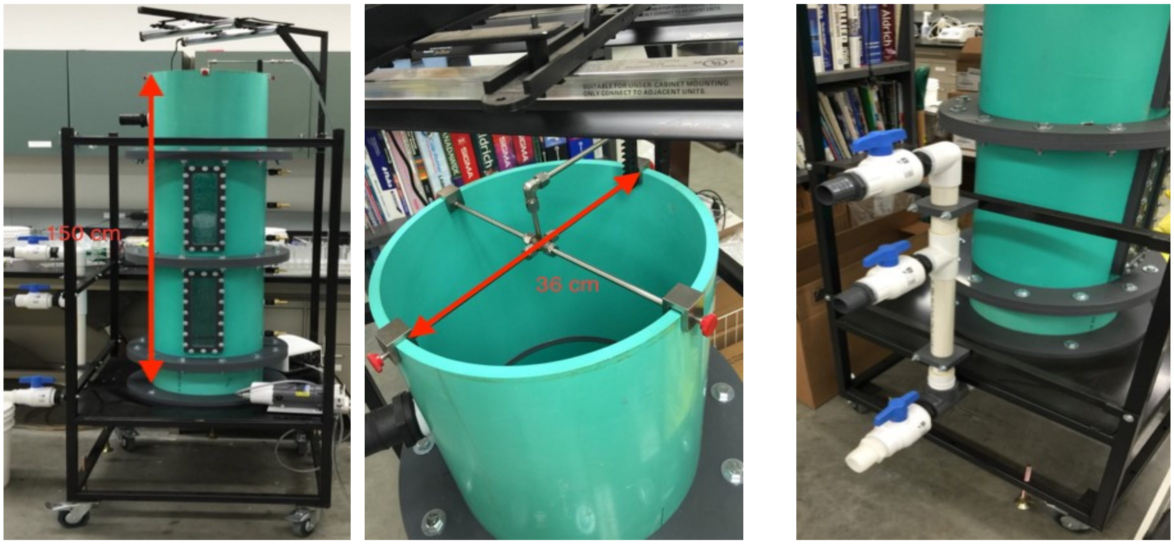


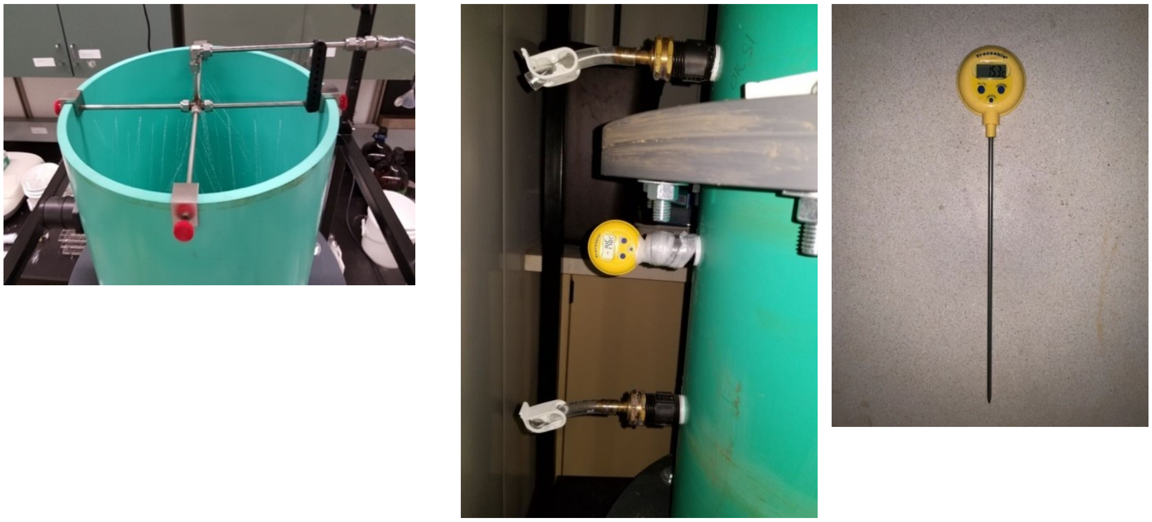
Figure 3: Particle size distribution curve of two types of soil media

3.2 Bioretention Columns

Four large bioretention columns were designed as filtration-only bioretention cells that captured all the runoff to drain to the outlet for water quantity and quality analysis. As the primary hydraulic function of this type of bioretention cells is to filter the rainwater, it is a conservative design with respect to volume reduction. Columns were constructed of polyvinyl chloride (PVC) pipes and coated with an inert waterproof sealant. Columns were assembled vertically by four sections of pipes held together with flanges. The inner diameter of the pipes is 36 cm and the total height is 150 cm (Figure 4). To supporting such a heavy system, a frame was designed and welded on each column. Wheels were also added so columns could be moved easily into and out of the cold room. A unique water distribution system was designed for this study (Figure 4b). Four 6 mm diameter steel tubes composed this system with twelve 1mm holes on each steel tube. This water distribution system functions under low water pressure, distributes water evenly across the area of the column and does not retain total suspended solids (TSS) in the steel tubes (Figure 4d). Figure 4c shows raised outflow ports designed to create an anoxic zone. A thermometer (Traceable Lollipop Thermometer, Fisher Scientific) was installed in each column on the middle sampling port along the side (Figure 4e). The sensor length of thermometer is 20.3 cm (Figure 4f) which makes the thermometer can reach the soil core and therefore test soil core temperature.



a) Large column b) Large column c) Raised outflow ports



d) Water distribution e) Thermometer in the column f) Thermometer

Figure 4: Large columns used in this study

In field studies, distinct hydrographs can be challenging to identify during frequent rainfall events, as it is difficult to identify the beginning and end of the events so that the runoff captured from the event might still be slowly discharging over the time of the subsequent event (Fassman & Blackbourn, 2010). Therefore, laboratory scale experiments have control on inflow and outflow to identify distinct hydrographs. Also, laboratory experiments have more control on temperatures and could be conducted several times within a short time, which is allowed to determine parameters that are affected by low temperatures and long-term operation.

Figure 5 shows the experimental setup of four large bioretention columns in the laboratory. The internal column configurations correspond to Figure 6. Stormwater was prepared and stored in four separate buckets, then pumped to the top of columns by peristaltic pumps (No.7553-80, No.7557-04, Cole-Parmer Instrument Company). The inflow flow-rate was controlled by the pump speed and connected tubings monitored and adjusted every 30 mins by measuring the volume left in the inflow buckets. The outflow flow-rate was measured manually by the quantity of outflow collected (recorded in mL) over a period of time (min). The frequency of outflow flow-rate measuring was varied to provide sufficient data for outflow hydrographs. The outflow from each column was collected in separate 8-gallon buckets so that the total volume of synthetic stormwater passed through each column could be monitored. Throughout the study, ponding depth, inflow and outflow flow-rates were consistently measured.

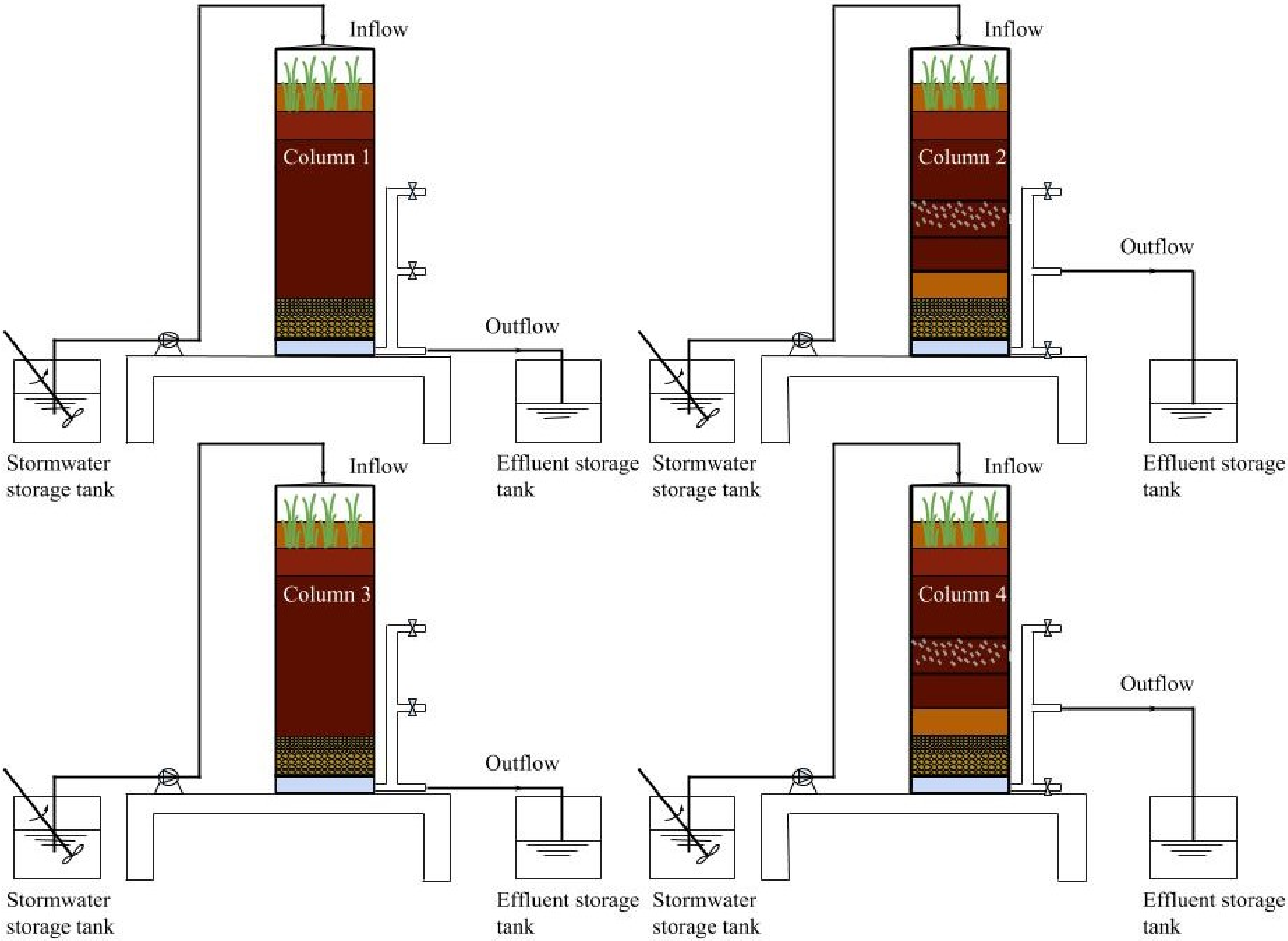


Figure 5: Experimental setup

Figure 6 shows a schematic of the four bioretention columns with different soil media and configurations for this study. The top space of 30 cm depth in each column was used for ponding and plants growth. A 25 cm drainage layer consisting of gravel was placed at the bottom of each column, which was thoroughly washed before use. Soil media A was used in Columns 1 and Column 3, and soil media B in Columns 2 and Column 4. By comparing Column 1 and Column 3 with Column 2 and Column 4, the impact of soil porosity on hydraulic performance can be determined. All columns have a surface media layer of 16 cm mixed with 20% compost (Second nature compost, Edmonton East Burnco Landscape Centre) to promote plant establishment and health. Column 1 and Column 2 consist of a conventional bioretention design that includes mulch and compost for plant maintenance and bioretention soil media. Column 3 and Column 4 correspond to Column 1 and Column 2, respectively, for having the same bioretention soil media, however, two extra 20 cm layers have been amended with 0.5% (by weight) of steel wool (JHQ very fine steel wool, Canadian Tire) to enhance phosphate capture and 5% (by weight) 2-5 mm woodchips (Medium wood bark woodchips, Edmonton East Burnco Landscape Centre) to promote denitrification in Column 3 and Column 4. The layer containing woodchips in Column 3 and Column 4 is also submerged via an upturned underdrain to ensure anoxic condition is formed. This anoxic zone is also called internal water storage layer in some literature. By comparing Column 3 and Column 4 with Column 1 and Column 2, the impact of the denitrification layer on hydraulic performance can be determined. All media used in this study were air-dried and mixed homogeneously. The media used in this study were all freshly installed in Column 1, Column 3 and Column 4 prior to regular operation of weekly simulated storm events. Column 2 was used for hydraulic conductivity study as tap water pumped through it to measure hydraulic performance, therefore it had approximately 1 years' worth of Edmonton precipitation at the beginning of this study.

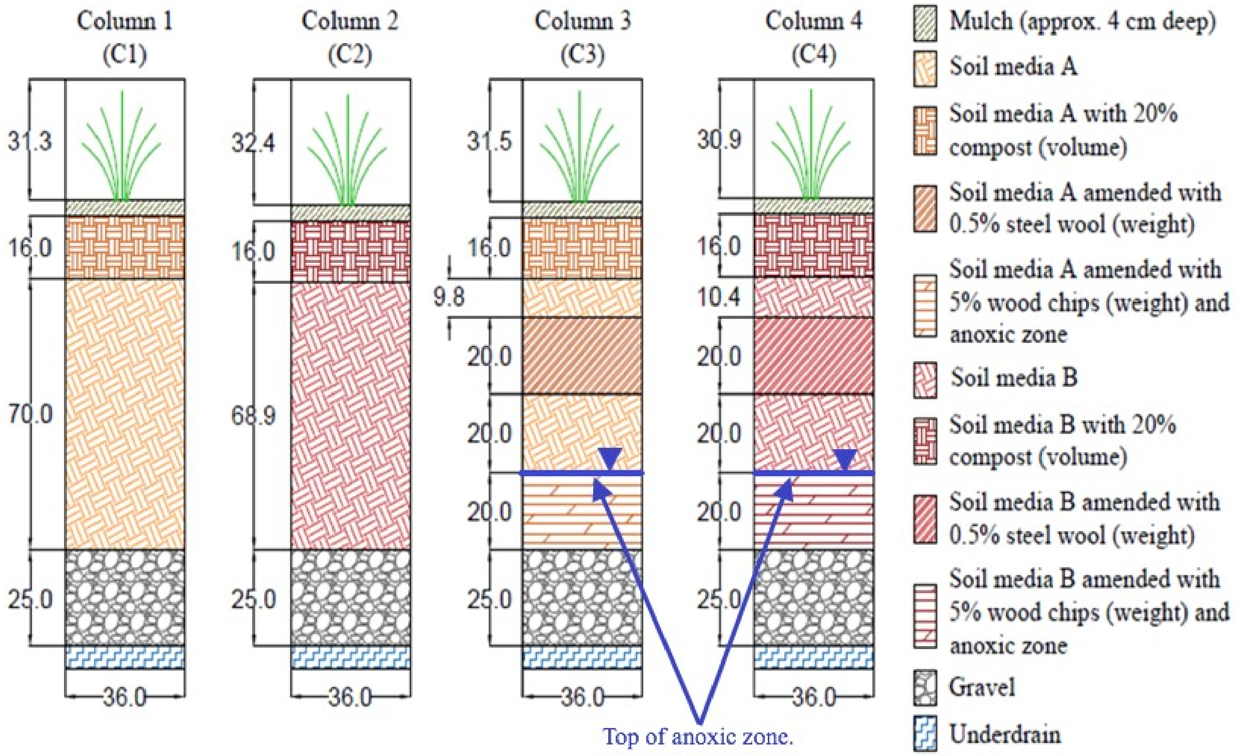


Figure 6: Schematic of bioretention columns for this study (annotations are in cm)

At first, three species of grass (Arrhenatherum elatum 'Variegatum', Panicum virgatum 'Heavy Metal' and Panicum virgatum 'Shenandoah') were chosen at the early stage based on the local climate. These species are all local species that are salt, drought and water tolerant. Then three species were planted into one large column in July 2017, only Panicum virgatum 'Heavy Metal' survived after a month (see Figure 7a). Therefore, Panicum virgatum 'Heavy Metal' was selected and other two dead species of grass were removed from the column.

