**Hydrologic and Water Quality Modeling of Bioretention Columns in Cold Regions**

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**ABSTRACT:** Bioretention is widely used in urban sustainable stormwater management. However, limited numerical research has been conducted on its performance in cold regions, particularly for winter snowmelt, spring runoff and summer large storms (> 50 mm) for urban flood mitigation. In this study, HYDRUS 1D was used to explore these knowledge gaps. The model was comprehensively calibrated and validated against 2-year hydrologic and water quality data of four bioretention columns with different designs under lab-simulated cold region conditions. The Morris method was used to measure the sensitivity and interaction of the calibrated hydraulic parameters. The model revealed that the effective hydraulic conductivity (*KS*) values of the soil media were similar for winter snowmelt and spring runoff when the soil temperature was around -0.5 °C. Preferential flow is likely to occur in soil media during winter or spring of cold regions. The summer modeling showed that the bioretention could substantially reduce peak flow, ponding depth and duration for large storm events (even for 1:100 local storm with 83.4 mm in 4 hours). The water quality modeling confirmed experimental results that the bioretention effectively removed phosphate and ammonium but had leaching issues for chloride and nitrate. Finally, optimization and recommendations of bioretention columns were provided.

**Keywords**: Bioretention, Cold Region, Hydrological Performance, HYDRUS 1D, Large Storm, Water Quality

# 1. Introduction

Increasing disturbance in land use due to urbanization has substantially changed urban hydrological cycle and pollutant loads, causing significant impacts to aquatic environments (Rashid et al., 2018; Salerno et al., 2018; Freeman et al., 2019). Low Impact Development (LID) is a sustainable approach to land development that works with nature to manage stormwater as close to the source as possible in terms of both water quantity (peak and volume) and water quality (Coffman, 2002; HUD, 2003; US EPA, 2010; Eckart et al., 2017). LID facilities replace or complement the conventional storm sewer system and create a hydrologically functional landscape where runoff can be micromanaged and controlled within each LID site (Coffman, 2002; Pour et al., 2020).

The bioretention system is one of the most recognized LID-BMPs (best management practices) for urban stormwater management (Davis et al., 2009). Bioretention captures stormwater runoff in a shallow depression treatment area, which typically consists of several layers, including ponding layer, organic or mulch layer, plants and planting soil layer, soil filtration media layer, and optional underdrain or drainage layer (US EPA, 2000; COE, 2014a; Liu et al., 2014). In recent years, bioretention has been used more and more globally (Shrestha et al., 2018). Meanwhile, there is a substantial growth in studies that tested bioretention’s hydrological performance and water quality treatment ability through laboratory and/or field experiments (Spraakman et al., 2020).

Bioretention has been demonstrated to significantly reduce runoff volume and peak and delay peaks for relatively small storm events (Davis, 2008; Hunt et al., 2008; Meng et al., 2014; Liu and Fassman-Beck, 2017a, 2017b; Shafique and Kim, 2017; Xia et al., 2018). However, limited tests and experiments have examined its performance during large storm events (Khan et al., 2012a, 2012b; Jackisch and Weiler, 2017; Bacys et al., 2019; Sohn et al., 2019; Wang et al., 2021). According to these studies, the overall functionality of bioretention decreases as rainfall becomes more intense. Therefore, more efforts are imperative to evaluate and improve its performance for large storm events, particularly in the context of climate change that will induce more extreme rainfalls in the future for certain regions (Sun et al., 2018; IPCC, 2021).

Bioretention has also been reported to be promising in reducing pollutant loads or concentrations (Davis, 2007; Passeport et al, 2009; Chapman and Horner, 2010; DeBusk and Wynn, 2011; Mangangka et al., 2015; Shrestha et al., 2018). Recent studies show the potential of bioretention in removing dissolved nutrients especially nitrogen and phosphorus (Yang and Lusk, 2018; Luo et. al., 2020). Field and laboratory results illustrated significant removals of total suspended solids (TSS), total phosphorus (TP), ammonia (NH4+-N), total nitrogen (TN), heavy metals and oil and grease, which are up to 54 - 99%, 85.6 - 92.4%, 83.1 - 92.7%, 57.1 - 74.1%, 74 - 99% and > 90%, respectively, in terms of concentrations (Hsieh and Davis, 2005a, 2005b; Davis et al., 2009; Luo et al., 2020). However, removal of dissolved nutrients can be highly variable, depending on the design configurations including vegetation, soil media amendments and the existence of internal water storage zone (IWS) (Hatt et al., 2009; David et al., 2017; Shrestha et al., 2018). More water quality studies are needed to examine the effectiveness of different configurations.

In cold regions, bioretention has been insufficiently studied in terms of both hydrological performance and pollutant removal, particularly the effect of freeze-thaw cycles (Kratky et al., 2017; Ding et al., 2019). Soil infiltration rate is the key parameter that affects bioretention performances (Muthanna et al., 2008). When the soil temperature is below the range of 0 to -0.6 °C, soil such as sand, loam, sandy loam and silt loam becomes frozen and impermeable (Watanabe et al., 2011; Watanabe and Osada, 2017). And pore ice (frost) formed by frozen moisture blocks the soil pores and therefore reduces soil hydraulic conductivity (Flerchinger et al., 2005). Several studies found that bioretention had different hydrological performance in winter (when soil was partially frozen) compared to summer (Muthanna et al., 2008; Al-Houri et al., 2009; Roseen et al., 2009; Khan et al., 2012b). Different factors of soil media, vegetation, snow accumulation, inflow pattern, freeze-thaw cycle frequency, preferential flow and others could contribute to the varieties of bioretention performance in cold climates (Paus et al., 2016; Kratky et al., 2017; Shrestha et al., 2018; Ding et al., 2019). Hence, more mechanism-oriented studies are desired (Ding et al., 2019).

In fact, freeze-thaw cycles are frequently encountered in cold regions when days are warm, and nights are cold. For example, in the City of Edmonton of Canada (the location of this study), the average freeze-thaw cycles are 12-18 per month in March, April, October and November (Edmonton weather nerdery, 2019). Frequent freeze-thaw cycles can bring challenges and changes to the stability and performance of bioretention (Ding et al., 2019). Wang et al. (2015) reported that silty soil with different degrees of compactness experienced different levels of deformation and changes of strength property after repeated freeze-thaw cycles.

