PROPER SIZING OF INFILTRATION TRENCHES & BIORETENTION CELLS FOR URBAN STORMWATER MANAGEMENT PURPOSES

Proper Sizing of Infiltration Trenches and Bioretention Cells for Urban Stormwater Management Purposes

By

Elizabeth Rowe

B.Eng.

Faculty of Engineering
Department of Civil Engineering

A Thesis
Submitted to the School of Graduate Studies
In Partial Fulfillment of the Requirements
For the Degree of

Master of Applied Science

McMaster University
Hamilton, Ontario, Canada

MASTER OF APPLIED SCIENCE (2019) McMaster University
(Civil Engineering) Hamilton, Ontario

TITLE:	Proper Sizing of Infiltration Trenches and Bioretention Cells for Urban Stormwater Management Purposes
AUTHOR:	Elizabeth Rowe B.Eng. (McMaster University)
SUPERVISORS:	Dr. Yiping Guo and Dr. Zhong Li
NUMBER OF PAGES:	xiv, 67

Abstract

The Ministry of Environment and Climate Change establishes design criteria for the sizing of Low Impact Development (LID) practices in the province of Ontario. The current sizing standards are based on the concept of the 90th percentile storm and require LIDs to provide enough storage capacity to store catchment runoff from a 25 mm rainfall event. The notion of 90th percentile storm means that 90% of all rainfall events have event volumes below a 25 mm rainfall event. This research examines the performance and cost of infiltration trenches and bioretention cells sized for alternative sizing standards ranging from 5–50 mm. Analytical probabilistic equations are used to determine the runoff reduction rates of infiltration trenches and bioretention cells, while the Sustainable Technologies Evaluation Program (STEP)'s LID Practices Costing Tool is used to estimate the overall cost of each LID. The costs are used to create a ratio denoted the fraction of maximum cost by dividing each cost by the cost of the 50 mm sized LID to receive a unitless ratio. This ratio is compared with the runoff reduction rates of both LIDs. Four different catchment sizes and various soil types are included to broaden the scope of the analysis and make the conclusions more dependable. Results indicate that the current sizing standard of 25 mm is probably too high and not cost-effective. In fact, depending on the type of soil and LID, little increase in performance occurs while there is a large increase in cost. A new methodology is proposed for setting sizing criteria for infiltration trenches and bioretention cells which focuses on achieving a desired capture efficiency instead of a required volume of rainfall. The method proposes using the capture efficiency, fraction of maximum cost and sizing criteria to determine what value is an economically more justifiable sizing standard based on individual catchment size and soil type. Use of the analytical probabilistic approach allows for the capture efficiency to be easily calculated and provides better sizing targets on a case by case basis. Recommending a specific capture efficiency can be more uniformly applied LID design in any soil conditions or any catchment size. This can reduce government spending when building LIDs and greatly reduce the possibility of over-design.

Acknowledgements

I would like to thank my supervisor Dr. Yiping Guo for the opportunity to learn and grow under his supervision. I am truly grateful for all his patience, understanding and his consistent support throughout graduate studies. I am appreciative of everything that he has taught me about water resources engineering in both undergraduate and graduate classes. Thank you for your valuable insight and guidance about LIDs and urban stormwater management.

Secondly, I would like to extend my thanks to my co-supervisor Dr. Zoe Li for all her encouragement and positivity. Thank you for all the feedback and advice over these past two years.

My sincere appreciation extends to my defense committee members Dr. Sonia Hassini and Dr. Paulin Coulibaly for their time and helpful comments to improve my work.

I would like to thank Sarah Sullivan for always being so helpful and caring. Thank you for believing in me and helping me realize that graduate school was an option for me. Thank you for always helping me with any problems that arose, and I am thankful for all the nice chats about school and otherwise that I had with you.

I would like to thank Sally Williams for being a constant mentor to me and encouraging me to never give up and believe in myself. Thank you for your leadership, kindness and all the wisdom that you have passed along to me.

In addition, I would like to thank Joanne Gadawski for being so gracious and supportive. I am truly appreciative of all that you have done for me in the department and for always being open to talk with me.