After vegetation selection, plants used in the columns were purchased from Millcreek Nursery, Edmonton, Canada, and kept in the outdoor (Figure 7b) for one month before being installed into the columns, allowing vegetation to grow and mature.

a) Only Panicum virgatum 'Heavy Metal' grass on the left side survived out of three species in early August.

b) More matured Panicum virgatum 'Heavy Metal' species in August.

Figure 7: Pictures for plants used in bioretention cells

3.3 Stormwater

The synthetic stormwater was prepared using tap water amended with typical stormwater contaminants that are outlined in Table 4. The focus of this thesis was to evaluate the hydraulic performance of designed bioretention cells instead of water quality improvement. Therefore, water quality performance was not stated in this thesis and it was covered in Hannah Kratky's 2018 MSc thesis titled "Stormwater Quality

Improvement through Bioretention in a Continental, Cold Climate" (Kratky 2018). The synthetic stormwater was made up one day ahead of experiments and allowed stormwater to equilibrate to room temperature (in winter operation, that would be the air temperature in the cold room) before use.

Table 4: Composition of synthetic stormwater and spring runoff

Parameter	Source	Unit	Concentration
TSS	Local topsoil < 0.500 mm	(mg/L)	150
COD	Glucose	(mg/L)	40
Total Nitrogen (TN)	See below	(mg/L)	4
Ammonium (NH_4^+-N)	NH_4Cl	(mg/L)	2
Nitrate (NO_3^--N)	KNO_3	(mg/L)	1.5
Nitrite (NO_2^--N)	$NaNO_2$	(mg/L)	0.5
Phosphate (PO_4^{3-}-P)	KH_2PO_4	(mg/L)	2
Chloride (Cl^-)	NaCl	(mg/L)	15* 320** 1280***
Cadmium (Cd)	$Cd(NO_3)_2 \cdot 4H_20$	(µg/L)	5
Copper (Cu)	$CuSO_4 \cdot 5H_20$	(µg/L)	150
Lead (Pb)	$Pb(NO_3)_2$	(µg/L)	50
Zinc (Zn)	$ZnSO_4 \cdot 7H_20$	(µg/L)	400

* During summer operation and the 1:5 and 1:10 year events
** During winter operation and the major melt of spring runoff event
*** During 4x concentrated spring runoff event

Note: All contaminants except chloride remained the same concentration during all stages of operation except for the 4x concentrated spring runoff event, in which contaminants other than COD were quadrupled.

To apply certain depth of precipitation in the form of synthetic stormwater on columns, the size of the catchment area has to be decided. The Edmonton's LID Design Guide recommends a catchment area ratio of 5%-20% (CoE 2014). In this study, the catchment area ratio of bioretention cells was defined as 10%, which reflects the need for a small catchment area ratio in cold climates as discussed in section 2.3. That means the cross section area of 0.102 m^2 of each bioretention column corresponds to a catchment area of 1.02 m^2. Typically, a catchment area would be partially pervious and partially impervious. For this project, an assumption of 100% imperviousness of the total catchment area was selected to predict the worst case scenario, as runoff is mainly generated from the impervious area and only directed to the bioretention cells. Therefore, the volume of synthetic stormwater applied for each event is equal to the product of the catchment area and the precipitation depth.

3.4 Experimental Approach

In this study, a total of 120 storm events were conducted with 30 events on each of the four large column bioretention cells. A summary of these designed events is provided in Table 5.

Table 5: Summary of designed events

Operation	Week	Date	Precipitation depth (mm)	Volume (L)	Duration (hr)	Description of Event
1st Summer	1	2017/9/26	22.6	23	4	Ran simulated 1:2 event on columns 1 and 2.
	2	2017/10/10	22.6	23	4	Ran simulated 1:2 event on columns 1 and 2.
	3	2017/10/17	22.6	23	4	Ran simulated 1:2 event on columns 1, 2, 3, and 4.
	4	2017/10/24	22.6	23	4	Same as above.
	5	2017/10/30	22.6	23	4	Same as above.
	6	2017/11/6	22.6	23	4	Same as above.
	7	2017/11/14	22.6	23	4	Same as above.
	8	2017/11/20	22.6	23	4	Same as above.
	9	2017/11/27	22.6	23	4	Same as above.
	10	2017/12/4	22.6	23	4	Same as above.
	11	2017/12/11	22.6	23	4	Same as above.
	12	2017/12/18	22.6	23	4	Same as above.
	13	2017/12/26	22.6	23	4	Same as above.
	14	2018/1/2	22.6	23	4	Same as above.
	15	2018/1/8	22.6	23	4	Same as above.
	16	2018/1/15	22.6	23	4	Same as above.
	17	2018/1/23	22.6	23	4	Ran simulated 1:2 event on columns 3 and 4.

Operation	Week	Date	Precipitation depth (mm)	Volume (L)	Duration (hr)	Description of Event
	18	2018/1/30	22.6	23	4	Ran simulated 1:2 event on columns 3 and 4.
	19	2018/2/7	22.6	23	4	Ran simulated 1:2 event on columns 1, 2, 3, and 4.
Winter	21	2018/2/20	22.6	23	5	Ran snowmelt test on thaw columns 1, 2, 3, 4.
	23	2018/3/9	22.6	23	5	Ran snowmelt test on frozen columns 1, 2, 3, 4.
	27	2018/4/2	22.6	23	5	Ran snowmelt test on thaw columns 1, 2, 3, 4.
	29	2018/4/16	22.6	23	5	Ran snowmelt test on frozen columns 1, 2, 3, 4.
Spring Runoff	32	2018/5/8	9.8	10	29	Spring runoff* - high concentration inflow, low volume.
	32	2018/5/10	39.3	40	48	Spring runoff - typical concentration, high volume.
2nd Summer	37	2018/6/14	22.6	23	4	Ran simulated 1:2 event on columns 1, 2, 3, and 4.
	38	2018/6/21	22.6	23	4	Same as above.
	39	2018/6/26	22.6	23	4	Same as above.
	40	2018/7/4	22.6	23	4	Same as above.
	41	2018/7/9	22.6	23	4	Same as above.
Large Events	42	2018/7/16	37.3	38	4	Ran simulated 1:5 event on columns 1, 2, 3, and 4.
	43	2018/7/23	45.2	46	4	Ran simulated 1:10 event on columns 1, 2, 3, and 4.

Note: All contaminants except chloride remained the same concentration during all stages of operation. The contaminants other than COD were quadrupled in the * high concentration spring runoff event. More information can be found in Table 4.

Among these events there are four phases of operation:

1) In 1st summer phase, seventeen 1:2 year events were conducted in room temperature from Week 1 to Week 19.

2) In winter phase, four snowmelt events and two spring runoff events were conducted in the cold room at 1 ℃ air temperature from Week 21 to Week 32.

3) In 2nd summer phase, five 1:2 year events were conducted in room temperature from Week 37 to Week 41.

4) In large events operation phase, one 1:5 year event and one 1:10 year event were conducted in room temperature in Week 42 and Week 43, respectively.

In 1st summer, seventeen 1:2 year, 4-hour Chicago distributions of storm events were applied to each of the four columns described in section 3.3 using synthetic stormwater.

There were two reasons for running seventeen 1:2 year events in 1st summer in the laboratory. First, for Edmonton area rainfall, the depth of the 95th percentile storm was 25 mm, which means approximately 95% of actual storm events are less than 25 mm. The designed storm of 1:2 year with Edmonton data calibrated 4-hour Chicago distribution is 22.6 mm, which closed to 25 mm. Therefore, running 1:2 year Chicago storm events is representative to most Edmonton area rainfall. Second, seventeen 1:2 year events (384 mm) represent one year equivalent Edmonton's rainfall (364 mm). This period of operation can also accelerate the natural maturation process, minimize variability of runoff durations and investigate changes in hydraulic performance over time.

In 1st summer, each event consisted of applying 23 liters (or 22.6 mm) of synthetic stormwater to each column in 1:2 year Chicago distribution, as shown in Figure 9. This period of operation can be considered as a warm season with average annual rainfall when vegetation is established and biological activity is functioning. During 1st summer, all four columns were subjected to room temperatures, approximately 21±2 °C.

After 1st summer, the submerged zone was drained in Column 3 and Column 4, and the four columns were moved into a temperature-controlled cold room in which winter operation began. In this phase, all four columns were frozen at −20 °C and thawed at 1 °C air temperature to simulate one freeze-thaw cycle. A snowmelt event consisted of high salt (500 mg/L NaCl) was carried out right after a freeze-thaw cycle on the columns at an inflow rate of 76.7 mL/min. As Northern Prairies regions such as Edmonton has a long and dry winter with intermittent warming periods throughout winter, the freeze-thaw cycle was repeated three times to simulate snowmelt generated in this stage.

After experiencing three freeze-thaw cycles, the columns stayed in the cold room at 1 °C air temperature for 3 weeks. Then a simulated spring runoff was conducted in which 10 liters of concentrate synthetic stormwater were applied at an inflow rate of 5.8 mL/min to simulate the first flush of accumulated pollutants in the bottom of snow piles. Then 40 liters, normal synthetic stormwater was applied at a constant inflow rate of 14 mL/min to simulate the major melting of the snowpack. These two spring runoff events were applied at 1 °C air temperature in the cold room.

In 2nd summer, the submerged zone was recreated in Column 3 and Column 4, five 1:2 year events with the same operation conditions as in 1st summer were conducted to compare the hydraulic performance before and after winter operation.

In the final phase of this study, one 1:5 year (38 liters or 37.3 mm) and one 1:10 year (46 liters or 45.2 mm) 4-hour Chicago distributions of Edmonton storm events were conducted in room temperature to simulate large volume events.

Over a one-year testing period, 778 liters of synthetic rainwater was applied to each cell. This was the equivalent of 1.6 years (764.4 mm) annual precipitation for Edmonton.

The temperature of the experimental condition was adjusted as shown in Figure 8. The internal temperature of the columns was also monitored and it was observed that the exterior temperature matched the internal column temperature if the columns were given

1 to 3 days to adjust. It took longer, however, when the exterior temperature was transitioning from negative to positive degree.

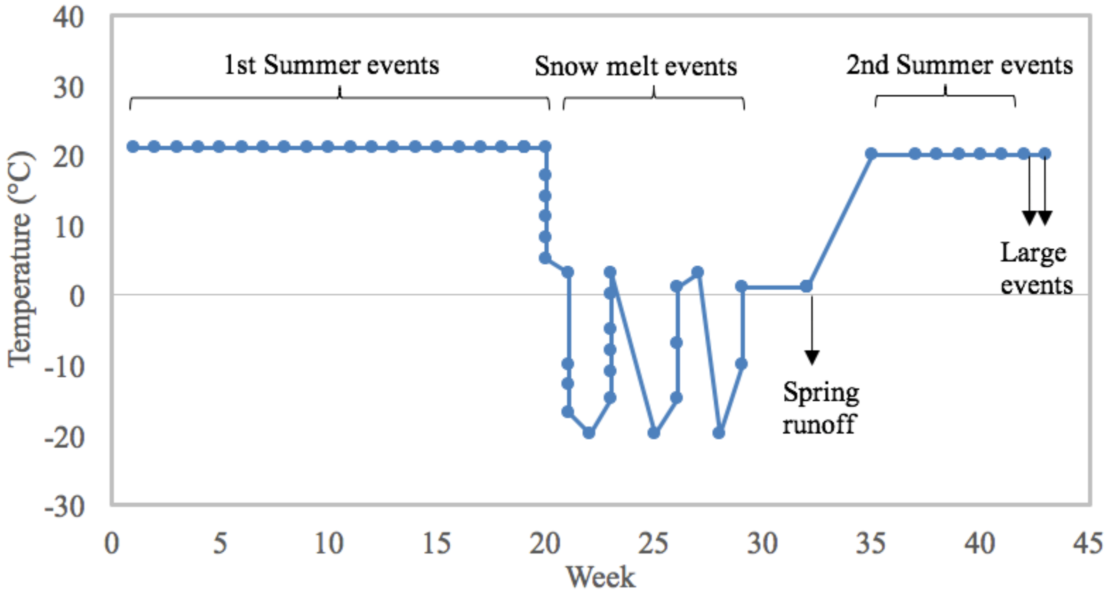


Figure 8: Exterior temperature subjected to four columns

3.5 Hydraulic Analysis

Bioretention hydraulic performance can be evaluated by several parameters including saturated hydraulic conductivity, peak flow reduction, peak delay, ponding, and peak outflow flow-rate.

In this study, falling head measurements were conducted with tap water to measure the saturated hydraulic conductivity between seasons to see if the columns had sufficient hydraulic performance over time. The falling head method was chosen because it measures the K_{sat} values without maintaining a constant head on the top of the column, and it measures the K_{sat} of surface layer in which clogging typically occurs. Paus et al. (2016) illustrated that this method is limited by (1) ponding formed on the top of cells; (2) no influent flow into the cells; (3) soil media completely saturated; (4) a required minimum hydraulic gradient. This K_{sat} measurement may be affected by factors such as water retained by mulch or evaporation, but for this controlled laboratory study, their impacts are considered minimal.