Another common challenge that bioretention is facing in cold regions is water quality concerns due to high concentrations of sodium chloride (and/or calcium chloride) in runoff resulted from the use large amounts of road de-icing salts (Fay et al., 2019), which brings issues such as plant health and media clogging (Denich et al., 2013). Such inflow of high salts into bioretention during snowmelt and spring runoff events can increase effluent phosphorus concentration and consistent release of high concentrations of sodium and chloride in spring (Denich et al., 2013; McManus and Davis, 2020; Goor et al., 2021). Only a few studies (Khan et al., 2012b; Denich, 2018) investigated the removal of chloride by bioretention but with different results. Denich (2013) and Khan et al. (2012b) reported chloride ions are difficult to remove (i.e., leaching issue), but Denich (2018) reported a chloride removal rate of 45 - 85%. The other concern on cold region bioretention is its long-term performance, which has been inadequately studied (Spraakman et al., 2020). According to existing studies (Davis et al., 2009; Liu et al., 2014; Kratky et al., 2017; Willard et al., 2017; Johnson and Hunt, 2020; Wang et al., 2021), the overall performance of bioretention decreases as it ages.

Numerical tools can be efficient and useful in exploring these challenges. There are numerous models for bioretention such as MOUSE, SWMM, MUSIC, HEC-HMS, SWAT, and L-THIA-LID. These models are used typically for large-scale stormwater management and therefore more suitable for preliminary and conceptual designs of LID (Elliott and Trowsdale, 2007; Kaykhosravi et al., 2018). RECARGA, HYDRUS 1D and GIF-MOD are considered as suitable tools for the design and optimization of single-unit bioretention (Kaykhosravi et al., 2018) because of their abilities to model multiple layers of soil or porous media, surface ponding, water movement, vapor flow, root water uptake, and snow hydrology. RECARGA is recommended for estimation because of its restrictions in soil types (pre-specified), soil layers (maximum 3), boundary conditions (non-definable), and underdrain location (fixed) (Kaykhosravi et al., 2018). HYDRUS 1D and GIF-MOD are both capable of modeling customized soil media layers (can be > 3 layers), solute transport through soil columns, and features with inverse modeling for model calibration. DRAINMOD is also used to model bioretention hydrological performance (Brown et al., 2013; Winston et al., 2016), but its minimum temporal resolution is hours and therefore modeling a single storm event is restricted (Skaggs et al., 2012). Lisenbee et al. (2020) introduced DRAINMOD-Urban to allow higher temporal resolution.

Recent modeling studies from 2011 to 2021 are summarized in Table 1 for bioretention with typical media structure (i.e., planting soil on the top, engineered soil in the middle, and drainage layer at the bottom). This table shows that 50% (5/10) of them used HYDRUS 1D, 20% used SWMM, 20% used DRAINMOD, and 10% used 2D variable saturated flow model. Liu and Fassman-Beck (2017a, 2017b) conducted numerical simulations using HYDRUS 1D and SWMM and illustrated that HYDRUS 1D had better accuracy for single-unit bioretention. Meng et al. (2014) and Jiang et al. (2019) employed HYDRUS 1D to simulate the hydrological performance of bioretention with R2 > 0.70 for the outflow hydrograph. HYDRUS 1D was also used in Li et al. (2018) and Li, Liu, et al. (2021) to simulate nutrients and heavy metals removal in bioretention with different types of soil amendments. In other studies (e.g., Brown et al., 2013; Lisenbee et al., 2020), DRAINMOD and other tools have shown their limitations in modeling single-unit bioretention (e.g., limitations of time scales, boundary conditions, auto-calibration capacities, and soil structure). With the overall good performance in modeling hydrologic processes and pollutant removal, as well as its capacity to model heat transport (Xiang et al., 2012), HYDRUS 1D appears to be promising for modeling bioretention in cold regions.

So far, there have been limited modeling attempts (Roy-Poirier et al., 2015; Liu and Fessman-Beck, 2017a) on hydrological performance of bioretention in cold regions when the soil temperature is near to or lower than 0 °C, and limited discussions (Muthanna et al., 2008; Roy-Poirier et al., 2010; Khan et al., 2012a) on the preferential flow due to freeze-thaw cycles. The presence of preferential flow patterns in cold climates, according to previous studies (Muthanna et al., 2008; Roy-Poirier et al., 2010; Khan et al., 2012a), will reduce the bioretention's hydrological performance via affecting the infiltrability and flow characteristics of the frozen soil. Roy-poirier et al. (2010) reported that, due to the effect of preferential flow, stormwater volume retention rate decreased from 92.0% to 40.2%. Obviously, more modeling studies are needed for cold regions.

Moreover, as of yet, there has been rather limited modeling studies (Bacys et al., 2019, with PCSWMM) on single large storm events within short periods (e.g., >50 mm in a few hours) to assess the hydrological performance of bioretention. Hence, more modeling studies on bioretention during large storm events are needed. In addition, only Li et al. (2018) and Li, Liu, et al. (2021) carried out simultaneous modeling of hydrological performance and water quality for bioretention; however, they did not simulate outflow and surface ponding hydrographs.

To address the knowledge gaps mentioned above for cold-region bioretention, this study selected HYDRUS 1D as the modeling tool to: 1) evaluate the hydrological performance during large summer storm events (defined as rainfall depth > 50mm in 4 hours in this study) and improve the bioretention design; 2) reveal the hydrological performance in cold climates including snowmelt and spring runoff events, particularly the potential impact of freeze-thaw cycles; and 3) simultaneously simulate the nutrient removal and hydrological performance. The findings from this study will help better understand the performance of bioretention in cold regions for urban flood mitigation and water quality improvement.

# 2. **Numerical Modeling for Bioretention in Cold Regions**

## 2.1 Model introduction

HYDRUS 1D simulates one-dimensional movement of water, heat, and solute transport in variably saturated porous media (Simunek et al., 2005). The governing equation is a modified form of the Richards equation with assumptions of negligible influence of air phase and thermal gradient in water flow (Simunek et al., 2005):

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|  |  | (1) |

where is the soil moisture content [L3/ L3], *t* is time [T], *z* is the vertical direction spatial coordinate [L], *h* is the water pressure head [L], and *α* is the angle between the vertical direction and the flow direction. *K* is the unsaturated hydraulic conductivity of soil media [L/T] and is a function of *h* and *z*:

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|  |  | (2) |

where is the relative hydraulic conductivity [-], and is the saturated hydraulic conductivity of soil media [L/T].

### 2.1.1 Soil hydraulic properties

Soil moisture content and hydraulic conductivity of unsaturated soil are highly dependent on water pressure head as shown in Eq.1. Van Genuchten (1980) functions were commonly used to describe unsaturated soil hydraulic properties of soil media:

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|  |  | (3) |
|  |  | (4) |
|  |  | (5) |

where and are residual and saturated water contents, respectively [L3/ L3], *α* is the inverse of the air-entry value (also called bubbling pressure) [1/L], *n* is a pore-size distribution index, *l* is a pore-connectivity parameter. , , *α*, *n*, and *KS* are the five hydraulic parameters that need to be calibrated and validated. Both *α* and *n* are the empirical shape parameters in the soil water retention function.