I extend my sincere appreciation to my fellow members of Dr. Guo's research group, Pavneet Brar and Jun Wang. I am so grateful for your wise advice and mentorship. Thank you for taking me under your wings and helping me through my grad school experience and for being my friend.

I would like to express my sincerest gratitude to my friends in JHE 330. We have spent some long hours together working and helping one another. It may be a cold, dark room but I take away nothing but happy memories from our time working there. Thank you for your empathy and generosity over the last two years. Graduate studies would not have been the same without all of you! Your friendships mean so much to me.

Finally, I would like to thank my parents and sister for their support of my engineering career and returning to university to complete my master's degree. Thank you for all the sacrifices that you have made so I can pursue my goals, especially during these last two years.

Table of Contents

List of Figures

List of Tables

Nomenclature:

Abbreviations

APA	Analytical Probabilistic Approach
ASCE	American Society of Civil Engineers
CRE	Current Rainfall Event
CVC	Credit Valley Conservation
ET	Evapotranspiration
EWRI	Environmental and Water Resources Institute
HDPE	High Density Polyethylene
LID	Low Impact Development
MIT	Minimum Interevent Time
MOECC	Ministry of Environment and Climate Change
PDF	Probability Density Function
PRE	Previous Rainfall Event
STEP	Sustainable Technologies’ Evaluation Program
SWMM	Stormwater Management Model
TRCA	Toronto and Region Conservation Authority
WEF	Water Environment Federation
WQCV	Water Quality Control Volume for Bioretention Cells (m^3)
WQV	Water Quality Volume for Infiltration Trenches (m^3)

Symbols

A	area of catchment draining into an infiltration trench (m^2)

A_c	area of catchment that bioretention is receiving runoff from (m^2)
A_{IT}	surface area of infiltration trench (m^2)
B	void space of the stone reservoir of an infiltration trench (L)
b	interevent time (h)
$\bar{b}$	average interevent time (h)
C_e	capture efficiency of bioretention cell
d_c	design standard i.e. the depth of rainfall that the trench must provide enough storage for (mm)
d_r	chosen depth of the stone reservoir within the trench (mm)
$d_{p,max}$	maximum depth of bioretention cell (mm)
d_{rmax}	maximum depth of stone reservoir in trench (mm)
E_a	average evapotranspiration rate (mm/h)
$E(F_{iw})$	volume of infiltrated water needed to wet the filter media layer (mm)
$E(S_{dw})$	amount of the surface depression water contents of a bioretention cell system at the end of a previous rainfall event or when a current event begins (mm)
$E(v_i)$	expected value of inflow into a bioretention cell (mm of water over bioretention cell’s surface area)
$E(v_o)$	expected value of outflow out of a bioretention cell (mm of water over bioretention cell’s surface area)
f_c	native soil’s saturated hydraulic conductivity (mm/h)
f_m	native soil’s ultimate infiltration capacity (mm/h)
G	groundwater recharge rate from the infiltration trench (L/h)

$G_p(0)$	probability per operation cycle that some overflow occurs
k	infiltration capacity decay coefficient (h^{-1})
r	ration between contributing catchment and bioretention cell surface area
R	runoff reduction rate of an infiltration trench
R	constant ratio for bioretention cells
RVC_t	runoff volume control target (mm)
S_A	surface area of bioretention cell (m^2)
S_d	surface depression of bioretention cell (mm of water over catchment)
S_{dc}	surface depression of storage capacity of bioretention cell (mm of water over catchment)
S_{dw}	amount of the surface depression water contents of a bioretention cell system at the end of a previous rainfall event or when a current event begins (mm of water over bioretention cell's surface area)
S_T	total storage provided by a bioretention cell (m^3)
t	rainfall event duration (h)
t_d	time needed to completely drain out surface depression of bioretention cell (h)
t_s	time for trench to drain (h)
$\bar{t}$	average rainfall event duration (h)
v	rainfall event volume (mm)
v_r	void space ratio for the storage aggregate used in trench
$\bar{v}$	average rainfall event volume (mm)