Falling head tests were conducted on February 9, May 28, and July 23, 2018. The standard hydraulic conductivity for fresh columns is difficult to determine, as the hydraulic conductivity is unstable due to the initial physical soil characteristics including moisture content, temperature, texture, structure, and porosity. Also we avoided applying a large volume of tap water to wash the columns in between events to affect biological activities in the cells. Therefore, the first falling head measurement was conducted after applying one-year equivalent Edmonton's rainfall to better represent the hydraulic performance for columns. The first falling head measurement represented the hydraulic conductivity of bioretention cells after 1st summer operation and before cold weather exposure; the second falling head measurement represented the hydraulic conductivity after snowmelt and spring runoff operations; and the third one represented the hydraulic conductivity after 2nd summer and large events operations. These tests were used to evaluate the changes over time for infiltration capacity of bioretention growth media.

Saturated hydraulic conductivity calculation was adapted from Lucas and Greenway (2011) and ASTM D5084 (2016):

$$K_{sat} = \frac{\mathrm{a}L}{At} ln(\frac{h_1}{h_2}) \quad (1)$$

where,

K_{sat} = saturated hydraulic conductivity (cm/h),

a = cross-sectional area of the ponding, (m^2),

A = average media cross-sectional area (m^2),

L = media depth (cm),

h_1 = initial head (cm),

h_2 = final head (cm), and

t = elapsed time (hour).

To evaluate the performance of the bioretention cells to reduce peak flows, inflow and outflow flow-rates were consistently measured. The peak flow reduction (ΔQ) for each individual storm event was calculated by the following equation:

$$\Delta Q = \left(1 - \frac{Q_e}{Q_i}\right) \times 100\ \% \quad (2)$$

where,

ΔQ = peak flow reduction (%),

Q_e = maximum outflow flow-rate (mL/min), flow-rates were measured by the quantity of outflow collected (recorded in mL) over a period of time (min) and

Q_i = maximum inflow flow-rate (mL/min).

Peak delay was defined as the time, measured in minutes, from when inflow peak occurred to the time outflow peak occurred in the underdrain. Peak delay was calculated as follows:

$$Peak\ delay = t_e - t_i \tag{3}$$

where,

t_e = the time of outflow peak flow occur (min), and

t_i = the time of inflow peak flow occur (min).

The implementation of inflow hydrograph and measurement of outflow hydrograph are explained using an example as shown in Figure 9. In this figure, a typical inflow hydrograph was developed based on Edmonton's historical rainfall for 1:2 year, 4 hour Chicago distributions of a storm event. The inflow peak flow-rate was 384 mL/min. The outflow hydrograph was measured by the quantity of outflow collected (about 500 mL) over a period of time (recorded as min). The start of a designed storm event was defined as the time synthetic stormwater began to be pumped into the columns. The end of an event was defined as the time that no measurable effluent (only a few drops of effluent per minute) flowed out of the cells, which is about 48h.

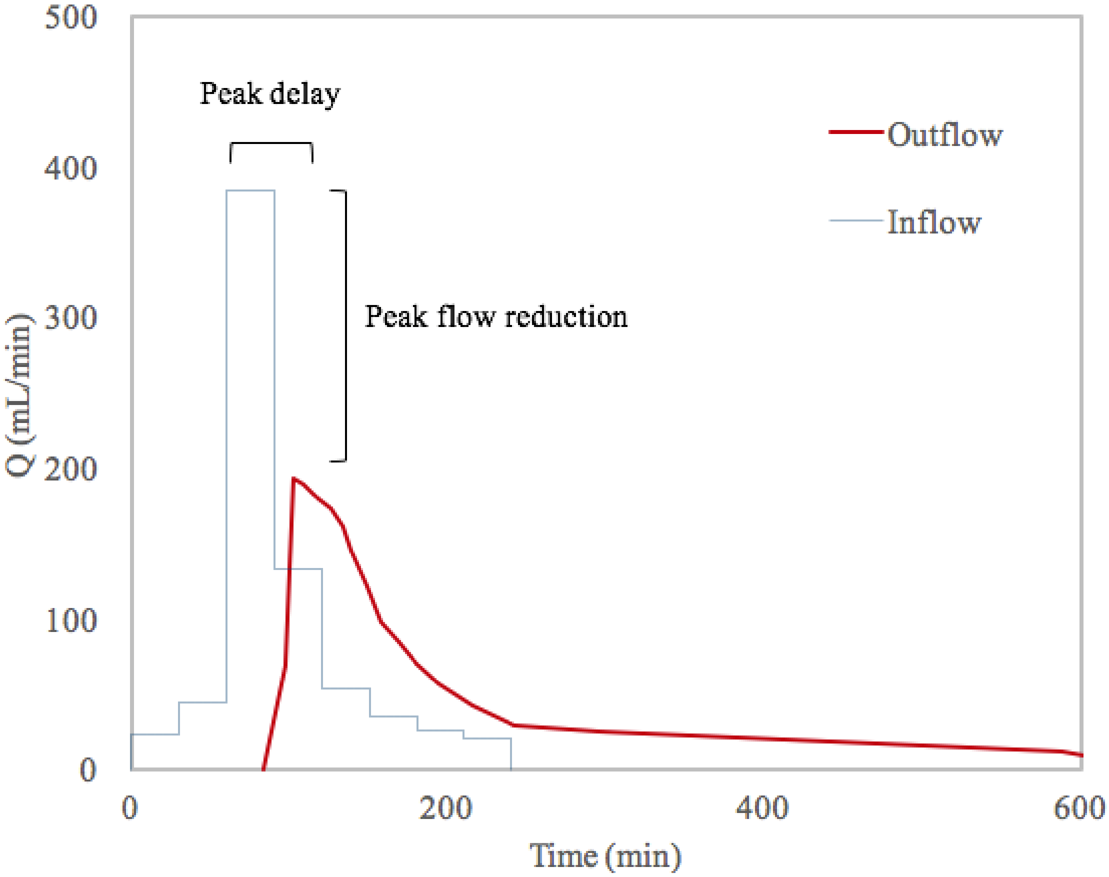


Figure 9: An example of inflow and outflow hydrographs

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Media Maturation

In literature, bioretention cells always need a "mature" period ranged from few weeks to few months before applying storm events (Fletcher et al., 2007a; Khan et al., 2012c; Lucas & Greenway, 2011; Zinger et al., 2013). This procedure could minimize the effects of organic matters and heavy metals leaching from columns. Once the stabilization occurred, water quality improvement will be observed. However, the question is how long a bioretention cell will take for "mature" process on hydrological performance. Figure 10 shows an example of inflow and outflow hydrographs subjected to one 1:2 year event. The blue line represents the inflow hydrograph for 1:2 year event and purple line represents the outflow hydrograph. The x-axis represents minutes since each individual event started. Outflow hydrographs were similar for each individual event in 1st summer, as all events subjected to the same 1:2 year distribution. Therefore, Figure 11 compares outflow hydrographs of all recorded events to see if there were peak differences between events over time. During 1st summer operation, all but three of the seventeen events were captured in the hydrographs shown in Figure 11. Figure 11 provides some interesting data regarding change of outflow hydrographs over time. In Figure 11, the solid-line inflow hydrograph represents all events in 1st summer because that these events all have the same 1:2 year, 4 hour Chicago distribution, so their inflow hydrographs were overlapped. If the outflow hydrographs from different events were highly overlapped, we considered that overlapped line as a stable outflow hydrograph. The red dots represent stabilized outflow hydrographs that have excluded the first 3 maturation events for Column 1 and Column 2, the first 4 maturation events for Column 3, and the first 6 events for Column 4. The green stars represent the maturation events. After subtracting the first 3 weeks' events for Column 1, the outflow hydrographs for the remaining 11 events were highly overlapped, which indicate the stabilized hydraulic performance since 4th week's event. Similarly, the outflow hydrographs of Column 3 and Column 4 stabilized after subtracting the initial 4 and 6 weeks' events, respectively. The reason for Column 3 and Column 4 to take longer time to mature compared to Column 1 is likely due to the high water mobility in the submerged zone. For Column 2, there was no change over time as this column has been applied with 417 liters of tap water before the stormwater events. Therefore, Column 2 can be treated as a "mature" column.

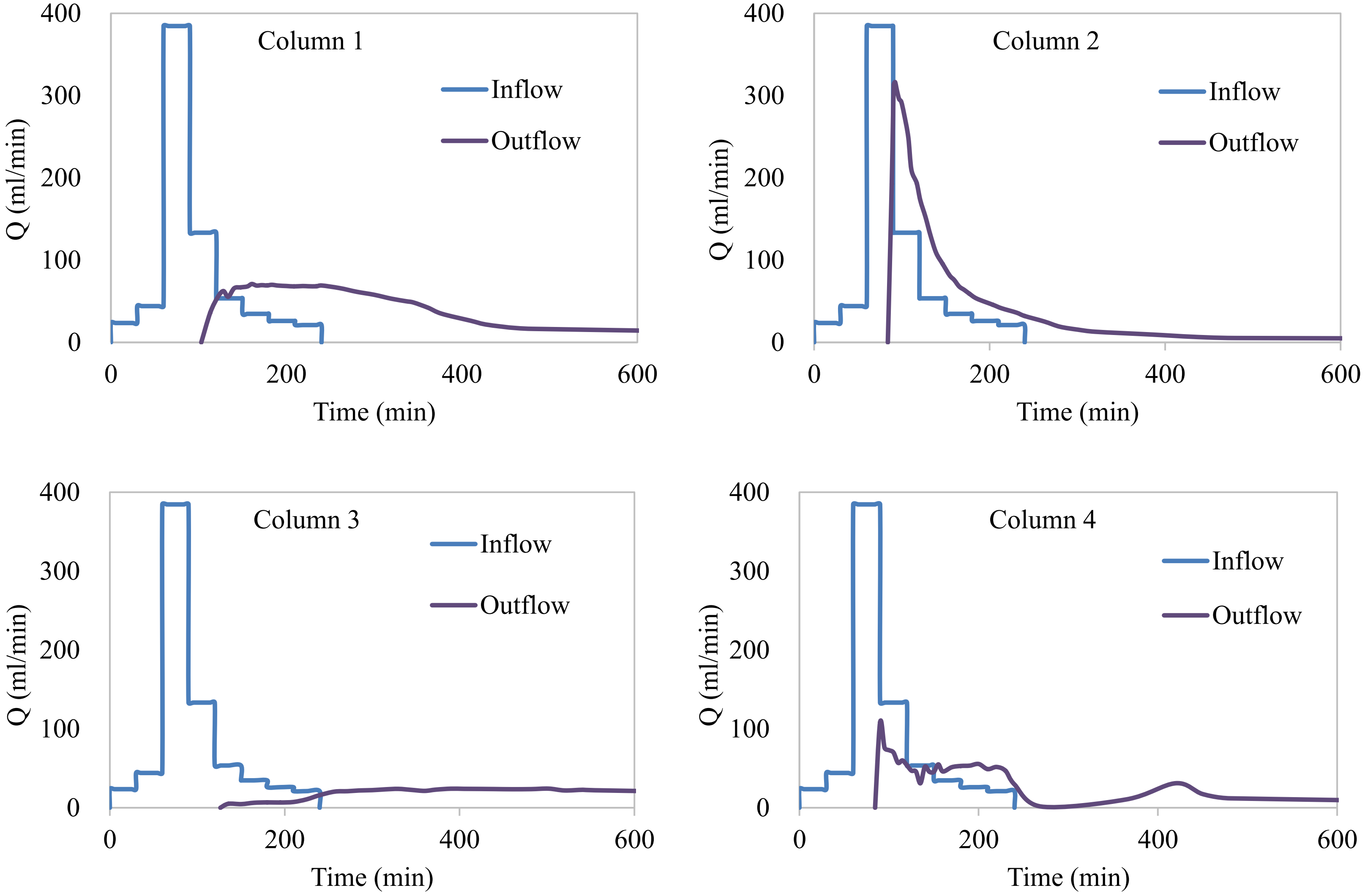


Figure 10: An example of inflow and outflow hydrographs for four columns conducted in Week 4

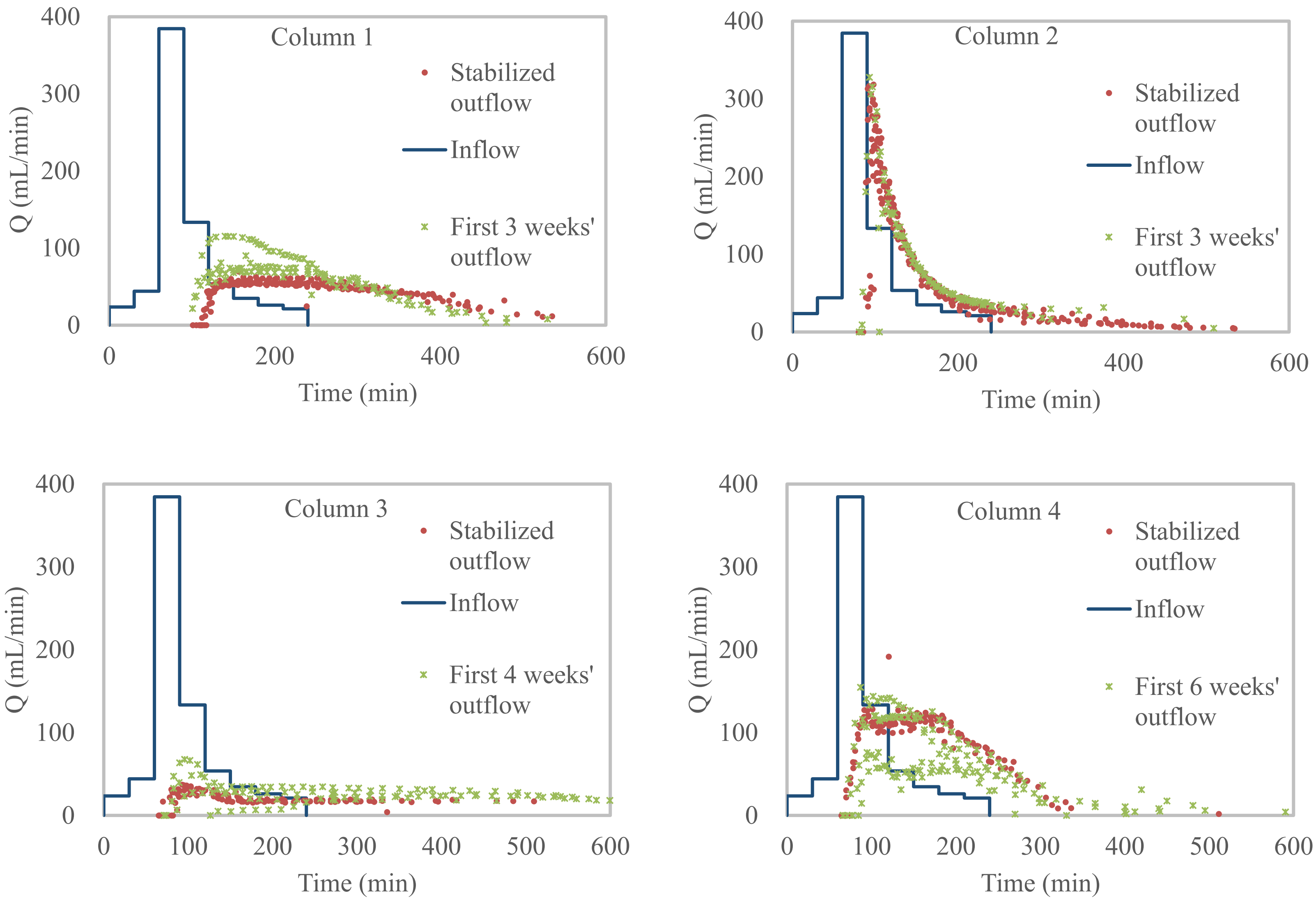


Figure 11: Collection of inflow and outflow hydrographs for four columns during 1st summer

4.2 Saturated Hydraulic Conductivity

A concern for hydraulic performance in bioretention is reduced hydraulic conductivity due to compaction and clogging in the media. Multiple studies have reported a reducing trend of saturated hydraulic conductivity due to self-compaction under hydraulic loading over a period of operation (Hatt et al., 2008; Khan et al., 2012a; Le Coustumer et al., 2012). To address that concern, falling head tests were conducted after 1st summer, winter, and 2nd summer operation, to evaluate hydrologic conductivity changes over time. The trends in the change of average K_{sat} is shown in Figure 12.