A dual-permeability type flow is used to describe and simulate preferential flow, which involves two mobile regions of matrix and macropores (fracture) (Simunek et al., 2005). The importance of preferential flow must be recognized when the soil column is subjected to prolonged operation, particularly after freeze-thaw cycles. HYDRUS-1D implemented the approach of Gerke and van Genuchten (1993, 1996) and flow equations for the two pore regions:

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|  | (6) |
|  | (7) |

where *w* is the ratio of macropore (fracture) volume and total soil system, is the transfer rate for water from one region to the other, and subscript *f* represents fracture region and subscript *m* represents matrix.

### 2.1.2 Heat transport

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|  |  | (8) |

To model bioretention in cold climate, heat transport needs to be considered, which is expressed as a convection-dispersion equation when vapor transport is negligible:

where *λ* () is the coefficient of apparent thermal conductivity of soil media [ML/T3K], *Cp* () is the volumetric heat capacity of the porous medium [M/LT2K], and *Cw* is the volumetric heat capacity of the liquid phase [M/LT2K]. The three terms on the right-hand side represent heat flow due to conduction, heat transported by flowing water, and energy uptake by root water uptake, respectively.

The apparent thermal conductivity *λ* () can be expressed as:

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|  |  | (9) |
|  |  | (10) |

where *λ*0() is the thermal conductivity of the porous medium without flow and macrodispersivity [ML/T3K], *βt* is the thermal dispersity [L]. Chung and Horton (1987) equation (Eq. 10) was used to describe the thermal conductivity and *b*1, *b*2, and *b*3 are empirical parameters [ML/T3K].

### 2.1.3 Solute transport

In this paper, HP1 (coupled Hydrus-1d and PHREEQC) (Parkhurst and Appelo, 1999) was used for solute transport modeling. Chemical reactions between different pollutants used in the model can be found in PHREEQC database. PHREEQC biogeochemical code simulates chemical reactions and transport which is based on a finite equation of 1D flow path of solution transport:

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|  |  | (11) |

where *C* is the solute concentration in water, *t* is time, *v* is the pore water flow velocity, *DL* is the hydrodynamic dispersion coefficient, and *q* is the concentration in the solid phase. The three terms on the right side represent solute advection, dispersion and chemical reactions respectively.

## 2.2 Global sensitivity analysis - the Morris method

Global sensitivity analysis was conducted in this study to better identify the uncertainty and relationships among the model parameters (Ge and Menendez, 2017). Morris (1991) introduced an approach to test the effects of model inputs by including the consideration of nonlinear effects and individual interactions among model inputs. Assume model input is uniformly distributed in [0,1] (transformed from their actual distribution) and vary across selected levels (the resolution of sampling), a *k*-dimensional *p*-level grid region of interest is formed. For a given value of *X*, the elementary effect of the *i*th model input is calculated as:

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|  |  | (12) |

where is magnitude of step or change of an input variable. With a group of random sample *X*, the sample mean and the standard deviation are the sensitivity measures.

## 2.3 Experiments for model calibration and validation

Li (2019) and Kratky (2019) at the University of Alberta, Canada, conducted laboratory experiments of four bioretention columns and their data were used for the HYDRUS 1D modeling (the experiments have been published as Li, Kratky, et al., 2021; Kratky et al., 2021). The columns were typical bioretention cells, which consisted of vegetation and mulch layer at the top, topsoil with organic matters as plant soil, middle soil media layer, gravel layer, and underdrain, as shown in Figure 1. Outflow pipes of all the four bioretention columns were located at the bottom of the columns. Columns 1-2 used free drainage as the underdrain method all the time. Columns 3-4 had IWS (Internal water storage) zone to create an anoxic zone to promote denitrification in summer and used free drainage (no IWS) in winter or spring. Two types of classical soil media were used in their experiments. Soil media A is a less porous soil matrix made up of 50.8% sand, 29.4% silt and 19.8% clay. It's classified as a loam and is typically used in landscaping in Edmonton, Alberta, Canada. Soil media B is a sandy loam made up of 67.2% sand, 19.6% silt, and 13.2% clay, and is more porous than Soil media A.

Preliminary tests were first conducted in Columns 1 and 2, which was equivalent to approximately one year of precipitation in the local municipality (Edmonton, Canada). The formal experiments consisted of five stages of operation, which was equivalent to 1.6 years of typical precipitation in Edmonton: 1) Year 1 summer small storm events; 2) Year 1 winter snowmelt events; 3) Year 1 spring runoff events; 4) Year 2 summer small storm events; and 5) Year 2 summer larger storm events (Kratky, 2019). The storm events were conducted weekly to bring bioretention columns back to air dry state. And target contaminants were added (as shown in Appendix Table A1) into the stormwater to imitate pollutants in actual runoff, and the standard methods and HACH kits were used to measure the concentrations of the pollutants in the samples (see Li 2019 for detail). The four bioretention columns experienced a “mature” period in Year 1, which became stable in Year 2 (Li, 2019).

During the first stage (Year 1 summer), nineteen 1:2 year storm events (22.6 mm precipitation per event) were applied to the columns, followed by four snowmelt events in the second stage (Year 1 winter). All the columns were moved into a cold room that can be kept at a controlled temperature, and cold water was applied directly to the top of the columns to simulate snowmelt events. When the soil was completely frozen with the ambient temperature of -20 °C, two snowmelt tests were performed on Columns 1 and 2, to study the bioretention performance. Then Columns 1 and 2 were thawed for two other snowmelt tests, during which the soil temperature was roughly -0.3 °C and the room temperature was 1 °C. After the snowmelt events, two spring runoff events in the third stage (Year 1 spring) were conducted. The second spring runoff event was a major melt of packed snow with lower concentration of salts (see Table A1), inflow rate of 14 mL/min, and a volume of water (39.3mm) in 40 hours. During the fourth and fifth stages (Year 2 summer), five 1:2 year storm events were conducted, followed by one 1:5 storm event (37.3 mm precipitation) and one 1:10 year storm event (45.2 mm precipitation) (Li, 2019). In all the experiments, rainfall events were designed using the 4-hr Chicago distribution according to IDF curves in the City of Edmonton Drainage Design and Construction Standards (COE, 2014b). Detailed rainfall intensity with time for the rainfall events is provided in Appendix Table A2 and Figure A1. The catchment area to surface area (CA/SA) ratio in the experiments was assumed to be 10, and the catchment area was assumed to be 100% impervious.