V	average annual runoff reduced per mm of sizing criterion (mm)
V_i	annual total volume infiltrated (L)
V_T	average annual volume of runoff into an infiltration trench (L)
ϕ	runoff coefficient of catchment area
ζ	inverse of the mean rainfall event volume (1/mm)
λ	inverse of the mean rainfall event duration (1/h)
ψ	inverse of the mean interevent time (1/h)
θ	average number of rainfall events per year

Declaration of Academic Achievement

This thesis was prepared on the “sandwich” format in accordance with the guidelines provided by the School of Graduate Studies at McMaster University. The author, Elizabeth B. Rowe, with the supervision and guidance by Dr. Yiping Guo and Dr. Zhong Li, conducted the research presented in this thesis. Chapters 2 and 3 are going to be submitted as two separate papers to suitable peer reviewed journals for publication.

1. Introduction

Detailed stormwater management regulations are still a relatively recent concept. In 1993 the Ministry of Environment (MOE) (now referred to as MOECC) and the Ministry of Natural Resources (MNR) in Ontario established and released policy documents pertaining to water resources management and urban planning (CVC & TRCA, 2010; Uda, Van Seters, Graham, & Rocha, 2013). Several additional documents were released in the subsequent years updating the policies with aims to improve water quality and controlling the quantities of stormwater runoff (CVC & TRCA, 2010; Uda et al., 2013). However, a new position has been taken by the governing agencies and now control of stormwater at its source and design of stormwater management facilities to mimic pre-development conditions are greatly advocated (CVC & TRCA, 2010; Uda et al., 2013). This new methodology and way of thinking has been largely classified as Low Impact Development (LID) (CVC & TRCA, 2010; Uda et al., 2013). LIDs aspire to provide stormwater management controls and to be as least disruptive as possible to the natural environment. A main idea associated with LID is the treatment train approach (CVC & TRCA, 2010; Uda et al., 2013). In order to meet the pre-development conditions or better, a treatment train approach is employed. A treatment train approach involves a combination of end-of-pipe, lot level and conveyance stormwater controls to improve the quality of runoff and reduce erosion and flooding (CVC & TRCA, 2010). Some of these LID practices include permeable pavement, rainwater harvesting, bioretention cells and infiltration trenches. Studies have shown that implementation of LIDs also has other economic and related benefits for the communities where they are placed in (Buckley, Soulhas, & Hollingshead, 2012; Odefey et al., 2012). Some of the other related benefits are improvements in air quality, and increase in energy efficiency; all these benefits can lead to long term fiscal savings (Odefey et al., 2012).

Although designing a LID for 25 mm seems like a conservative and cost-efficient idea, it may be spending a large sum of money for a minor increase in performance. The 25 mm sizing criterion is chosen by the MOECC for LID design and sizing because this volume represents the 90th percentile storm. In other words, 90% of all rainfall events have volumes below this value (CVC & TRCA, 2010). Exploring different possible sizing standards with respect to capture efficiency and cost will show where the location of the most appropriate range is. Using an analytical probabilistic approach (APA) proven analytical equations for infiltration trenches (Guo & Gao, 2015) and bioretention cells (Zhang & Guo, 2014), capture efficiencies are determined. The objective of this research is to propose a new methodology to be considered when sizing LID. As opposed to having a uniform quantity of rainfall to account for, this research considers achieving a desired capture efficiency instead. This method is also cost efficient as it is case specific. This methodology incorporates what sizing criterion for a LID requires the least amount of cost to construct while providing the most appropriate capture efficiency of the stormwater runoff, making it economically more justifiable.