After five months 1:2 year designed events on four columns, the average K_{sat} of Column 1 and Column 3 were 1.7 cm/hr and 1.6 cm/hr, respectively, and the average K_{sat} of Column 2 and Column 4 were 16.0 cm/hr and 11.6 cm/hr, respectively (Table 6). Columns with soil media A had lower K_{sat} values compare to columns with soil media B after 1st summer operation. The selected soil media B maintained a K_{sat} value that is higher than 10 cm/hr after one-year equivalent rainfall events.

After winter operation, K_{sat} measurements were conducted to investigate the change of hydraulic conductivity over a winter exposure. It turned out that the columns filled with soil media A experienced an increase in hydraulic conductivity after winter operation, from 1.7 cm/hr to 3.8 cm/hr for Column 1 and 1.6 cm/hr to 6.1 cm/hr for Column 3, respectively. A four-years study in Minnesota, United States, observed a similar positive relationship between K_{sat} and service time, and this relationship is likely attributed to development of macropores by earthworm activities and plant roots, and freeze-thaw cycles (Paus et al., 2013). As the vegetation in the cells only planted for 5 months, the impacts from vegetation and plant roots may have not been significant. Due to the restricted vegetation establishment and biological activity in winter conditions, the increase of K_{sat} in Column 1 and Column 3 can be attributed mainly to the freeze-thaw cycle expanding pore spaces in the media. Many studies in cold climates also observed the same trend of increased infiltration rates after freeze-thaw cycles (Roseen et al., 2009; Denich et al., 2013; Gnanaraj & Ranjith, 2018). A soil mechanical study (Xie et al., 2015) demonstrated that the increase of soil porosity is due to the water in the soil pore expanded and caused a rearrangement of the soil particles. In contrast, soil media B columns experienced the opposite effect, from 16.0 cm/hr to 11.3 cm/hr for Column 2, and 11.6 cm/hr to 9.7 cm/hr for Column 4 respectively, is likely due to the snowmelt events causing compaction of the pore spaces. Although multiple freeze-thaw cycles can expand pore spaces, the large volume of snowmelt went through soil media B columns during the winter caused compaction. Since soil media B contains more sand that resulted in larger pore spaces, compaction may be more significant in Column 2 and Column 4.

After 2nd summer operation, hydraulic conductivity decreased for all columns due to compaction by hydraulic loading. The average K_{sat} of Column 1 and Column 3 were 2.9 cm/hr and 4.7 cm/hr respectively, and the average K_{sat} of Column 2 and Column 4 were 9.6 cm/hr and 9.1 cm/hr respectively (Table 6). The soil media A still maintained a capacity greater than the minimum requirement of 2.5 cm/hr, and the soil media B was still close to the cold climate recommendation of 10 cm/hr. If water quality improvement is desired, the soil media A may have a better TSS and metal removal due to the high clay content. And the hydraulic conductivity may not constantly decrease as the freeze-thaw cycle will expand pore spaces in the media. If stormwater quantity control is desired, the soil media B may maintain a sufficient hydraulic performance in both summer and winter weather conditions in cold climates. However, this study only ran one winter operation. Long-term simulation of multiple years of operation is needed to truly evaluate the lifetime of these bioretention cells to see if the hydraulic conductivity continues to increase in the less porous media and decrease in the more porous media.

It is also important to notice that vegetation did not grow back after being out of the cold room for a few months. The absence of healthy vegetation may negatively impact the hydraulic performance to counteract compaction by hydraulic loading for bioretention in 2nd summer. Therefore, if healthy vegetation played a role in 2nd summer operation, bioretention columns may even have higher hydraulic conductivity in 2nd summer.

Table 6: Saturated hydraulic conductivity after 1st summer, winter and 2nd summer operations

Column	Ksat (cm/hr)		
	After 1st summer	After winter	After 2nd summer
Column 1	1.7±0.3	3.8±1.6	2.9±1.2
Column 2	16.0±5.2	11.3±4.0	9.6±1.7
Column 3	1.6±0.5	6.1±1.5	4.7±1.7
Column 4	11.6±0.6	9.7±1.3	9.1±4.6

All values are given as mean ± standard deviation.

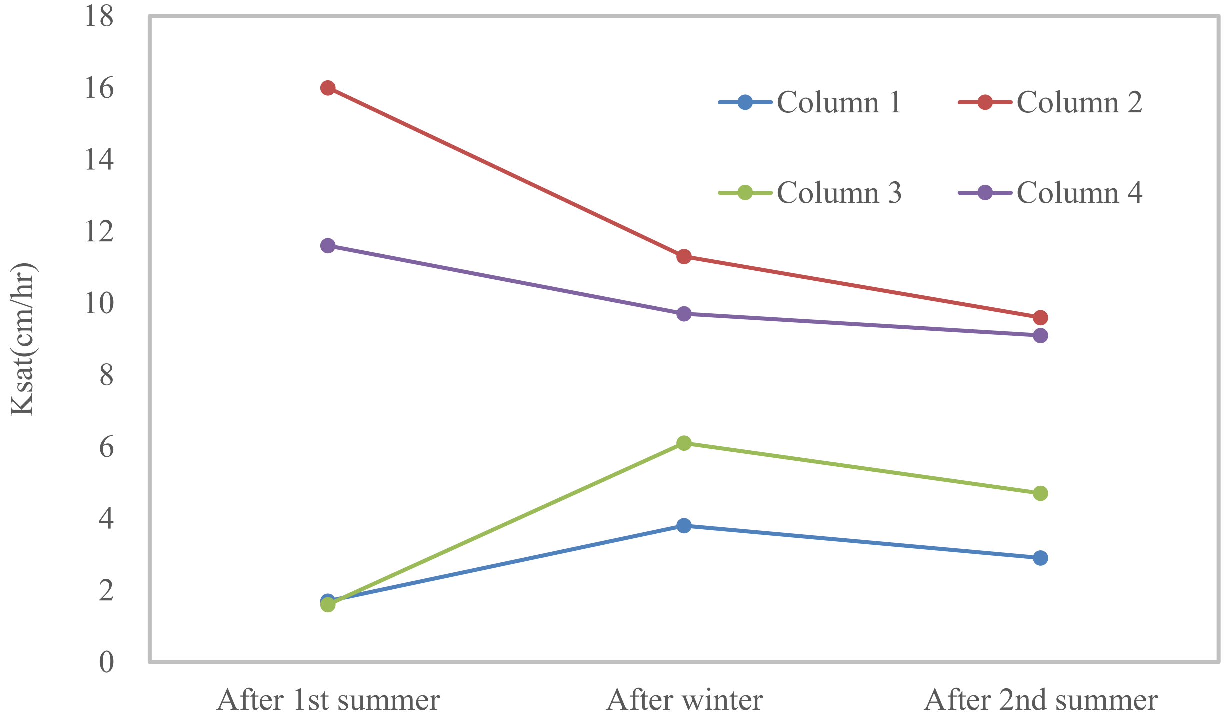


Figure 12: Changes in saturated hydraulic conductivity for four columns over time

4.3 Peak Delay and Peak Flow Reduction

The mean peak outflow flow-rate, peak flow reduction and peak delay during 1st summer are shown in Table 7. Column 1 and Column 3 filled with soil media A performed well on peak flow reduction. The mean peak outflow flow-rates were 64 mL/min and 35 mL/min respectively, while the peak inflow flow rate during 1st summer was 385 mL/min. This resulted in a peak flow reduction of 83% and 91% for Column 1 and Column 3, respectively.

From inflow and outflow hydrographs subtracted maturation events (Figure 13), Column 1 and Column 3 with soil media A can smooth outflow, with no apparent outflow peaks observed in all recorded events during 1st summer. Although both Column 1 and Column 3 had a good performance of peak flow attenuation, the mean peak delay differs widely, with 116 min on Column 1 and 54 min on Column 3. This difference can be attributed to the internal water storage layer in Column 3. As this layer stored a certain amount of water, the peak outflow flow-rate appeared quickly if outflow had begun. Another finding of the internal water storage layer is this layer can minimize peak outflow flow-rate. Peak outflow flow-rate was higher in Column 1 and Column 2 as compared with Column 3 and Column 4, most likely due to the hydraulic head loss from the upturned underdrain.

As Column 2 and Column 4 were filled with soil media B, they had high porosity and high hydraulic conductivity, leading to higher peak outflow rates compared to columns filled with soil media A. Furthermore, the hydrographs illustrated that both Column 2 and Column 4 had intense outflow peaks closely responding to inflow peaks, due to the high porosity resulted from high sand portion in the media.

Table 7: Peak inflow flow-rate, outflow flow-rate, peak flow reduction and peak delay in 1st summer

Column	Peak inflow flow-rate (mL/min)	Peak outflow flow-rate (mL/min)	Peak flow reduction %	Peak delay (min)
Column 1	385[a]	64±17	83±4%	116±25
Column 2		257±55	31±14%	38±6
Column 3		35±12	91±3%	54±19
Column 4		122±33	70±8%	53±27

All values are given as mean ± standard deviation except [a] peak inflow flow-rate.

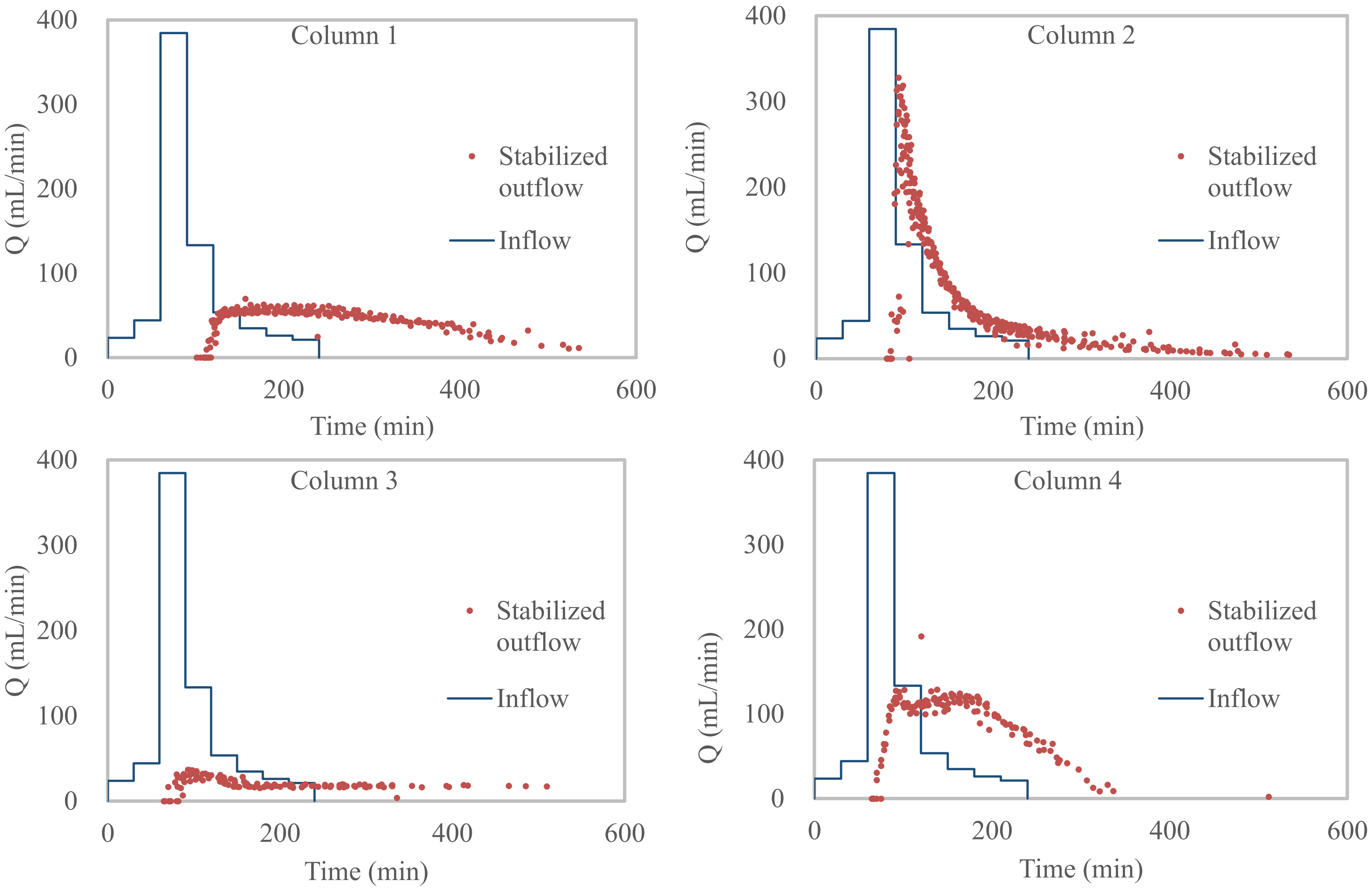


Figure 13: 1:2 year event inflow and outflow hydrographs in 1st summer with maturation events subtracted immature events

After winter operation, five 1:2 year events with same operation conditions as 1st summer were conducted to compare the hydraulic performance before and after winter operation. Although healthy vegetation did not grow back in the 2nd summer, the root systems were still existed and maintained the soil structure to counteract compaction. The impact from plant growth is generally considered minimal as the dominant mechanism of designed bioretention columns is infiltration.