## 2.4 Model setup

### 2.4.1 Hydrologic modeling for summer storm events

One of five 1:2 year storm events tested in Year 2 was selected for model calibration on hydraulic parameters, because the hydrological performance of the bioretention columns was more stable and mature in Year 2 (Li, 2019). The calibrated parameters in 1:2 year storm event were then applied to 1:5 and 1:10 year storm events for model validation, assuming these parameters are transferable to larger storm events with the same distribution (Chicago) and duration (4 hours). After validations, the calibrated soil hydraulic parameters were applied for large storm events, including 1:25, 1:50, and 1:100 storm events, to test bioretention columns’ hydrological performance under extreme conditions. Note that, in this modeling study, no overflow was considered for all the four columns during large storm events to better quantify the resultant flooding (surface ponding) of the columns.

HYDRUS 1D uses a Marquardt-Levenberg type of parameter optimization algorithm for inverse estimation of soil hydraulic, heat or solute transport parameters, and a maximum of fifteen parameters can be calibrated at one time. In this study, the initial values of , , *α*, and *n* were referred to Carsel and Parrish (1988) who summarized unsaturated hydraulic parameters for different soil classifications using van Genuchten (1980) model. The initial guess of *KS* was taken from Clapp and Hornberger (1978) whose average values of saturated conductivity were higher than Carsel and Parrish (1988)’s estimations, and the selection was based on the observation results in Li (2019) and Kratky (2019)’s experiments. Specifically, for the topsoil layer, the initial guesses of , , *α*, *n*, and *KS* of topsoil were all larger than those for the middle soil media layer because the compost added in topsoil increases effective friction angle, saturated hydraulic conductivity and water content (Duzgun et al., 2021). Due to the high deviation of each parameter (Carsel and Parrish, 1988) and uncertainties in the changes of soil properties caused by winter freeze-thaw cycles, this study tested a wide range of the five parameters. The initial values of soil’s *KS* and their testing ranges of topsoil and middle soil media are written as Table A3.

Gravel layer has very high hydraulic conductivity and sharp infiltration front, so it can turn into a dry state instantaneously making simulation unstable (Steffen, 2012). To stably simulate the gravel layer, this study adopted the method of Filipović et al. (2014), which employed hydraulic parameters of sand with higher *KS* to replicate gravel layer behavior in the model. In Columns 3 and 4, the gravel layer does not affect the outflow hydrograph because the entire gravel layer was submerged and saturated during a rainfall event as a result of the 45-cm anoxic zone (IWS zone) at the bottom.

Five hydraulic parameters of the top two soil layers (in total of ten) were calibrated and five hydraulic parameters of the gravel layer were fixed. In order to prevent optimization from falling into a local minimum during the calibration process, iterations of optimizations with different intervals as starting points were evaluated for all the parameters. Meanwhile, both local and global sensitivity analyses were conducted for the ten calibrated hydraulic parameters. Local sensitivity analysis changes one-unit increment (depending on its highest order of decimal) or 10% increment of original value for one parameter while keeping the other parameters unchanged. Percentage change of the peak outflow was used as the index to sort parameters’ sensitivities. The Morris method was chosen as the global sensitivity analysis approach for this study because Brunetti et al. (2018) and Paleari et al. (2021) found the Morris method represents a reliable, computationally cheap alternative to do the sensitivity analysis with satisfied achievement of indicating important factors. The sample size of the Morris method for this study is 10 simulations for each parameter with random increments combination and 4 levels of increment.

### 2.4.2 Hydrologic modeling for winter snowmelt and spring runoff events

Soil experience compaction and expansion in cold climates, and soil hydraulic parameters would significantly change after few freeze-thaw cycles. Therefore, calibration of soil hydraulic parameters was required for snowmelt events, and then calibrated parameters were validated in spring runoff event. The soil hydraulic parameters were calibrated for cold condition using one thaw test, because the soil temperature (-0.3℃) and room temperature (2-3℃) were recorded and needed for the model. The parameters were validated using the second spring runoff event for the same reason. Due to the similarity between Columns 1-2 and Columns 3-4 under cold climate, only the modeling results of Columns 1-2 are presented in this study.

To examine the possibilities on the existence of preferential flow due to freeze-thaw cycles, the dual-permeability model was applied to the winter snowmelt and spring runoff events. The dual permeability model is considered as a more appropriate approach for flow in macropores rather than the dual-porosity model or multi-region type models, because it is physically based and numerically robust to ease the parameterization problem (Šimůnek et al., 2003). Soil hydraulic parameters for dual-permeability model were referenced from Simunek et al. (2003) for the fracture region (= 0.0, = 0.5, =0.1 cm-1, =2.0, =0.5, =1.5cm/min) and the matrix-fracture interface (= 3, =0.4, =1.0 , =0.5, =7*x*10-6 cm/min). , the ratio between the volumes of the macropores or fracture domain and the total soil system, was calibrated for these events.

### 2.4.3 Water quality modeling

The water quality modeling focused on free drainage scenario (Columns 1-2) and nutrients (chloride, phosphate, nitrate, nitrite, and ammonium). The modeling was conducted for 1:2 year storm events in the second summer, because soil became more mature than Year 1 and hydraulic properties had been calibrated and validated. Chemicals were added into tap water in the experiments to meet targeted inflow pollutant concentration as shown in Table A1. Pollutant concentration (measured by the standard method and HACH kits) of runoff and that contained in the bioretention column were inputs for the model (Table 3), and the PHREEQC model was used to simulate the solute transport. Inflow pollutant parameters used target inflow pollutant concentrations in the experiments, and soil pollutant parameters used leaching test results to reflect pollutants contained in the bioretention columns. In this case, no water quality parameters are required to calibrate. The equilibrium phase of halite (NaCl) was added to the model to simulate the saturation state of chloride that existed in soil columns after winter operation with high salt concentration inflow.

### 2.4.4 Initial and boundary conditions

In HYDRUS 1D, initial conditions can be either water content or pressure head. In our model, the initial pressure head was assigned to describe bioretention columns as air dry at the starting point. The initial pressure heads for Column 1 from top to bottom were -220 and -100 cm, respectively, while the corresponding values for Column 2 were -180 and -100 cm. Bioretention columns were designed to be able to handle ponding at top to retain surface runoff. The upper boundary condition was set to be “atmospheric boundary condition with surface layer”, which allows water to build up on the surface. Columns 1-2 have outflow pipes under the gravel layer while Columns 3-4 have elevated outflow pipes (see Figure 1). Because gravel has nonlinear hydraulic properties and sharp infiltration front, “free drainage” was assigned for Columns 1-2 and “seepage face h = 45 cm” for Columns 3- 4 as lower boundary conditions. “Free drainage” is a zero-gradient boundary condition that describes a freely draining soil profile, and “seepage face” indicates boundary flux that will be triggered when the pressure head reaches a given value.