2. Proper Sizing of Infiltration Trenches for Urban Stormwater Management Purposes

Abstract: The current sizing criteria for low impact development practices (LIDs) including infiltration trenches are based on the concept of 90th percentile storms and require LIDs to provide enough storage capacity to store catchment runoff from the 90th percentile storm of the location of interest. The example 90th percentile storm used in Ontario, Canada has a depth of 25 mm. This study examines the performances and costs of infiltration trenches built in Ontario and sized according to alternative sizing criteria ranging from 5–50 mm. Analytical equations are used to determine the runoff reduction rates of infiltration trenches, and a cost estimation tool specifically developed for LIDs is used to estimate the overall costs. Three different catchment sizes and various soil types are included to broaden the analysis and make the conclusions more reliable. Results indicate that the current design standard of 25 mm is probably too high and not cost-effective. A methodology for selecting more appropriate sizing criteria for different locations is recommended. Use of the analytical equations allows for the runoff reduction rates to be easily calculated and can aid in obtaining more appropriate designs for all possible cases. This can reduce government spending when building LIDs. In addition, this can also reduce the probability of over-designing or under-designing an infiltration trench.

Keywords: Infiltration trench; Low Impact Development (LID); Probabilistic methods; Stormwater capture efficiency, Best management practices (BMP), stormwater management

2.1. Introduction

Infiltration trenches are rectangular excavations filled with gravel or other storage media that provide spaces for temporarily storing stormwater. Their objective is to capture/treat stormwater runoff and improve its overall quality. The storage space provided by trenches allows infiltration through the bottom and sides of the trench to take place through a longer time. Infiltration trenches remove pollutants from runoff through filtering that is provided by the storage media; they also reduce peak discharge rates, reduce surface runoff volumes, and increase groundwater recharge (Warnaars, Veldt Larsend, Jacobsen, & Steen Mikkelsen, 1999; CVC & TRCA, 2010; Fach & Dierkes, 2011; Guo & Gao, 2015). Trenches can contain an overflow pipe usually made of High Density Polyethylene (HDPE) and it is recommended to be perforated to ensure that water can flow through continuously (CVC & TRCA, 2010). Infiltration trenches act as a treatment facility serving various types of urban areas such as residential and commercial lots. Figure 2.1 shows a schematic of an infiltration trench.

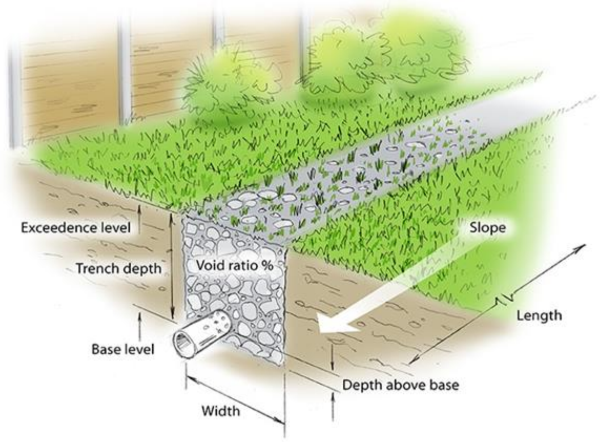

Figure 2.1: Schematic of an infiltration trench (Innovyze Research Center, 2016)

Trenches are typically filled with clean granular stone or other aggregates able to form voids and are lined with geotextiles such as a filter cloth (Warnaars et al., 1999; CVC & TRCA, 2010; Fach & Dierkes, 2011; ASCE, EWRI (Environmental and Water Resources Institute), & WEF (Water Environment Federation), 2012; Guo & Gao, 2015). The ratio between impervious catchment area and trench area is between 5:1 and 20:1. Widths at the bottom of the trench are typically between 600 mm and 2,400 mm (CVC & TRCA, 2010). Their recommended use is in areas where there is adequate permeability in native soils and the bottom of the trench is at least 1 m away from the groundwater table or the top of bedrock (CVC & TRCA, 2010).

The volume of the pores of the materials inside the trench act as a storage volume for the captured runoff. Sediments can build up over time within an infiltration trench and this process is the primary reason for clogging to occur in infiltration trenches (Siriwardene, Deletic, & Fletcher, 2007; Guo & Gao, 2015). Clogging can reduce the lifespan of an infiltration trench. Should clogging occur, infiltration through the bottom of a trench becomes insignificant because water cannot travel through. However, infiltration through the sides of the trench continues to occur regardless of clogging. Keeping debris and sediments out of the trench is imperative and can be achieved using pretreatment methods. These methods include adding a mesh leaf screen on building eavestroughs or roof downspouts, in-ground filters that can be placed inside a conveyance pipe, an oil and grit separator, and vegetated filter strips or grassed swales (CVC & TRCA, 2010).