Figure 14 shows the inflow and outflow hydrographs of the columns subjected to 1:2 year events before and after winter operation. As all events in 1st summer subjected to the same 1:2 year distribution, the inflow hydrographs were overlapped and represented as a solid line. The green stars represent the outflow hydrographs of all recorded events in 1st summer and the red dots are the outflow hydrographs of all recorded events in 2nd summer, after experiencing winter operation. By comparing the green stars and red dots, it is apparent that the hydrographs are quite similar and, therefore, winter conditions did not impact the hydraulic performance significantly.

A standard t-test was used to determine if there was a significant difference between the 1st summer and 2nd summer results. The mean peak outflow flow-rates were found to be statistically significantly different between 1st summer and 2nd summer on Column 1, Column 2 and Column 3 ($p = 0.002$, $p = 0.005$ and $p = 0.003$, respectively). There was no statistical difference for mean peak outflow flow-rates between 1st summer and 2nd summer on Column 4 ($p = 0.143$). The mean peak outflow flow-rates for Column 1 and Column 3 were 87 mL/min and 103 mL/min respectively in 2nd summer, versus 64 mL/min and 35 mL/min in 1st summer (Table 8). This resulted in a lower peak flow reduction of 77% and 73% in 2nd summer versus 83% and 91% in 1st summer. The mean peak outflow flow-rates for Column 1 and Column 3 were significantly higher in 2nd summer compare to 1st summer. The increase in peak outflow flow-rate can be attributed to increased pore sizes and increased hydraulic conductivity resulted from freeze-thaw cycles in winter operation. A sufficient hydraulic performance can be expected for soil media A over years' operation as the freeze-thaw cycle could expand pore spaces several times during the intermittent warming period in winter. In contrast, the peak outflow flow-rates for Column 2 was decreased from 257 mL/min in 1st summer to 205 mL/min in 2nd summer. This is due to reduced hydraulic conductivity over a winter operation. It is important to note that both Column 2 and Column 4 filled with same soil media B, however, there was no statistical difference in peak outflow flow-rates between seasons on Column 4. This can be attributed to the internal water storage layer maintaining a certain amount of water that can offset compaction by hydraulic loading. If nitrate removal is desired, a submerged zone in the bioretention cells will not negatively impact hydraulic performance in terms of peak outflow flow-rate.

Comparing the mean peak delay between 1st summer and 2nd summer, there was no statistical difference on Column 2, Column 3 and Column 4 ($p = 0.129$, $p = 0.745$ and $p = 0.657$ respectively). The mean peak delay was statistically significantly decreased on Column 1 from 116 min in 1st summer to 68 min in 2nd summer ($p = 0.000$). It also can be seen from the hydrographs (Figure 14) that the outflow peak was shifted forward between seasons on Column 1. This is likely due to the infiltration capacity of soil media A increased over freeze-thaw cycles, the outflow peak occurred quickly in 2nd summer. As Column 3 had a submerged zone storing a certain amount of water, the change of the peak delay was not significant as Column 1.

Table 8: Peak outflow flow-rate, peak flow reduction and peak delay before and after winter operation

Column	Peak outflow flow-rate (mL/min)		Peak flow reduction %		Peak delay (min)	
	1st summer	2nd summer	1st summer	2nd summer	1st summer	2nd summer
Column 1	64±17	87±9	83±4	77±2	116±25	68±16
Column 2	257±55	205±17	31±14	47±5	38±6	46±14
Column 3	35±12	103±28	91±3	73±7	54±19	58±20
Column 4	122±33	133±10	70±8	65±3	53±27	48±22

All values are given as mean ± standard deviation.

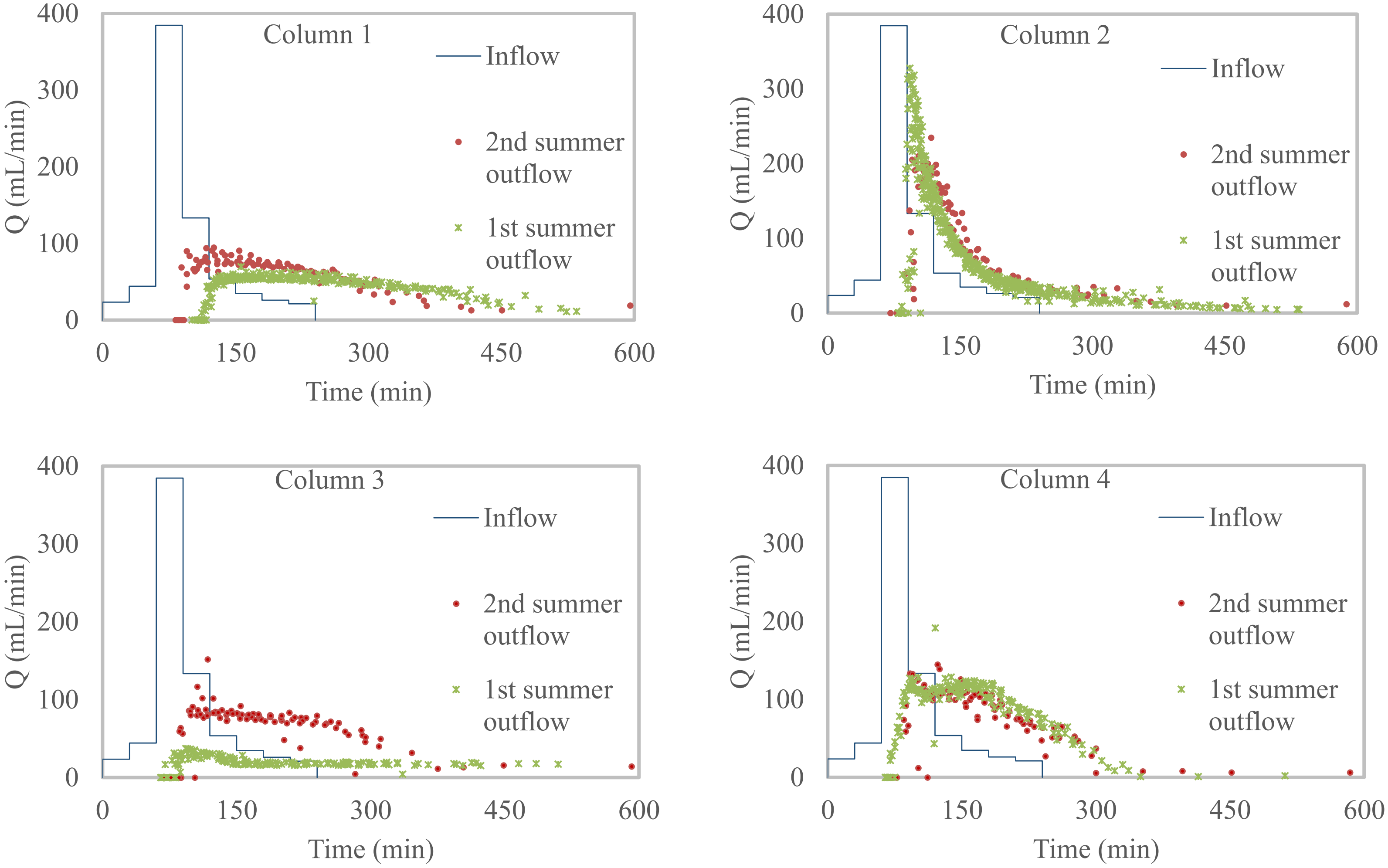


Figure 14: Comparison of 1st summer and 2nd summer inflow and outflow hydrographs for 1:2 year event

Stormwater volume reduction by designed bioretention columns was not assessed in this study. The preliminary data, as provided in APPENDIX C, shows only the volume reduction primarily due to storage capacity of the media in bioretention columns. The other two volume reduction mechanisms, evapotranspiration and exfiltration, did not play significant roles in this study. The experimental design of weekly events, although necessary to expedite the evaluation of more critical bioretention performances, weakened the effect of evapotranspiration on volume reduction. The capillary water was likely remained in the soil's micropores and did not have time to be sufficiently reduced via evapotranspiration. Exfiltration was not a focus of this laboratory study. The lack of evapotranspiration and exfiltration in the experiment design led to underestimating of volume reduction capacity of designed bioretention columns. Under field conditions with porous surrounding soil and sub-soil, better stormwater volume reduction performance can be expected.

4.4 Hydraulic Performance in Winter

In winter operation, four snowmelt events were conducted to simulate the limited snowmelt generated during the intermittent warming periods in winter, due to temperature increase compounded with the use of de-icing chemicals. Two snowmelt events were conducted on thaw columns to simulate the moderate condition when the warming period continued for several days and ground was thawed, two were conducted on frozen columns to simulate the extreme condition when ground was solidly frozen and received melting snow at air temperature above 0 °C. As water ran into the columns at a constant flow-rate to simulate melted snow from snow piles, inflow peak did not appear.

As water ran through thaw columns quickly, ponding water was not formed in all four columns at air temperature of 1 °C and core temperature of –0.2 to –0.7 °C, depending on the columns.

Figure 15 shows how water penetrates through the frozen columns during one selected snowmelt event. The blue area represents the ponding volume, the gray area represents the water retained in the columns and the orange area represents the effluent volume. The total inflow volume is 23 liters and the retained water volume was calculated by inflow volume subtracting ponding and outflow volume. The X-axis shows the time since the event started. Figure 15 only shows the data after 43 hours, as minimal effluent generated prior to that time.

Ponding was formed in all 4 columns when columns were frozen at a core temperature of −10 °C. When ponding was formed and effluent was flowed out of the cells, there were 10 liters of water held in each of Column 1 and Column 3, 15 liters and 12 liters of water held in Column 2 and Column 4, respectively (Figure 15). The volume of water held in soil media B columns was higher than that of the soil media A columns. Columns with soil media A also took longer time to thaw compared to columns with soil media B. Column 1 and Column 3 (soil media A) took 67 hours and 61 hours, respectively, to generate outflow, while Column 2 and Column 4 (soil media B) took 46 hours and 51 hours, respectively, to generate outflow. The above time periods are representative of the typical duration of warming periods in Edmonton. It is important to notice that this experiment was conducted under the extreme condition where columns were solidly frozen at core temperature of −10 °C. It is expected that in reality, the soil temperature would gradually increase with the air temperature resulted in shorter thawing time.

Figure 16 shows the changes of soil core temperature during the same snowmelt event. At the beginning of the event, all four columns had a core temperature of −10 °C. Since the event started, the soil core temperature of Column 2 and Column 4 increased faster than Column 1 and Column 3 under 1 °C air temperature. This indicates that soil media B took less time for soil thawing and water breakthrough than soil media A columns. This capacity of soil media B facilitates water infiltration and drain from the columns during intermittent warming periods throughout winter. As soil media B has a higher porosity, the time for ponding to vanish over frozen soil media B columns was less than that in soil media A columns. Furthermore, the inflow volume for designed snowmelt events did not take sublimation into account. The losses due to sublimation and snow hauling could be significant in Edmonton’s winter. Therefore, the inflow volume of snowmelt events can actually be lower than designed events. Using soil media B in bioretention cells may be sufficient to infiltrate snowmelt during intermittent warming periods in winter. This portion of snowmelt reduction should be taken into consideration when sizing bioretention cells in cold climates.

Spring runoff experiments were applied right after snowmelt events at air temperature of 1 °C in Week 32, representing typical early spring conditions with low biological activity. A 10 liters spring runoff event with high concentration loading (as shown in Table 4) and low flow-rate (5.8 mL/min) was conducted to simulate the first flush of accumulated pollutants in the bottom of snow piles. Then another 40 liters spring runoff event with normal concentration and high flow rate (14 mL/min) was applied to simulate the major melting of the snowpack. All four columns can effectively capture and infiltrate the high hydraulic loading of spring runoff events quickly with no ponding formed.