### 2.4.5 Model evaluation

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|  |  | (13) |

In this study, calibration was done for the model to maximize the fitness of simulated outflow series and observed outflow points. To evaluate the fitness of the simulated results compared to the experimental data, the statistical measure, R-Squared for regression (R2) in HYDRUS 1D was used.

where is the weight factor, *f* is the predicted value, *y* is the observed data, and *j* is the total number of observed data. Weight factors were assumed to be 1 for all the observed data.

# 3. Modeling results and discussion

## 3.1 Hydrologic model calibration

Calibration results for 1:2 year storm event are shown in Figure 2 and Calibrated soil hydraulic parameters of four bioretention columns are provided in Table 4. R-squared (R2) between the simulated outflow hydrograph and experimental data were 0.92, 0.96, 0.97, and 0.84 for Column 1, 2, 3 and 4, respectively. The differences between the timing of peak flow of the outflow hydrograph were 8, 9, 9 and 7 minutes, respectively, for four columns, which are considered to be small because the time intervals between the observed outflow data points are 3 - 10 minutes. Meng et al. (2014) calibrated two bioretention cells’ hydrological performance using field results during natural rainfall, and R2 were 0.76 and 0.61 for the two cells. Despite the overall good performance of the model, there were also some discrepancies. Simulated outflow hydrograph did not catch a few observed peak points for Columns 1-2. The peak outflow observed in Columns 1-2 were 94 and 210 ml/min, while the simulated peaks were 71.3 and 189.4 ml/min. Other than the uncertainties of numerical model itself, the possible reason for such discrepancy is that: after one year of operation particularly the freeze-thaw cycles in winter and the use of high concentration of contaminants in spring runoff events, the soil media could have experienced the expansion, compaction, and clogging, potentially forming fractures and preferential flow paths inside the soil column. In Column 4, a sudden drop of simulated outflow occurred at around 210 min while the observed outflow showed a smooth decrease. The sudden drop of outflow occurred when the simulated ponding diminished which resulted in negative surface water pressure. The smooth decrease observed in experiments indicated that water was contained in the soil column after ponding ended. In addition to accelerating outflow, preferential flow can also constrain outflow by retaining water in macropores and blocking flow paths in fractures (Allaire et al., 2009).

Surface ponding was observed in Columns 1, 3 and 4. R-squared (R2) between the simulated ponding and experimental data were 0.83, 0.89, and 0.90 for these columns, respectively. The simulated ponding depth of Columns 3 and 4 fitted well with observed values. For Column 1, the maximum simulated ponding depth was 6.1 cm, slightly lower than the maximum observed ponding of 8.4 cm; and the simulated ponding duration was approximate 3 hours, which was 30 min longer than the observed data. Overall, based on both outflow hydrograph and ponding depth, the simulated results are reliable and satisfactory.

## 3.2 Hydrological Performance Validation

Model validation for 1:5 and 1:10 year storm events are shown in Figure A2 and Figure 3. R2 between the observed and simulated outflows were 0.82, 0.92, 0.83, and 0.62 for the four columns, respectively, during 1:5 year storm event. Similarly, R2 between the observed and simulated outflows were 0.86, 0.80, 0.83, and 0.69 for during 1:10 year storm event. The simulated outflow hydrograph fitted well with the observed outflow in Columns 1, 2, and 3 (with R2 > 0.8) during both 1:5 and 1:10 storm events, while it was satisfactory for Column 4 (with R2 > 0.6). Despite the overall good performance of the model, discrepancy was also noticed. Sudden reductions were observed in the stimulated outflow for Columns 2, 3, and 4, while the experimental outflow decreased gradually. Moreover, in all the simulations, the timing of peak flow was close to observed data (within 10 minutes). The simulated peak outflows were 8.8, -0.8, 6.8, and 7.7 mL/min higher than the observed peaks for four columns during a 1:10 storm event, respectively.

In term of surface ponding, R2 between the observed and simulated were 0.97, 0.47, 0.81, and 0.79 for the four columns, respectively, during 1:5 year storm event. During 1:10 year storm event, the corresponding R2 values were 0.82, 0.81, 0.88, and 0.86 respectively. The simulated ponding depth of Column 1 closely fitted with observed data from a 1:5 storm event with the same ponding duration (error < 5min). During a 1:10 storm, the simulated ponding depth was approximate 8 hours, which was 2 hours shorter than observed. The simulated peak ponding depth was 23.1 cm, which was 2.4 cm less than the observed. Column 2 had a simulated peak ponding depth of 9.9 cm, which is larger than the observed peak ponding depth of 5.4 cm, and the ponding duration is 2.5 hours (experimental ponding duration is 1.5 hours) during a 1:5 storm. Column 2’s simulated ponding hydrograph fitted well with observed ponding during a 1:10 storm (the difference of duration is 14 min and that of the peak is 1.4 cm). Columns 3 and 4’s simulated pond hydrograph matched well with observed data. The difference of peak ponding depth was 1.0 cm and 0.2 cm for Column 3, and 0.7 cm (did not include one “outlier peak point”) and 1.1 cm for Column 4 during 1:5 and 1:10 storms, respectively. The simulated ponding durations of Colum 3 were approximately 5.5 hours and 6.8 hours, which were about 30 min and 60 min less than the observed results, and the difference of ponding duration was 1 min and 15 min for Column 4 during 1:5 and 1:10 storms, respectively.

The overall fitness is promising for outflow and ponding hydrographs, even though R2 decreases from 1:2 year storm event to larger (1:5 and 1:10 year) events (the R2 values are comparable for the 1:5 and 1:10 year events, see Table 5). The decreasing trend of R2 values with larger storms can also be found in other hydrologic modeling studies (e.g., Ferreira et al., 2019). From the modeling perspective, this trend is understandable, because the 1:2 year event is for model calibration and the other two events are for model validation, and it is expected that R2 values are higher in model calibration than validation. The simulated peak outflow was slightly lower than the observed peak during 1:2 and 1:5 storm events, whereas it was slightly greater than the experimental data during 1:10 storm events for all four columns, which might indicate that the effective *KS* of the bioretention columns declines as the intensity of storm events increases (Hawke et al., 2006; Langhans et al., 2010; Dou et al., 2014). The validation results suggest that the five hydraulic parameters including *KS* do not change significantly from 1:2 to 1:10 year storm events for all four bioretention columns.

Using Column 1 as an example, the local sensitivity analysis results indicate that *KS* of the middle soil layer is the most sensitive parameter, followed by the empirical shape parameters *α* and *n* of the middle layer (Table 2). The rest parameters of both layers are not sensitive. The 70-cm middle soil layer’s hydraulic parameters are dominant compared to those of the 16 cm top planting soil layer for all four columns, which demonstrates the important role of the middle soil layer in bioretention. However, the global sensitivity results using the Morris method indicates that *α* and *n* in the soil water retention function have highest sensitivity value, followed by the , and and have lower sensitivity value as shown in Figure 4. The global sensitivity results are similar to those of Brunetti et al. (2018) who conducted on a numerical analysis of permeable pavements. In short, both local and global sensitivity analysis indicated that the middle soil layer has higher domination on the hydrological performance of bioretention columns rather the top planting soil layer.