There are some concerns about the suitability of using infiltration trenches, e.g., the risk of soil and/or groundwater contamination, standing water attracting mosquitoes, seepage if placed too close to a building or house, and winter operation (CVC & TRCA, 2010). These are general misconceptions and have not been brought to reality. Steps are taken in design and construction to prevent contamination. These include trenches not receiving runoff from heavy traffic areas where lots of de-icing salts are used and from areas where there is potential for highly polluted runoff such as agricultural lands, heavy industrial sites, storage sites for hazardous materials and automobile related facilities (i.e. gas station, car repair garage, etc.). Instead runoff should be received from roofs, low traffic roads, and parking lots. In addition, adding an oil and grit separator or another pretreatment device aids in preventing contamination (CVC & TRCA, 2010). Increased mosquito volumes due to standing water is unlikely because water that is stored in a trench is exclusively underground. In order to prevent seepage, the trench should be set-back 4 m from building foundations and overflow pipes should discharge to pervious areas that are minimum 2 m away from a building and be sloped in the direction away from the building (CVC & TRCA, 2010). Finally, during the winter infiltration trenches will continue to operate as long as the inlet pipe and top of facility are located below the maximum frost penetration depth (Ministry of Transportation (MTO), 2005; Guo & Gao, 2015).

It is essential to monitor or calculate the overall performance of an infiltration trench to ensure that it is designed properly and is functioning well and not becoming clogged. The performance of a trench can be evaluated by monitoring or calculating the total amount of pollutants removed from the captured runoff over a long term. Since it is more costly to monitor or calculate the pollutants removed, the best surrogate measure of performance is the percentage of runoff infiltrated over the long term. This percentage or ratio is often referred to as the runoff reduction rate and may be used to evaluate the overall performance of a trench. However, since the long-term average runoff reduction rate is also difficult to calculate, in many jurisdictions, the current practice is to size infiltration trenches so that it has enough storage space to store runoff from its catchment as a result of a storm with a specified depth.

For example, in Ontario, Canada, the Ministry of Environment and Climate Change (MOECC), together with the Credit Valley Conservation Authority (CVC) and Toronto and Region Conservation Authority (TRCA) require that, infiltration trenches, similar to other types of low impact development practices (LIDs) must be able to provide enough storage for runoff from a 25 mm rainfall event, and this quantity comes from the requirement that the LID should be able to accommodate the 90th percentile storm (CVC & TRCA, 2010; Uda et al., 2013; Aquafor Beech & EarthFX, 2016). It is believed that accommodating the 90th percentile storm would ensure a similar percentage of runoff reduction for all possible design cases. The exact performance of infiltration trenches is usually not evaluated in detail.

The long-term average runoff reduction rate that a trench can provide mainly depends on local climate conditions and the sizing criterion that the trench is sized to satisfy. Across different jurisdictions, sizing criteria for infiltration trenches vary, and the time it takes for a trench to empty after a rainfall event, which is known as the drawdown time, is usually required to be between 24 to 72 hours (ASCE et al., 2012; Guo & Gao, 2015). This study examines the performance and cost of infiltration trenches designed for alternative sizing criteria. A methodology that may be used for selecting more appropriate sizing criteria is developed. The appropriateness of the current sizing criterion used in Ontario is examined and alternative sizing criteria for Ontario are recommended.

2.2. Methodology

The detailed sizing and design procedure used in Ontario is used in this study to obtain the required dimensions of an infiltration trench serving a specific catchment and satisfying different sizing criteria. An analytical probabilistic approach (APA) is applied to determine the runoff reduction rate provided by individual trenches. In Ontario, the Sustainable Technologies Evaluation Program (STEP) has created a LID Practices Costing Tool (hereafter referred to as the STEP tool). This tool is used to calculate the cost for the installation of infiltration trenches.