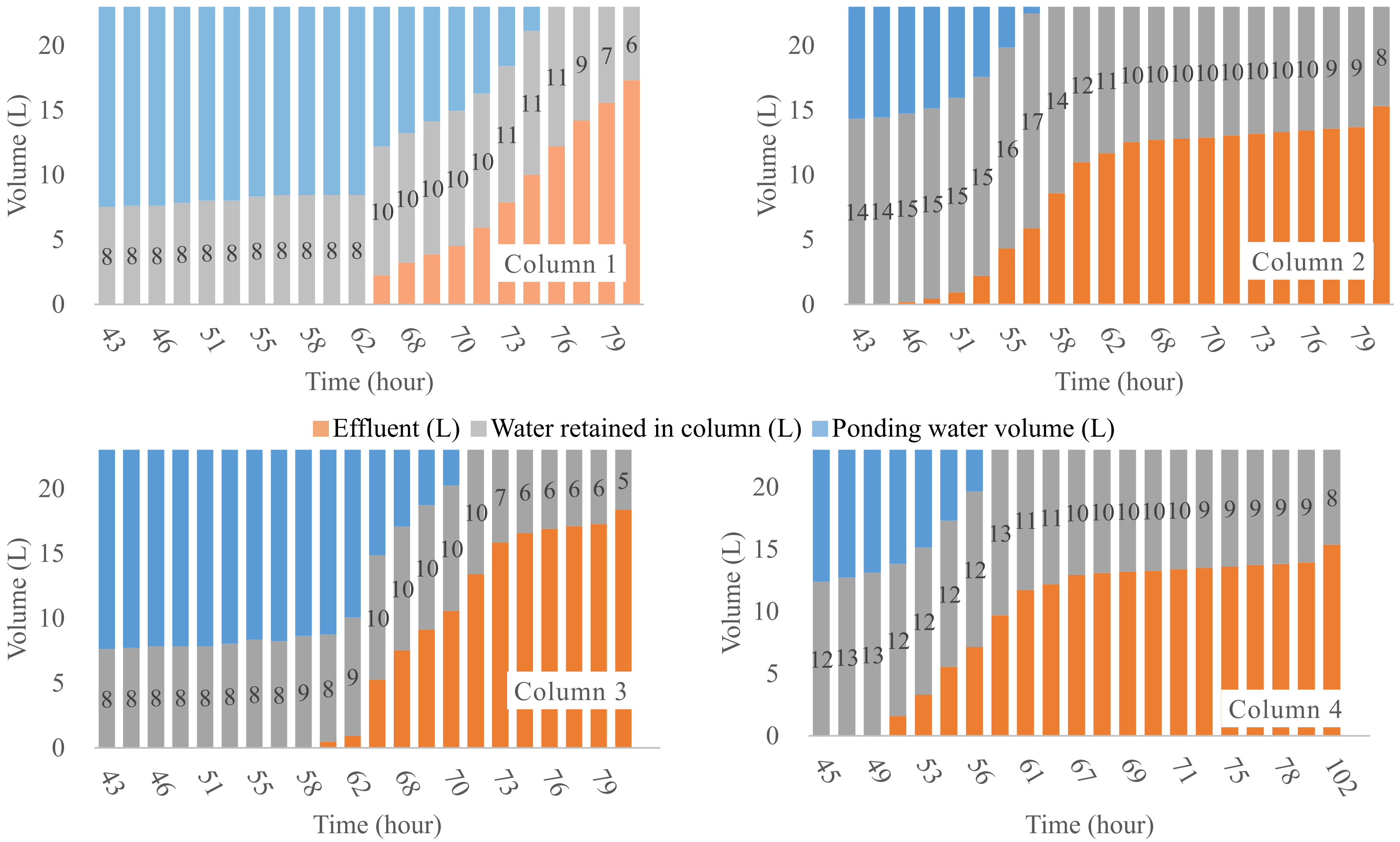


Figure 15: Water breakthrough of frozen columns conducted in Week 29

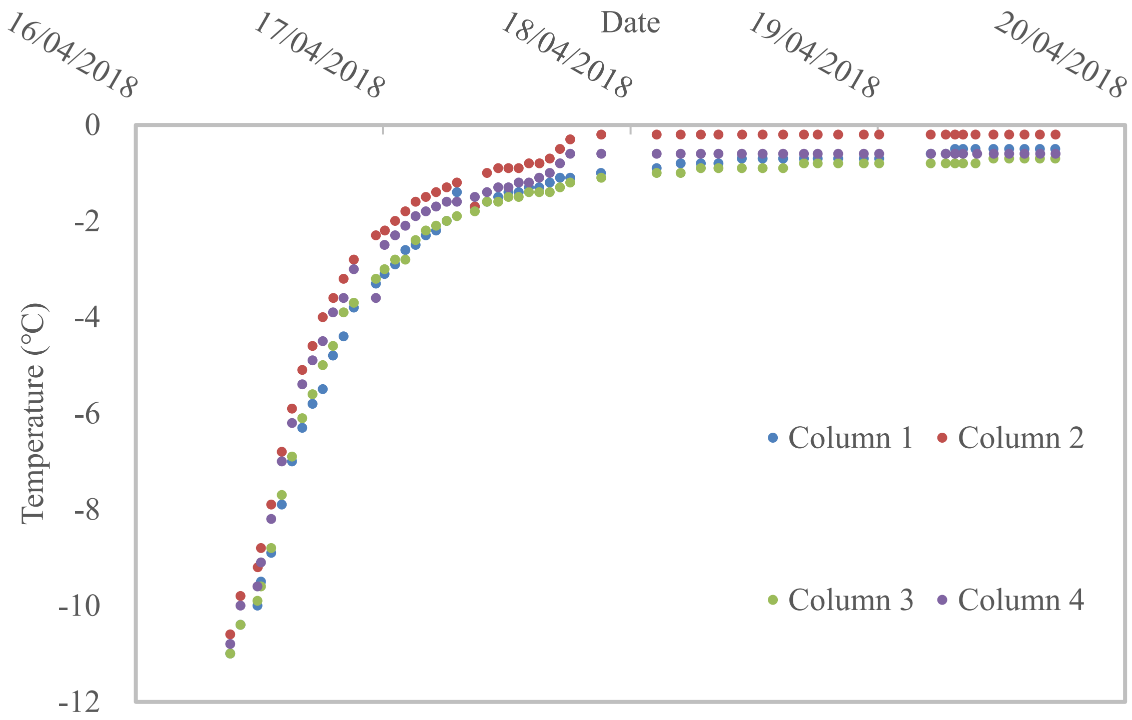


Figure 16: Soil core temperature of four columns for snowmelt event conducted in Week 29

4.5 Large Events Operation

Figure 17 shows the comparison of inflow, outflow hydrographs and ponding depth subjected to 1:2, 1:5, and 1:10 year events on Column 4. All three storm sizes followed the 4-hour Chicago distribution. The variable hydraulic loading rates from the three different inflow hydrographs did not have a significant effect on the outflow hydrographs, therefore, inflow peak did not impact the outflow peak. Once columns were saturated, stormwater would be retained within the media and form ponding on the surface, then slowly be released via infiltration.

Figure 18 shows the comparison of outflow hydrographs subjected to different size events for all four columns. Solid lines represent outflow hydrographs and dash lines represent ponding depth. By comparing the responses to different storm sizes, it is apparent that the outflow hydrographs are quite similar for all four columns and therefore, the peak outflow flow-rates are close when soil media reached saturation.

All columns managed two large events well by having no overflow generated. The maximum ponding depth was 25.5 cm and the maximum ponding duration was 10 hours – both are for column 1, with the soil media A (Table 9). The other three columns showed even better performance. All ponding depths and durations were less than the maximum allowable in the City of Edmonton's current LID guidelines of 0.3 m maximum ponding depth and 48 hr ponding duration (CoE 2014). It is important to note that the soil media B columns' ponding only lasted 1.61 • hours for 1:5 year event and 2.9 hours for 1:10 year event, meaning these columns had excellent runoff reduction and therefore flood mitigation potential. The above preliminary results indicate that soil media B has the ability in attenuating peak flow-rate and reducing bypass runoff for large events. However, more experiments of large events on hydraulic performance are needed to establish design guidelines for appropriate operation and maintenance procedures.

For more frequent 1:2 year events, no overflow was generated and ponding lasted no more than 24 hours for all columns in both 1st summer and 2nd summer. As water runs through soil media B columns quickly, ponding water was not formed on Column 2 at all throughout the study period and ponding water was formed on Column 4 occasionally but vanished within 3 hours. This indicates that soil media B has the potential to attenuate stormwater runoff and reduce subsequent flooding risk.

In summary, all columns successfully managed 1:2 year events, as well as larger volume events.

Table 9: Maximum ponding depth and duration for 1:5 and 1:10 year events

Column	**Maximum ponding depth (cm)**		**Ponding duration (hr)**	
	1:5 year event	1:10 year event	1:5 year event	1:10 year event
Column 1	17.9	25.5	6.8	9.8
Column 2	4.4	13.0	1.6	2.9
Column 3	16.0	21.1	6.0	7.8
Column 4	16.5	20.0	3.9	4.8

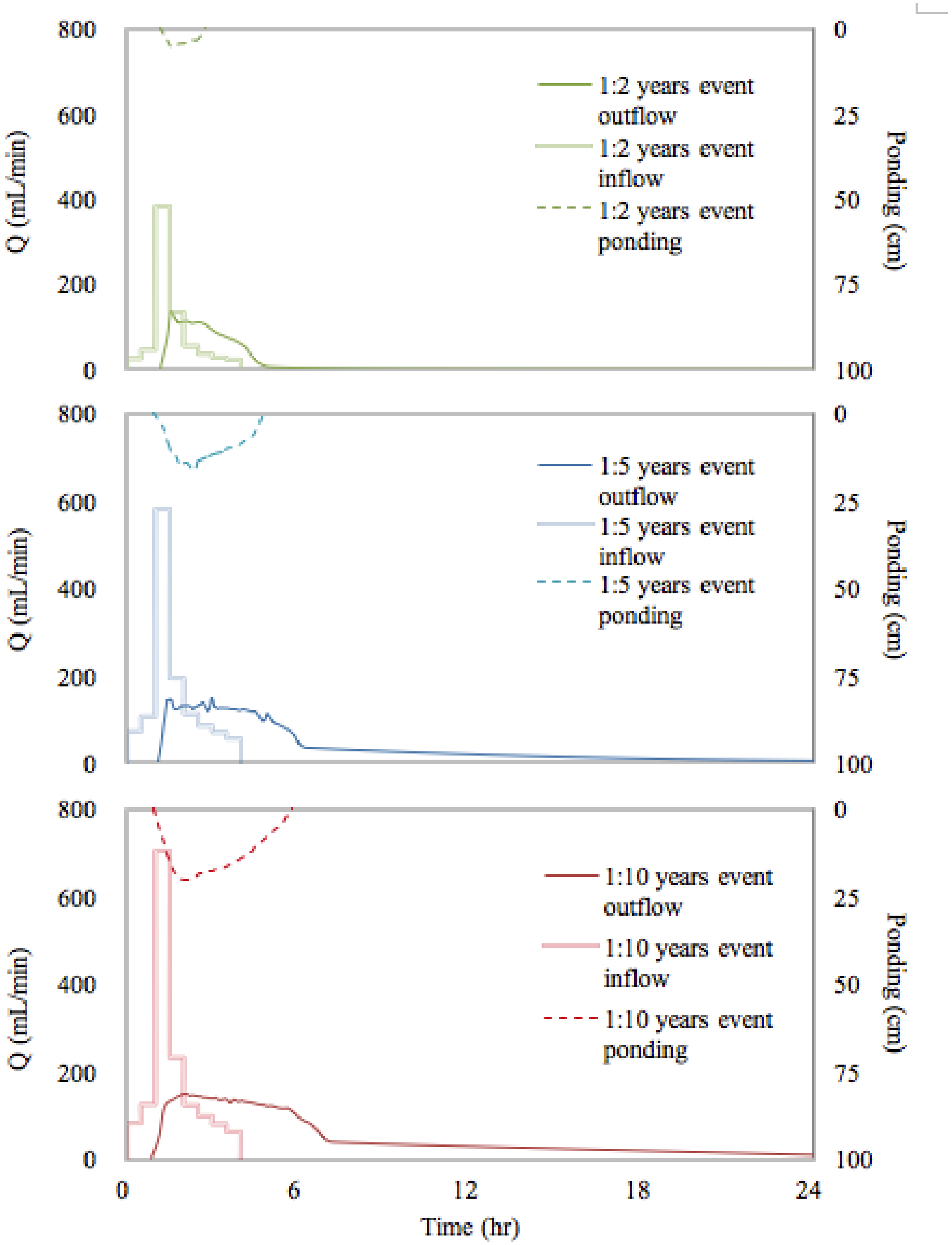


Figure 17: Comparison of inflow and outflow hydrographs and ponding depth for 1:2, 1:5, and 1:10 year events on Column 4 conducted in Week 40, Week 42 and Week 43

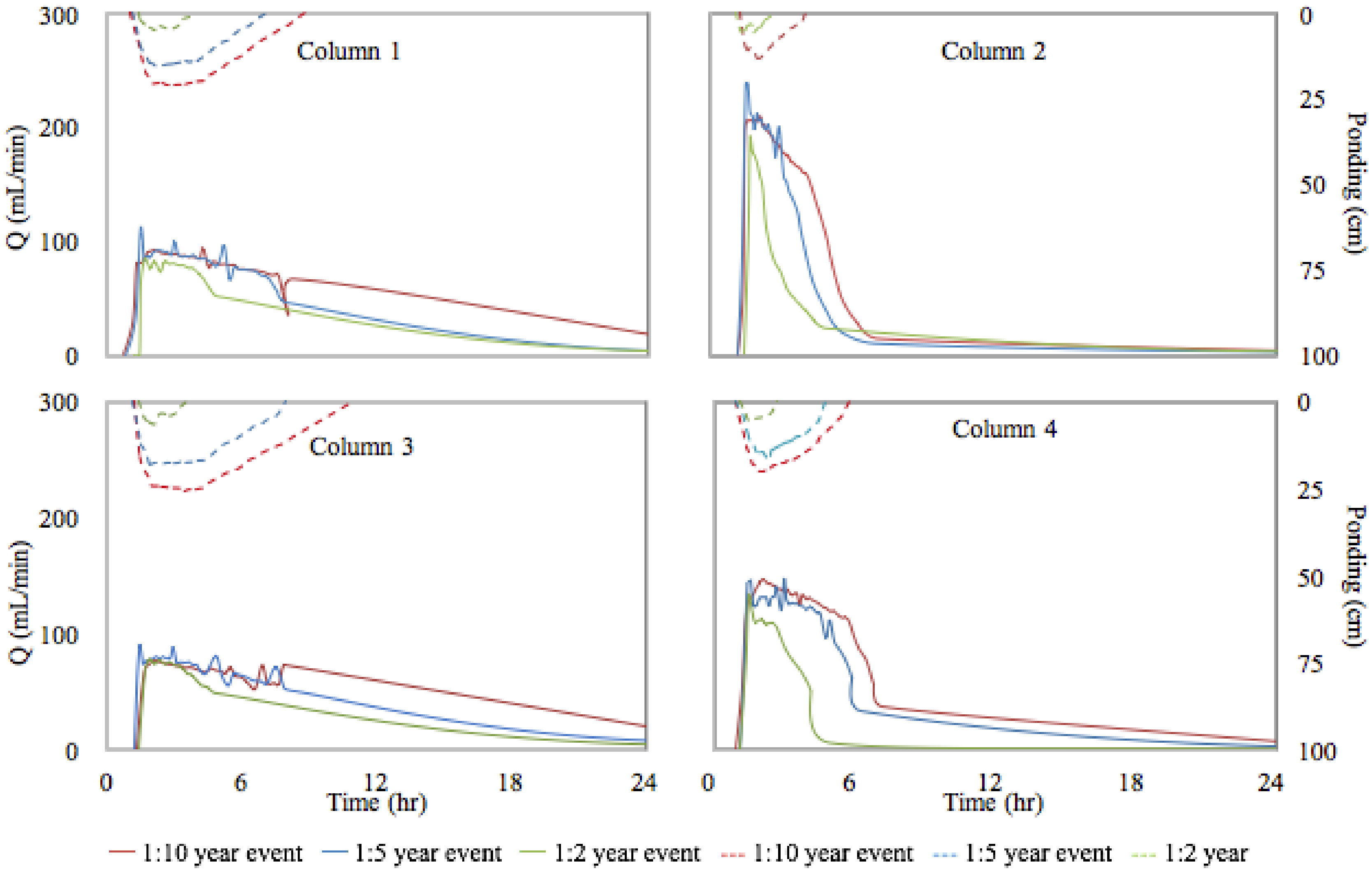


Figure 18: Comparison of outflow hydrographs and ponding depth for 1:2, 1:5, and 1:10 year events on four columns conducted in Week 40, Week 42 and Week 43

CHAPTER 5: CONCLUSIONS AND FUTURE RESEARCH

5.1 Hydraulic Performance

Over the entire study period, 30 designed events were conducted on four large column bioretention cells to investigate the impacts of two soil types and an internal water storage layer on hydraulic performance in cold, semi-arid climate such as in Edmonton.