## 3.3 Hydrological performance for summer large storm events

The validated hydraulic parameters were applied in predicting bioretention performance during large storm events, including 1:25, 1:50, and 1:100 year storm events in the City of Edmonton, Canada. Detailed rainfall intensity with time for these design storms is shown in Appendix Table A2. The cumulative depths of 1:25, 1:50 and 1:100 year rainfall events are 56.2 mm, 68.8 mm and 83.4 mm, respectively. Simulated outflow hydrograph illustrated that four columns reduced the peak flow by 95.7%, 88.7%, 94.3%, and 91.5% during a 1:100 storm respectively (Figure 5), which is promising for urban flood mitigation since LID is usually designed for small storm events, e.g., the design storm of LID is 1:5 year storm in Edmonton (COE, 2014a). The peak flow of all four columns did not increase significantly when the intensity of storm events was getting larger, because the outflow rate is mainly constrained by the effective *KS* of the middle layer soil media of the bioretention column.

In the meantime, both ponding depth and duration significantly increased when the return period of storm events increased. Column 2 has the peak ponding depth of 24.3 cm and ponding duration of near 4 hours during a 1:25 storm, and they are 31.6 cm and near 5 hours during a 1:50 storm. The rest three columns experienced a higher peak ponding depth of around 30 cm and a longer ponding duration (approximate 10 hours, 8.3 hours, and 5.5 hours for Columns 1, 3, and 4) during 1:25 year storm. During 1:50 year storm, the maximum ponding depth of Columns 1, 3, and 4 exceeded 35 cm (approximate 44.9 cm, 40.7 cm, and 37.1 cm for Column 1, 3, and 4), which is the maximum design ponding depth as per Edmonton LID design guideline (COE, 2014a). During a 1:100 year storm, the maximum ponding depths of four columns are 58cm, 41cm, 53cmm, and 48cm respectively, and the ponding duration are approximate 15 hours, 5.5 hours, 11.5 hours, and 7.5 hours, respectively. Hydrological performance of bioretention columns during large storm events demonstrated that coarser soil media could significantly reduce the ponding duration than finer soil media with a tradeoff of increasing peak outflow.

Sun et al. (2019) used SWMM to investigate how rainfall intensity and pattern affected bioretention hydrological performance and found the storms with less duration and larger intensity resulted in greater overflow and outflow and thus more severe ponding and flooding. With our test results on large storm events (rainfall depth > 50 mm in a 4-hr duration), a bioretention column with coarser soil media and a free underdrain can effectively reduce peak flow approximately 90% while maintaining ponding depth below design standards, mitigating the pressing urban flooding issues due to extreme weathers caused by climate change.

## 3.4 Hydrological performance for winter snowmelt and spring runoff events

Hydrological performance of bioretention Columns 1-2 was calibrated for snowmelt events and validated for spring runoff events with the consideration of the presence of preferential flow, as shown in Figure 6. The calibrated soil hydraulic and thermal properties are presented in Table 6. For snowmelt events using the single-porosity model, R2 of outflow for Columns 1-2 were 0.77 and 0.86. After using the dual-permeability model with preferential flow taken into account, R2 of outflow increased to 0.94 and 0.96, assuming the ratio w was 0.07 and 0.05 for Columns 1-2, respectively. The comparison between the two models indicated that preferential flow had high possibilities of existence, which created fractures and macropore flow inside soil columns and altered the flow path.

According to simulation results on spring runoff events for model validation, R2 of outflow for Columns 1-2 were 0.72 and 0.84, using the single-porosity model. The R2 values increased to 0.80 and 0.86, using dual-permeability model with preferential flow taken into account and assuming the ratio w was 0.17 and 0.15 for Columns 1-2, respectively. Higher values of w, compared to those for the snowmelt events, suggested that more fractures could potentially occur after the first flush experiment and more severe preferential flow existed inside the soil column. The first flush event contained a high concentration of salt and high intensity of inflow, which was likely to create more macropores inside the soil column. The observed outflow hydrograph had several fluctuations, which can potentially be caused by the instability of experimental apparatus for a long-period operation (> 60 hours).

It is interesting to notice the change of effective *KS* from summer to winter/spring condition in both soil A and B. The effective *KS* of Soil A in Column 1 increased from 0.044 cm/min (in summer condition when the temperature is around 21℃) to 0.10 cm/min (in winter/spring condition when the temperature is around 2-3℃ and soil temperature is around -0.5℃). However, effective *KS* of soil B (Column 2) decreased from 0.15 cm/min in summer to 0.11 cm/min to winter/spring. The modeling results of increasing hydraulic conductivity for Soil A (loam texture) and decreasing hydraulic conductivity of Soil B (sandy loam) agreed with the laboratory experiments (Li, 2019).

Weigert and Schmidt (2005) conducted lab experiments on two soil columns of sandy and loamy soil under partially frozen condition and simulated with a physical infiltration model. The calculated hydraulic conductivities of two soil types were close, indicating that hydraulic conductivities can theoretically be similar (Weigert and Schmidt, 2005). Meanwhile, due to recognized fracturing during the freezing process, the experimental hydraulic conductivity of loamy sand was underestimated by physical infiltration mode, indicating that hydraulic conductivity of soil was dominated by preferred flow when soil fractures were present (Weigert and Schmidt, 2005). Other studies have also supported that the formation of macropores in frozen soil can significantly affect the soil infiltration rate depending on the frozen water content and the formation of frost layer, both of which are, however, variable and difficult to predict (Watanabe et al., 2013; Watanabe and Kugisaki, 2017; Mohammed et al., 2018; Demand et al., 2019). Watanabe and Osada (2017) found that hydraulic conductivity of soil increased exponentially with higher unfrozen water content when the soil temperature rose from -0.5 °C to -0.2 °C; and it reached a constant value between -0.2 °C and 0 °C, which is greater than the estimated hydraulic conductivity of unfrozen soils. However, in the field experiments conducted by Roseen et al. (2009) in New Hampshire, USA, and by Khan et al. (2012b) in Calgary, Canada, bioretention maintained similar hydrological performance during winter (when soil was partially frozen) compared to summer. In addition, some other filed studies indicated that the hydrological performance declined with average peak flow reduction from 42% in summer to 27% in winter (partially frozen) (Muthanna et al., 2008) and approximately 80% reduction in soil infiltrability after freezing (frost depth of 45 cm) (Al-Houri et al., 2009). The different changes of hydraulic conductivities of two types of soil were likely because finer soil media (Soil A) was expanding pore space due to freezing water expansion and formation of macropores, while coarser soil media (Soil B) had a reduction in pore space due to compaction and pore ice blocking (Denich et al., 2013; Li, 2019).