2.2.1. Detailed Sizing and Design Procedure

To cover a large spread and to include the current Ontario sizing criterion of 25 mm, the range of design standards considered is from 5 mm to 50 mm. Four different underlying soil types are also used to cover a wide range. These include coarse sand, sand, loamy sand and loam. The input parameters used for the underlying soil's saturated hydraulic conductivity f_c are shown in Table 2.1. The soil types with low saturated hydraulic conductivity are included to represent site conditions where soils are compacted to a high degree or where clogging is occurring.

Table 2.1: Saturated hydraulic conductivities of different soil types

	Coarse Sand	Sand	Loamy Sand	Loam
f_c (mm/h)	120	30	15	6

Catchment areas of 2,500 m^2, 4,000 m^2 and 10,000 m^2 are chosen to show the performance of a trench with varying catchment sizes. In addition, the catchment areas were assumed to be either a combination of pervious and impervious areas, or 100% impervious to show how much an effect they might have on cost and performance. For the areas that contain both pervious and impervious sections, a runoff coefficient of 0.7 is applied to account for both types. Using a selected sizing standard and following the current Ontario design procedure, it is first necessary to calculate the Water Quality Volume (WQV) that the trench needs to be able to store. This is expressed as:

$$WQV = d_c \times A \times \phi \tag{2.1}$$

where d_c is the sizing standard (mm), i.e., the depth of the rainfall event that the trench must provide enough storage for, A is the catchment area that drains into the infiltration trench (m^2) and ϕ is the runoff coefficient of the catchment area. For the purpose of this analysis, a runoff coefficient of 0.7 is chosen which coincides with the City of Toronto standards for an area that includes semi-detached residential housing (Klimas, 2009). Using the *Low Impact Development Stormwater Management Planning and Design Guide* (2010) (hereafter referred to as *LID Guide*), the maximum depth of the stone reservoir in the trench, d_{rmax} is determined next. The equation used is:

$$d_{rmax} = f_c * t_s / v_r \tag{2.2}$$

where t_s is time for the trench to drain, and v_r is void space ratio for the storage aggregate used in the trench. The *LID Guide* recommends using 48 hours for a typical time to drain and a void ratio of 0.4 which is the ratio for common 50 mm clear stone (CVC & TRCA, 2010).

There is also a safety correction factor that the infiltration rate must be divided by in order to produce a conservative design. This factor is based on the ratio of the mean value at the proposed bottom elevation of the practice to the mean value in the least permeable soil horizon within 1.5 meters of the proposed bottom elevation (CVC & TRCA, 2010), and in this case it is 2.5. When sizing infiltration trenches, the soils directly underneath and beside the infiltration trench may be assumed to be always fully saturated. Therefore, for design purposes, when there is water within the trench, the infiltration rate will always equal the soil's saturated hydraulic conductivity (Chahar, Graillot, & Gaur, 2012; Guo & Gao, 2015). It should be noted that infiltration rates are high during the first stages of a storm because the soils are usually unsaturated. In this case, the infiltration rates are commonly greater than the soil's saturated hydraulic conductivity (Chahar et al., 2012; Guo & Gao, 2015). As a result, assuming a constant infiltration rate in the design stage ensures a marginally conservative design (Chahar et al., 2012; Guo & Gao, 2015), which is the reason why it is generally accepted in design practices (Maryland Department of Environment, 2000; Pennsylvania Department of Environmental Protection, 2006; Guo & Gao, 2015).

Once the depth of the reservoir is determined, the surface area footprint of the trench (A_{IT}) was calculated using the *LID Guide* (2010). The equation for A_{IT} is:

$$A_{IT} = WQV/(d_r \times v_r) \tag{2.3}$$

where d_r is the chosen depth of the stone reservoir within the trench (mm) and A_{IT} is measured in square meters (m^2).