1) Based on the laboratory experimental conditions, all designed bioretention columns have stabilized outflow hydrographs after running 3-6 weekly events, indicating columns were matured in terms of hydraulic performance.
2) In summer conditions, soil media A (50.8% sand, 29.4% silt, and 19.8% clay) can smooth stormwater outflow hydrographs by reducing peak flow 83% and 91% for Column 1 and Column 3 respectively, for 1:2 year events. Soil media B (67.2% sand, 19.6% silt, and 13.2% clay) reduced peak flow by 31% and 70% for column 2 and column 4, respectively, for 1:2 year events.
3) Soli media A achieved a hydraulic conductivity of 1.7 cm/hr and 1.6 cm/hr for Column 1 and Column 3 respectively. Soil B can achieve a high hydraulic conductivity of 16.0 cm/hr and 11.6 cm/hr for Column 2 and Column 4 respectively, which is needed for cold weather operation.
4) In winter conditions, columns with soil media A took 67 hours and 61 hours for soil thawing and snowmelt breakthrough in Column 1 and Column 3 respectively. Columns with soil media B took 46 hours and 51 hours for soil thawing and snowmelt breakthrough in Column 2 and Column 4 respectively. These preliminary results showed the soil media B can potentially maintain hydraulic performance during intermittent warming periods in Edmonton's winter.
5) After three freeze-thaw cycles, all designed bioretention columns can effectively capture and infiltrate designed spring runoff with high volume melted snow with no ponding formed.

6) Before and after one season of winter operation, the hydraulic conductivity on the columns was changed over time. The soil media A columns experienced an increase in hydraulic conductivity after winter, likely due to the freeze-thaw cycle expanding pore spaces. The soil media B columns experienced the opposite, which is probably due to the snowmelt causing compaction of the pore spaces. After 2nd summer operation, hydraulic conductivity decreased for all columns due to compaction by the hydraulic loading. Overall, columns with soil media B constantly have a high hydraulic conductivity that closes to 10 cm/hr throughout the study. The soil media A still maintained a capacity greater than the minimum requirement of 2.5 cm/hr. However, experiments simulating multiple years of operation are needed to truly evaluate the lifetime of these bioretention cells to see if the infiltration rate continues to increase in the soil media A and decrease in the soil media B.
7) During 1st summer and 2nd summer operations, all columns effectively managed 1:2 year events (22 events in total) in terms of the infiltration rate, ponding depths and durations being within City of Edmonton guidelines. The less frequent 1:5 and 1:10 year events were only conducted once for each, but these preliminary results showed that both soil media A and B can accept and drain the large volume within typical guideline requirements. The soil media B columns' ponding only lasted less than 4.8 hours for the 1:10 year event, indicating these columns had excellent bypass runoff reduction and therefore flood mitigation potential.

Overall, this study showed that the designed bioretention cells can perform well on hydraulic performance for more frequent, small volume events. After columns underwent an extreme winter condition of columns frozen at −20 °C air temperature three times, their hydraulic performance was able to rebound quickly. The high infiltration capacity of soil media B helps maintain hydraulic performance to a certain degree during intermittent warming periods in winter, and potentially help mitigate flooding issues in summer.

5.2 Significance

Based on the preliminary results from two summer seasons and one winter season operation, both these two types of soil media were successful in managing 1:2 year events with no overflow generated. This indicates that soil media with a sand (particle size>50 µm) portion ranged from 51% to 67% may be adequate for applications in Edmonton bioretention systems.

Soil media A (i.e. loam) with more clay content can minimize peak outflow. If peak flow reduction and low cost are desired, soil media A is recommended as its functionality for small volume events (1:2 year events) and lower cost from less sand. Soil media B (i.e. sandy loam) with more sand content can maintain a hydraulic conductivity that closes to 10 cm/hr after a winter exposure. This capacity of soil media B enables bioretention cells to function during intermittent warming periods and infiltrate snowmelt within few days. Soil media B also has a better potential than media A in flood mitigation for large volume events (1:5 and 1:10 year events). If flooding control and snowmelt infiltration are desired, soil media B is recommended for bioretention applications in Edmonton area.

This study shows that bioretention systems may function under multiple freeze-thaw cycles in which the air temperature reached −20 °C and soil core was solidly frozen. After columns underwent an extreme winter condition, their hydraulic performance was able to rebound quickly. These findings support bioretention systems to be implemented in Edmonton area.

5.3 Recommendations for Future Research

During the one year study period, 1.6 years equivalent annual precipitation was applied to each column. Simulation of multiple years of operation is needed in the future to truly evaluate the lifetime of these bioretention cells.

Large volume, less frequent events were also conducted only once with one 1:5 and one 1:10 year event. Further experimental studies are needed to truly evaluate large volume, less frequent events on hydraulic performance.

Vegetation did not grow back after being out of the cold room for a few months. This hindered the role of the vegetation played on hydraulic and water quality performance for bioretention in 2nd summer. With proper vegetation establishment, a better treatment performance can be expected.

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APPENDIX A: DAILY MAX TEMPERATURES FOR WINTER (MID-NOVEMBER TO MID-MARCH) IN EDMONTON FROM 2005-2015

Date	**2014 to 2015**	**2013 to 2014**	**2012 to 2013**	**2011 to 2012**	**2010 to 2011**	**2009 to 2010**	**2008 to 2009**	**2007 to 2008**	**2006 to 2007**	**2005 to 2006**
15-Nov	-1.6	**4.8**	**2.0**	-5.8	**6.2**	**5.6**	**7.9**	**2.3**	**5.3**	-5.9
16-Nov	-6.5	-	**0.9**	-3.3	-3.0	**14.8**	**1.3**	**1.1**	**5.4**	**5.2**
17-Nov	**1.7**	-10.2	-0.4	-7.8	-10.2	**17.4**	**2.2**	**2.0**	**3.2**	**10.3**
18-Nov	**2.2**	-13.1	**0.6**	-14.8	-12.6	**5.3**	**6.2**	**4.4**	**2.8**	**12.2**
19-Nov	-2.7	-	-3.9	-18.3	-14.1	**9.0**	-3.1	**2.4**	**8.2**	**13.5**
20-Nov	**5.7**	-17.5	-7.8	-16.0	-15.1	**6.5**	-0.3	-5.2	**4.4**	**12.3**
21-Nov	**6.7**	-11.3	-12.6	-9.1	-14.2	**1.7**	**4.4**	-3.0	-0.9	**11.4**
22-Nov	**2.4**	-9.1	-8.6	**6.3**	-16.7	**1.1**	**7.2**	**3.2**	-13.9	**18.8**
23-Nov	-1.7	**0.8**	-7.0	**1.8**	-19.0	**1.9**	**3.8**	**4.5**	-15.0	**14.9**
24-Nov	**1.5**	**3.9**	-5.1	**0.3**	-11.9	**2.8**	**8.1**	**3.3**	-16.6	**11.2**
25-Nov	-3.5	-1.8	-6.4	**2.7**	**3.4**	**2.9**	**7.2**	**1.4**	-19.3	**8.9**
26-Nov	-5.7	**2.0**	-7.0	**4.4**	**3.4**	**3.5**	**5.0**	-15.5	-21.3	**3.4**
27-Nov	-9.3	**0.7**	-2.9	**9.3**	**0.2**	**2.3**	**3.8**	-12.7	-21.8	**1.1**
28-Nov	-18.1	-6.1	-6.0	**1.9**	-3.6	**2.2**	**3.5**	-13.1	-23.6	-3.3
29-Nov	-19.9	**0.2**	-13.2	**5.5**	-4.5	**7.9**	**6.7**	-11.2	-15.6	-10.7
30-Nov	-17.5	-1.1	-12.7	**1.8**	-7.1	**4.4**	**5.1**	-11.2	-3.6	-11.8
1-Dec	-8.4	-2.2	-12.6	**5.9**	-5.8	-2.5	**7.2**	-	-13.6	-12.3
2-Dec	-7.4	-3.5	-12.7	**5.7**	-4.6	-6.1	-2.2	-16.4	-10.2	-12.6
3-Dec	-1.4	-12.8	-12.1	-0.9	-6.0	-9.3	-7.1	-16.4	-2.8	-15.0
4-Dec	-2.6	-15.5	-7.1	-4.9	-6.0	-2.2	-2.8	-15.5	-2.3	-14.6
5-Dec	-4.5	-20.3	-9.1	**5.8**	-5.1	-3.8	**3.6**	-15.2	**2.4**	-13.4
6-Dec	-6.8	-24.7	-14.6	**9.2**	-13.0	-13.3	**4.2**	-11.4	-3.8	-17.7
7-Dec	-0.3	-13.5	-14.5	-2.9	-11.8	-20.2	**3.9**	-10.9	**3.4**	-6.0
8-Dec	-4.1	-13.3	-14.8	-9.0	-9.4	-18.6	-9.0	-10.7	**3.5**	**3.9**

9-Dec	**12.7**	-4.6	-7.2	**3.7**	-10.1	-13.5	-5.8	-2.4	**1.7**	**8.6**
10-Dec	**8.7**	-7.7	-0.4	**5.6**	-14.6	-10.2	**3.5**	-2.8	-1.2	**12.1**
11-Dec	**9.2**	-10.5	**2.4**	-1.1	-13.6	-9.9	**1.0**	-3.0	**4.9**	**9.7**
12-Dec	**4.8**	-14.6	-13.2	-4.2	-10.8	-23.4	**0.1**	**2.1**	**7.9**	**4.4**
13-Dec	**1.9**	-17.3	-4.7	**0.6**	-1.1	-28.5	-18.1	-0.4	**1.1**	**1.6**
14-Dec	-1.9	-2.8	**2.6**	-0.4	-1.6	-25.3	-24.8	-0.2	**2.7**	**0.3**
15-Dec	-2.8	**4.2**	-6.8	-5.3	-1.0	-20.4	-13.2	-5.1	**0.7**	-5.0
16-Dec	-4.2	**2.7**	-4.2	**0.9**	-15.3	-11.8	-11.4	**0.1**	-5.6	-14.7
17-Dec	-4.5	**2.9**	-8.5	**2.9**	-11.4	-1.2	-12.5	-4.1	-9.1	-11.1
18-Dec	-3.9	-5.1	-10.9	**0.8**	-10.8	-2.7	-17.0	-2.6	**4.9**	-6.5
19-Dec	-2.8	-14.3	-10.9	**3.4**	-12.3	**0.5**	-21.2	-6.1	**4.7**	-2.6
20-Dec	**1.2**	-13.9	-10.7	**5.8**	-10.6	-7.2	-21.8	-7.7	**0.9**	-4.0
21-Dec	-0.9	-18.8	-14.1	-0.7	-14.7	-12.6	-20.8	-13.3	**7.8**	**7.3**
22-Dec	**2.1**	-17.1	-16.6	**3.0**	-16.7	-14	-22.2	-7.4	**1.0**	**4.8**
23-Dec	-0.2	**3.1**	-17.2	**6.0**	-15.5	-16.7	-17.5	-1.4	**0.4**	**8.7**
24-Dec	**0.9**	**2.2**	-20.7	**6.3**	-8.0	-12.2	-11.4	**2.6**	-0.1	**7.2**
25-Dec	-7.4	**3.0**	-20.4	**7.6**	-9.9	-8.5	-16.7	**0.4**	**2.2**	**6.9**
26-Dec	-5.8	**6.4**	-17.0	**5.7**	-8.7	-3.6	-14.0	-6.2	-0.8	**4.1**
27-Dec	-5.4	**4.9**	-19.1	**3.7**	-7.0	-10.0	-4.0	-6.7	-3.9	**2.7**
28-Dec	-11.4	-17.3	-4.4	-1.7	-5.7	-12.5	-4.3	-8.3	-3.6	**4.5**
29-Dec	-15.1	-11.5	-1.5	**4.6**	-13.2	-12.2	-10.0	-10.6	-3.6	0.0
30-Dec	-	-17.3	-2.9	-0.9	-14.8	-16.3	-15.1	-13.3	**1.6**	-1.4
31-Dec	**3.4**	-15.7	**1.0**	-2.8	-15.6	-20.4	-15.8	-9.2	-2.8	-2.2
1-Jan	**3.5**	-10.4	**2.0**	-2.8	-1.4	-16.4	-21.3	-8.6	-0.7	-1.5
2-Jan	-10.7	**2.2**	**1.1**	-1.1	-1.0	-14.8	-24.0	**2.5**	**8.6**	-3.4
3-Jan	-19.7	**0.4**	**3.0**	**5.3**	-1.6	-12.7	-23.6	-0.2	**6.2**	**0.7**
4-Jan	-21.7	-19.0	-2.5	**11.7**	**0.4**	-14.1	-7.7	**2.9**	**1.3**	**1.2**
5-Jan	-17.4	-	-1.4	**5.9**	**2.3**	-18.8	-7.5	**0.5**	-1.2	**6.8**
6-Jan	-16.4	-5.9	**1.4**	**1.9**	**2.7**	-17.7	-7.2	**0.9**	**0.2**	**5.1**
7-Jan	-7.4	-8.2	-0.1	**2.1**	-1.9	-12.5	-15.5	-2.9	**1.9**	-0.1