## 3.5 Water quality modeling

In comparison with the observed results, the simulation results on water quality performance of bioretention during a 1:2 year storm event were generally reasonable, as shown in Figure 7. Both bioretention columns demonstrated a high pollutant load reduction capability for phosphate, nitrite, and ammonium, but chloride and nitrate loads increased after the bioretention due to leaching effect. During the winter experiments, influent with a high concentration of sodium chloride flowed into the soil columns (Li, 2019), which made soil reach the saturation state of solute NaCl and salt precipitated. Chloride concentration was significantly larger in the outflow with 142% and 22% increase than that of inflow in the first summer week in Year 2 right after the winter season. After the first week of summer, chloride concentration reduction of both columns was around 0% with an error of approximately 7% during the next four weeks. The simulated reduction of chloride was -9.6% and -8.0% for Columns 1 and 2, which are very close to observed chloride concentration reduction following summer weeks. Mile High Flood District of Colorado, USA, summarized that bioretention and other types of LID were ineffective at treating road salts in several studies, and that bioretention temporarily stored the salts and chloride leaching occurred during the first flush in spring (MHFD, 2020).

The increase of nitrate in the outflow was because of nitrogen rich soil used in the columns and nitrification process that converted ammonium to nitrite and further to nitrate (US EPA, 2002). Organic nitrogen and ammonia nitrogen can be effectively contained by the medium of bioretention systems and transformed into nitrate (Wan et al., 2017). The simulated nitrate reduction of -276% and -81% for Columns 1-2 was different from the observed results of -132% and -223% that were the average value for five 1:2 year storm events in the summer of Year 2. In the experiments, nitrate reduction for both columns differed significantly in the second summer from weeks to weeks (Kratky, 2019). In the first week, the reductions of Columns 1-2 were -200% and -515%, but it decreased to -10% and -94% in the fifth week. Nitrite is unstable in solution, which is why it is barely seen in the outflow of bioretention columns (Moeller, 2012). Meanwhile, no evident nitrite inhibition was observed in experiments, and therefore no nitrite accumulation occurred. Li et al. (2018) tested three bioretention columns through lab experiments and numerical simulations using HYDRUS 1D, and demonstrated that average reduction rates of nitrate, ammonium, and total phosphate were approximately 65%, 75%, and 80%, respectively, in all design scenarios of different fillers. Because IWS was used in their bioretention, they were able to achieve positive nitrate removal, which is in opposite to our findings. IWS creates an anoxic zone that stimulates the denitrification process and has been demonstrated with successive nitrogen removal in a few studies (Palmer et al., 2013; Li et al., 2014; Qiu et al., 2019). Mulch or wood chips can also be considered as one possible denitrification measure since they convert to a carbon source for denitrifying bacteria (Liu et al., 2021) and promote anaerobic condition at top layer (Wan et al., 2017). Mulch was used in Li (2019) and Kratky (2019)'s experiments, however owing to its thin thickness of 4 cm, the denitrification benefits of mulch were deemed insignificant. The simulated results and observed results illustrated significant removal capacity of bioretention columns for ammonium and phosphate in the outflow, but negative removal for nitrate and chloride without appropriate denitrification measures.

## 3.6 Optimization of bioretention columns

Three measures can be used to improve the design of bioretention columns. The first measure is to replace soil media B in the bioretention column with a coarser soil media. In bioretention’s practice, the fundamental design component is its soil media, and many studies and design guidelines have suggested coarse soil media as engineering soil media because of its higher permeability (Hunt and Lord, 2006; Davis et al., 2009; Dhalla and Zimmer, 2010; Liu et al., 2014; Dell and Brim, 2017). To gain a better functionality of the bioretention column, sand or loamy soil with a high percentage of sand (up to 100%) in the middle-engineered soil media layer is recommended, to increase infiltration rate and sufficiently remove pollutants at the same time (Ewing, 2013). The second measure is to increase the soil layer depth inside the bioretention column because a larger layer thickness of soil indicates additional storage space for stormwater. Decreasing the CA/SA is the last measure. Using coarser soil media for surrounding soil was one measure reported by He and Davis (2011) because higher hydraulic conductivity of surrounding soil reduces outflow. HYDRUS 1D neglects side wall effects in simulation, so this measure is not considered in this paper.

Loamy sand is considered a replacement of sandy loam (soil B) to avoid overflow (flooding) caused by exceeding maximum ponding depth during large storm events. Sandy soil has higher permeability and lower water content, which reduce clogging potential (Tirpak et al., 2021), has better performance in cold weather and increases permeability following the thawing process (Moghadas et al., 2016). Coarser media with larger pores is helpful to prevent concrete frost (one type of frost in soil) and form granular or porous frost instead in cold conditions (Kratky et al., 2017). Soil media has a premature period and hydraulic parameters of soil change significantly during that period and after freeze-thaw cycles in winter. Accurate determination of hydraulic parameters of a new soil media at a mature state requires experiments, testing, and model calibration. A soil C classified as the loamy sand texture is proposed by increasing sand percentage in soil B. The ratio of *KS* between loamy sand and sandy loam is approximate 3 to 5 according to Clapp and Hornberger (1978) and Carsel and Parrish (1988). To simulate the hydrological performance of bioretention column replaced with soil C, effective hydraulic conductivity of soil C is assumed to be 0.23 and 0.31 cm/min (*KS* ratio = 1.5 and 2).

The hydrological performance of replacing Soil B in the middle layer of Column 2 with Soil C (loamy sand texture) during 1:100 year storm is illustrated in Figure 8a. The ponding depth reduced from 41.5 cm to 35.6 cm and 31.6 cm when the effective hydraulic conductivities of two types of Soil C were 0.23 and 0.31 cm/min, respectively, but the peak outflow increased from 276 mL/min to 370 and 458 mL/min. The peak inflow of 1:100 year storm was 2436 mL/min, and therefore the bioretention columns replaced by two types of Soil C could still reduce the peak flow by 85% and 81%. To achieve more accurate hydraulic performance, experiments are necessary to test the values of all the five hydraulic parameters of the loamy sand. Loamy sand with a higher ratio of sand is likely to manage a local 1:100 storm event without flooding.