8-Jan	-12.8	-4.5	**1.2**	**8.5**	-5.9	-5.9	-15.3	-9.3	**2.9**	-0.8
9-Jan	-16.6	-0.9	-2.0	**10**	-13.3	**2.0**	-2.4	-16.4	-3.2	**2.5**
10-Jan	-13.8	**0.2**	-7.8	**3.9**	-16.0	**3.5**	**3.9**	-15.2	-6.2	**0.1**
11-Jan	-10.6	-0.9	-14.2	-3.2	-17.3	**5.9**	**2.2**	-1.4	-21.2	-1.5
12-Jan	-5.7	-2.4	-9.0	**1.2**	-22.5	**4.0**	-9.6	**0.8**	-9.3	-0.7
13-Jan	**4.3**	**1.6**	-9.3	**2.5**	-21.0	**0.5**	-0.2	**1.6**	-7.3	-2.4
14-Jan	**5.7**	-	**3.6**	-3.0	-23.6	**2.0**	-11.0	**0.6**	-12.1	-6.2
15-Jan	-1.4	**9.7**	**8.0**	-9.8	-21.6	**6.4**	**4.1**	-1.3	**0.7**	-5.4
16-Jan	**4.8**	**3.4**	**5.7**	-24.2	-20.5	**2.7**	**6.2**	**1.2**	**1.5**	-1.0
17-Jan	**4.2**	**6.6**	**5.8**	-27.9	-19.3	-2.1	**8.9**	**1.8**	-4.2	**2.5**
18-Jan	**0.9**	**8.0**	**6.2**	-21.2	-4.5	-2.9	**9.3**	-9.9	-4.9	-0.1
19-Jan	**4.7**	**6.8**	-8.0	-17.7	-4.6	**0.2**	**7.9**	-10.1	-0.7	-8.5
20-Jan	**2.6**	**0.8**	-17.7	-16.2	**3.6**	-8.6	**6.1**	-13.9	-2.5	-7.5
21-Jan	**5.5**	**0.9**	-11.8	-14.5	**2.6**	-7.5	**4.7**	-3.5	-4.1	-6.6
22-Jan	**9.9**	-7.6	-11.5	**1.4**	**3.1**	-5.1	-5.6	-1.1	**5.0**	**5.2**
23-Jan	**7.9**	**6.2**	-12.5	**2.6**	**7.2**	-5.4	-19.5	-1.7	**5.1**	**5.7**
24-Jan	**6.3**	**7.4**	-5.1	**0.9**	**3.7**	-8.1	-18.9	-7.1	**5.1**	**7.2**
25-Jan	**9.6**	**7.0**	**3.0**	**3.7**	**5.8**	-12.4	-13.9	-7.0	**8.4**	**8.7**
26-Jan	**7.5**	**3.3**	**0.6**	-1.5	**6.6**	-14.4	-9.6	-1.2	-3.2	**4.7**
27-Jan	**2.6**	-10.0	-2.2	**0.2**	**8.7**	-10.4	**2.3**	-4.3	-3.5	-2.1
28-Jan	**0.1**	**2.3**	-8.8	-2.7	**2.7**	-8.7	**0.4**	-27.5	-0.7	-4.8
29-Jan	-1.4	-4.0	-21.7	**1.2**	-12.4	-10.2	**3.5**	-27.4	-5.3	**0.4**
30-Jan	-3.4	-14.7	-22.0	**4.9**	-19.8	-9.7	**6.4**	-24.1	-1.7	-3.7
31-Jan	-12.9	-	-6.7	**5.4**	-20.8	-10.2	**1.6**	-24.4	-4.3	-2.3
1-Feb	-12.4	-7.3	**3.6**	**1.7**	-11.8	-6.4	-2.0	-19.2	-10.1	-1.7
2-Feb	-13.2	-8.1	**3.0**	**2.5**	**6.8**	-7.4	-1.1	-12.8	-11.3	**6.9**
3-Feb	-13.2	-11.1	**3.6**	**6.2**	**6.1**	-4.7	**4.8**	-17.2	-8.9	**7.5**
4-Feb	-0.7	-18.7	**3.1**	**4.6**	**6.8**	-6.6	**7.4**	-14.7	-9.8	**1.3**
5-Feb	-3.9	-18.3	-2.3	**2.3**	**2.6**	-8.9	**4.1**	-4.3	-5.1	-1.4
6-Feb	-16.3	-10.3	-2.6	-2.0	-10.4	-6.7	-2.5	-0.4	-12.2	-1.5
7-Feb	-13.2	-11.6	-4.7	-1.7	-10.1	-5.9	**4.0**	-12.4	-11.1	**2.7**
8-Feb	-12.4	-13.9	**2.5**	-4.6	-10.1	-5.6	**4.5**	-18.0	-15.4	**7.0**
9-Feb	-14.2	-18.0	**3.8**	-6.3	**0.7**	-2.4	-1.5	-24.6	-16.0	**1.1**
10-Feb	-11.5	-17.6	-2.8	-9.4	**3.9**	**1.7**	-1.7	-14.6	-10.6	**0.0**
11-Feb	-9.8	-18.2	**4.9**	-5.8	**6.4**	-1.7	-3.9	**1.6**	-14.1	**9.7**
12-Feb	**4.9**	-14.8	**4.2**	**5.8**	**5.4**	-8.6	-9.7	**0.5**	-17	**11.7**
13-Feb	**2.9**	-11.1	**3.0**	**3.5**	**5.4**	-6.1	-14.6	-10.7	-16.7	**6.7**
14-Feb	**3.1**	-4.9	-0.1	-0.1	**7.2**	-5.1	-11.8	-0.3	-7.1	-2.3
15-Feb	**3.7**	**0.6**	**8.9**	**3.1**	-2.6	**4.8**	-11.1	**9.6**	**4.5**	-7.9

16-Feb	**1.5**	-4.9	**4.6**	**2.2**	-18.3	**1.0**	-9.2	**4.3**	**2.7**	-20.2
17-Feb	-6.1	**4.0**	**1.8**	**5.0**	-20.2	**2.3**	-4.4	**0.3**	**3.8**	-5.3
18-Feb	**4.9**	**3.9**	-5.0	-0.3	-20.2	**2.0**	-0.3	**5.8**	**4.5**	-3.9
19-Feb	**6.5**	-0.5	-9.0	-1.0	-18.0	-2.4	-4.0	-3.2	-5.8	**3.2**
20-Feb	**3.5**	-3.9	-5.0	-1.4	-11.9	-6.3	-2.4	**2.1**	**1.1**	**1.6**
21-Feb	-6.9	-9.5	-3.4	**5.9**	-0.7	**0.4**	-1.2	**9.0**	-8.4	**0.0**
22-Feb	**0.4**	-14.5	**1.2**	**2.9**	-4.2	-5.1	-1.9	**3.6**	-7.3	-5.6
23-Feb	**8.3**	-18.8	**2.6**	**1.8**	-16.4	-5.1	-7.9	**2.4**	-4.1	-7.7
24-Feb	**6.8**	-11.9	**4.2**	-3.6	-20.8	**4.2**	-14.3	**1.8**	-0.1	-6.8
25-Feb	-8.2	-8.5	**0.4**	-8.7	-9.1	**5.5**	-18.5	**2.1**	-7.8	-10.9
26-Feb	-9.4	-5.3	-0.5	-10.9	-3.8	**7.3**	-17.5	**6.3**	-7.3	-9.3
27-Feb	-8.8	-7.0	-1.5	-5.2	-6.5	**0.6**	-4.7	**6.1**	-9.2	-5.7
28-Feb	-2.5	-18.7	**5.9**	-2.2	-19.8	**7.0**	-10.7	**4.2**	-7.7	-6.7
29-Feb	-	-	-	-8.4	-	-	-	**6.2**	-	-
1-Mar	-1.5	-22.3	**6.0**	-7.6	-20.6	**6.0**	-10.3	**4.1**	-8.6	-7.9
2-Mar	-1.4	-20.4	**4.1**	**0.4**	-21.2	**2.8**	-5.5	-6.3	-6.8	-9.1
3-Mar	-10.6	-16.2	**0.1**	**2.4**	-18.4	**7.2**	**0.6**	**1.9**	**9.9**	-9.8
4-Mar	-3.5	-14.9	-2.4	**1.0**	-12.7	**8.6**	**6.7**	**0.4**	-4.5	-8.2
5-Mar	**5.9**	-13.3	-2.8	-1.7	-13.5	**8.7**	-5.7	-1.7	-10.3	-6.0
6-Mar	**6.0**	-14.6	-3.9	-5.2	-14.1	**10.4**	-10.1	**0.3**	-6.3	0.0
7-Mar	**6.3**	-	-6.0	**3.0**	-10.5	**8.7**	**0.2**	**7.0**	**10.4**	**4.4**
8-Mar	**11.5**	-	-0.1	**5.2**	-6.9	**3.7**	-12.6	**10.3**	**9.0**	**4.1**
9-Mar	**10.0**	**9.5**	**1.5**	**13.5**	**0.4**	-	-22.8	**7.5**	**10.6**	**1.1**
10-Mar	**5.2**	**5.8**	**6.2**	**8.1**	-11.0	**3.5**	-19.9	**11.5**	**5.8**	-1.4
11-Mar	**3.5**	**7.2**	**2.2**	**8.9**	-16.5	**6.2**	-7.8	**11.4**	**6.4**	-4.9
12-Mar	**14.0**	**12.7**	**0.1**	**7.0**	-6.6	**9.1**	**4.9**	**6.5**	**3.6**	-8.1
13-Mar	**15.1**	**5.8**	-3.4	**7.6**	**3.4**	**5.8**	**10.0**	**2.5**	**2.4**	-7.0
14-Mar	**16.8**	**4.4**	-12.2	**5.5**	**5.5**	**7.8**	**1.8**	-0.1	-1.9	-3.7
15-Mar	**8.2**	**7.9**	-12.3	**9.1**	**2.9**	**12.2**	-3.9	-2.5	**2.8**	-1.2

All data is based on Edmonton City Centre AWOS station (Environment Canada, 2018).
-No data available

APPENDIX B: EXPERIMENT RESULTS

Date	Column	Peak outflow rate (mL/min)	Peak flow reduction	Peak delay (min)	Volume reduction	Maximum ponding depth (cm)	Ponding duration (hr)
2017/9/26	1	-*	-*	-*	84%	-*	-*
	2	157	60%	52	11%	-	-
2017/10/10	1	115	70%	84	15%	-*	-*
	2	306	21%	35	3%	-	-
2017/10/17	1	81	79%	115	8%	-*	-*
	2	328	15%	28	13%	-	-
	3	-+	-+	-+	98%	-+	-+
	4	-+	-+	-+	98%	-+	-+
2017/10/24	1	71	82%	101	7%	-*	-*
	2	317	18%	32	6%	-	-
	3	24	94%	442	40%	8.2	<24hr
	4	106	72%	30	40%	-	-
2017/10/30	1	59	85%	120	8%	-*	-*
	2	285	26%	33	9%	-	-
	3	68	82%	36	14%	8.5	<24hr

Date	Column	Peak outflow rate (mL/min)	Peak flow reduction	Peak delay (min)	Volume reduction	Maximum ponding depth (cm)	Ponding duration (hr)
	4	155	60%	27	9%	1.5	1.0
2017/11/6	1	58	85%	130	12%	-*	-*
	2	194	49%	42	12%	-	-
	3	49	87%	55	13%	6.5	<24hr
	4	144	63%	42	9%	-	-
2017/11/14	1	70	82%	96	6%	3.2	1.2
	2	205	47%	42	8%	-	-
	3	-*	-*	-*	9%	-*	-*
	4	-*	-*	-*	14%	-*	-*
2017/11/20	1	55	86%	165	10%	7.0	3.4
	2	288	25%	33	12%	-	-
	3	29	93%	96	9%	4.2	6.3
	4	60	84%	58	7%	-	-
2017/11/27	1	60	84%	140	5%	7.5	3.4
	2	240	38%	39	4%	-	-
	3	29	93%	72	11%	8.7	<24hr
	4	125	67%	112	3%	5.8	2.0

Date	**Column**	**Peak outflow rate (mL/min)**	**Peak flow reduction**	**Peak delay (min)**	**Volume reduction**	**Maximum ponding depth (cm)**	**Ponding duration (hr)**
2017/12/4	1	57	85%	153	8%	5.5	2.6
	2	319	17%	38	5%	-	-
	3	24	94%	45	14%	6.0	<24hr
	4	76	80%	48	5%	-	-
2017/12/11	1	55	84%	97	19%	7.0	3.2
	2	306	20%	34	-9%	-	-
	3	37	90%	35	5%	9.9	<24hr
	4	113	70%	33	4%	4.2	1.8
2017/12/18	1	55	84%	113	7%	4.3	3.0
	2	239	28%	38	8%	-	-
	3	31	92%	71	5%	9.8	<24hr
	4	129	70%	78	7%	6.3	2.0
2017/12/26	1	-*	-*	-*	6%	-*	-*
	2	-*	-*	-*	5%	-*	-*
	3	-*	-*	-*	13%	-*	-*
	4	-*	-*	-*	7%	-*	-*
2018/1/2	1	55	86%	102	7%	7.2	3.7

Date	**Column**	**Peak outflow rate (mL/min)**	**Peak flow reduction**	**Peak delay (min)**	**Volume reduction**	**Maximum ponding depth (cm)**	**Ponding duration (hr)**
	2	239	28%	38	8%	-	-
	3	35	92%	43	1%	12.8	<24hr
	4	192	53%	60	2%	5.3	1.9
2018/1/8	1	54	86%	119	6%	6.7	3.6
	2	249	27%	38	6%	-	-
	3	33	92%	40	7%	11.1	<24hr
	4	121	74%	36	4%	6.2	2.0
2018/1/15	1	55	85%	83	6%	7.4	3.0
	2	179	46%	42	5%	-	-
	3	31	92%	57	9%	11.8	<24hr
	4	119	73%	36	5%	5.7	1.9
2018/1/23	3	36	91%	38	15%	11.6	<24hr
	4	127	71%	32	8%	5.9	1.9
2018/1/30	3	30	92%	63	12%	10.8	<24hr
	4	118	68%	98	8%	5.8	1.6
2018/2/7	1	-*	-*	-*	-*	-*	-*
	2	-*	-*	-*	-*	-*	-*

Date	**Column**	**Peak outflow rate (mL/min)**	**Peak flow reduction**	**Peak delay (min)**	**Volume reduction**	**Maximum ponding depth (cm)**	**Ponding duration (hr)**
	3	-*	-*	-*	-*	-*	-*
	4	-*	-*	-*	-*	-*	-*
2018/6/14	1	95	75%	66	7%	2.5	1.2
	2	205	47%	36	4%	-	-
	3	152	61%	58	55%	5.7	3.7
	4	139	64%	65	51%	-	-
2018/6/21	1	91	76%	94	6%	4.3	2.2
	2	200	48%	53	4%	-	-
	3	92	76%	94	7%	4.6	3.2
	4	119	69%	48	15%	3.5	1.4
2018/6/26	1	78	80%	70	14%	4.9	2.4
	2	94	50%	42	16%	-	-
	3	86	78%	37	7%	7.0	3.2
	4	130	66%	34	5%	5.0	2.0
2018/7/4	1	77	80%	54	8%	6.3	2.4
	2	191	50%	39	11%	-	-
	3	85	78%	38	4%	4.7	2.6

Date	**Column**	**Peak outflow rate (mL/min)**	**Peak flow reduction**	**Peak delay (min)**	**Volume reduction**	**Maximum ponding depth (cm)**	**Ponding duration (hr)**
	4	133	65%	32	23%	5.3	1.6
2018/7/9	1	94	76%	57	3%	8.3	2.5
	2	235	39%	57	2%	-	-
	3	102	74%	64	3%	6.8	3.4
	4	145	62%	63	2%	6.6	1.2
2018/7/16	1	90	85%	28	6%	17.9	6.8
	2	285	51%	29	6%	4.4	1.6
	3	130	78%	20	5%	16.0	6.0
	4	174	70%	19	6%	16.5	3.9
2018/7/23	1	109	84%	421	6%	25.5	9.8
	2	209	70%	68	8%	13.0	2.9
	3	94	87%	197	13%	21.1	7.8
	4	147	79%	64	6%	20.0	4.8

-[+] No outflow was generated for the first event on Column 3 and Column 4

-[*]The data was not recorded accordingly due to human error.

- No ponding formed.