With ±10 cm, ±30 cm, and ±50 cm increments added to the original 70 cm middle layer of Soil B in Column 2, the hydrological performance (peak flow and pond depth) during 1:100 year storm event is shown in Figure 8b. As the thickness of the middle soil layer decreased, ponding depth became smaller and peak outflow increased due to the shorter duration of water flow through this layer. Increasing the thickness resulted in opposite outcome. An exponential trend was shown in the correlation between ponding depth and soil thickness, as well as between peak outflow and soil thickness. When the soil thickness increased from 20 cm to 40 cm, 4.6 cm increase in peak ponding depth and 102.3 mL/min decline in peak outflow were observed. When the soil thickness was in the higher range and increased from 100 cm to 120 cm, there was only 0.6 cm increase in ponding depth and 12.7 mL/min decline in peak flow.

For bioretention column filled with sandy loam such as Column 2, the middle soil layer thickness is recommended to be smaller to reduce ponding depth. Meanwhile, higher soil layer thickness provided extra pollutant reduction capacity (Li et al., 2020). Therefore, 60-80 cm of middle layer thickness is suggested to achieve promising peak flow reduction, contaminants removal with minor overflow.

The third option of modifications was decreasing the catchment area to surface area (CA/SA) ratio. Figure A3 illustrated that ponding depth, ponding duration and outflow decreased when the ratio became larger. The ponding depth decreased from 41.5 to 14.8 cm, and the peak outflow decreased from 276 to 218 mL/min when CA/SA ratio reduced from 10 to 5. Ponding depth was approximately 30 cm when the CA/SA was 8, which meets the requirements of COE design guidelines, in which the maximum permitted ponding depth is 35 cm. The maximum outflow was 252 mL/min, which means 90% reduction of peak flow with CA/SA = 8.

## 3.7 Model Limitations

Several model limitations need to be mentioned. First, the calibrated and validated hydraulic parameters of bioretention columns were assumed to be transferable from medium (1:10 year) to large (1:25, 1:50, and 1:100 year) storm events, based on the transferability demonstrated between small (1:2 year) and medium (1:5 year and 1:10 years) storm events. This assumption was made also due to the same distribution (Chicago) and duration (4 hours) of these storm events. However, the hydraulic properties of bioretention could change when rainfall intensity increases. Hawke et al. (2006), Langhans et al. (2010) and Fou et al. (2014) reported that the saturated hydraulic conductivity is highly dependent on rainfall intensity (as well as unsaturated soil slopes and rainfall distribution). This can potentially affect hydrological performance of bioretention columns during large storm events and affects the design recommendations. It is therefore important to conduct experiments in the future on these large events to further look into the bioretention performance and the transferability issue.

Second, the calibrated parameters themselves have uncertainties. HYDRUS 1D uses a Marquardt-Levenberg type of parameter optimization algorithm for inverse estimation, which is a gradient-type optimization algorithm. When the number of optimized parameters is large (e.g., 10 in this study), the algorithm could experience a local minimum issue during optimization because the correlation and non-uniqueness of the soil hydraulic parameters depend on the initial values of optimized parameters and the shape of the objective function in complex nonlinear problems (Hopmans et al., 2002; Imnek and Hopmans, 2002). Even a large number of iterations with different sets of selected optimized parameters and different initial values were used in this study, it is still not valid to state that the global optimization had been absolutely achieved for all the parameters due to the high dimensionality of optimized parameters and their complex interactions. The finalized calibrated parameters in this study are more suitable to be considered as one set of near-optimum solutions (Brunetti et al., 2019). Different optimization algorithm can be used in future studies to improve the optimal solutions and reduce the uncertainties. For example, the Particle Swarm Optimization algorithm has been used in a few LID studies and achieved convincible optimal results (Brunetti et al., 2016; Brunetti et al., 2018; Zhou et al., 2022). Furthermore, the uncertainties in the hydraulic parameters could propagate to the solute transport modeling and thus result in model uncertainty. The propagation issue also requires more comprehensive and systematic experiments and numerical simulations to investigate in the future.

# 4. Conclusions and future research directions

Bioretention is one of the most cost-effective LID facilities that has been widely studied and practiced. However, limited studies have been conducted on its hydrological performance in cold regions, particularly for winter snowmelt, spring runoff, and summer large storms (> 50 mm), as well as on simultaneous modeling of hydrologic processes and water quality benefits. In this paper, HYDRUS 1D was selected for modeling four bioretention columns of different designs (with CA/SA = 10) in a cold region (Edmonton, Canada) to explore the knowledge gaps.

The model was calibrated and validated for the 1:2, 1:5 and 1:10 year summer storm events (22.6, 37.3 and 45.2 mm, 4-hour Chicago distribution) in the cold region in terms of both outflow hydrograph and ponding depth. The R2 of the simulated results against the measurement data were typically > 0.8. The soil hydraulic parameters appeared not to change substantially from the 1:2 to 1:10 storm event. The four bioretention columns reduced the peak flow by 95.7%, 88.7%, 94.3%, and 91.5%, respectively, during the 1:100 storm event (83.4 mm, 4-hour Chicago), demonstrating their potential in urban flood mitigation in cold regions. However, their ponding depths exceeded the design limits of 35 cm for 6.8, 1.8, 4.8, and 2.2 hours, respectively. To address this issue, it is recommended to use loamy sand as a replacement soil media or use a smaller CA/SA ratio. The soil media thickness of 60-80 cm is recommended to achieve the tradeoff of ponding depth mitigation, peak flow reduction, and pollutant removal.

The model was also calibrated and validated for winter snowmelt event and spring runoff event using both single-porosity and dual-permeability models. The results showed that the dual permeability model had higher fitness to the experimental data, indicating a high potential of preferential flow caused by freeze-thaw cycles in bioretention in cold climates. The modeling results also showed that the effective hydraulic conductivity (*KS*) values of the soil media were similar (approximately 0.1 cm/min) for both winter snowmelt and spring runoff when the soil temperature was around -0.5 °C. Interestingly, the finer texture soil experienced increasing effective *KS* in cold climates, while it was opposite for the coarser soil texture, likely due to the different soil media’s reactions (compaction, pore expansion or pore ice blocking) to freeze-thaw cycles.

Based on the experiments and the modeling, bioretention columns had high (> 90%) pollutant load removal rates for phosphate, nitrite, and ammonium. However, leaching of chloride and nitrate occurred, which were caused by road de-icing salts in winter and nitrification process, respectively. Despite nitrate leaching, the total nitrogen reduction rate was still positive. Overall, bioretention demonstrated a promising capability for nutrient removal in this study.

More bioretention studies in cold regions are needed in the future, including laboratory experiments, field monitoring and numerical simulations. Specifically, in the area of numerical simulations, research is suggested to investigate (a) the transferability issue of model parameters for storm events of different return periods, (b) the uncertainty issue of model parameter calibration (i.e., global sensitivity issue), and (c) the uncertainty propagation issue from hydrologic processes to water quality modeling. To better facilitate the modeling, it is also suggested that, during laboratory or field measurements, water contents at different soil depths and initial soil hydraulic and thermal properties be measured.

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