2.2.2. Analytical Probabilistic Approach for Estimating Runoff Reduction Rates

Knowing A_{IT}, d_r and other characteristics of an infiltration trench and its catchment, the long-term average runoff reduction rate provided by the trench can be estimated with continuous simulation that numerically models time step-by-time step the operation of the trench under the input of an observed long-term rainfall record. After each simulation run, the long-term average performance of the trench is obtained by averaging out the performance of it throughout the entire length of simulation. This is time-consuming and is usually not used for regular design purposes. An analytical probabilistic approach (APA) was developed as an alternative to continuous simulation. The general probabilistic approach for analytically analyzing the rainfall-runoff-streamflow processes was first introduced by Eagleson (1972) who demonstrated that using derived probability distribution theory, flood frequency distributions of small watersheds can be analytically determined taking into consideration local rainfall and catchment characteristics. This general approach was expanded for use in urban stormwater management by Guo & Adams (1998a, 1998b) and Guo & Gao (2015) and many other studies. A brief introduction of this approach and specifically as it was developed for infiltration trenches is given below.

Instead of using directly the historical continuous rainfall series as input for computer simulation models, the APA first separates a continuous rainfall series into individual rainfall events according to a pre-selected minimum dry period known as the minimum interevent time (MIT) (Guo & Adams, 1998a, 1998b; Guo & Gao, 2015). The MIT is defined as the minimum time period without rainfall that separates consecutive rainfall events. Rainfall episodes that are separated by dry times shorter than MIT are considered as belonging to the same rainfall event. Each separated individual rainfall event is characterized by its volume, duration, and the interevent time preceding the occurrence of the event. It was discovered that, for many locations, exponential probability density functions (PDFs) fit well the observed frequency distributions of rainfall event volumes, durations and interevent times (Adams & Papa, 2000; Guo & Gao, 2015). The PDFs of the exponential distributions are shown below.

$$f(v) = \zeta e^{-\zeta v} \tag{2.4}$$

$$f(t) = \lambda e^{-\lambda t} \tag{2.5}$$

$$f(b) = \psi e^{-\psi b} \tag{2.6}$$

In these equations, v is the rainfall event volume (mm), t is the rainfall event duration (hours), and b is the interevent time (hours); ζ, λ, and ψ are distribution parameters (Guo & Baetz, 2007; Zhang & Guo, 2012, 2015; Guo & Gao, 2015). Using the method of moments, the distribution parameters ζ, λ, and ψ can be estimated as, respectively, the inverse of the mean rainfall event volume ($\bar{v}$), the inverse of the mean rainfall event duration ($\bar{t}$), and the inverse of the mean of the interevent time ($\bar{b}$) for a location of interest.

The representative area chosen for this study is Toronto, Ontario, however this method can be used for other areas if data is available. Table 2.2 below shows the input parameters used for the PDFs for the city of Toronto which was obtained in the previous study by Guo & Adams (1998a).

Table 2.2: Input parameters for PDF

City	MIT (hours)	$\bar{v}$ (mm)	$\bar{t}$ (hours)	$\bar{b}$ (hours) (modified)	$\bar{b}$ (hours) (unmodified)	θ (number of events/year)
Toronto, ON	6	9.3	8	128	104.9	57.2

In Table 2.2, θ represents the average number of rainfall events per year. Rainfall periods that have a dry period longer than the IETD of 6 hours are considered separate rainfall events while those that are less than 6 hours are classified as the same event (Guo & Adams, 1998a)

The APA that can be used to estimate the runoff reduction rate provided by infiltration trenches was developed by Guo and Gao (2015) where they also compared results from APA with those from continuous simulations. To derive the analytical equations that can be used to calculate the runoff reduction rate, Guo and Gao (2015) analyze in detail the operation of a trench under a cycle of a dry period followed by a rainfall event. Both the dry period length and the rainfall event's volume and duration are treated as random variables following their respective exponential distributions. Knowing the PDFs of the random input rainfall event and dry period characteristics and the properties of the trench and its catchment, Guo and Gao (2015) derived equations needed to probabilistically describe the operation and performance of the trench. Specifically, knowing the catchment size A (in hectares) and its runoff coefficient ϕ, incorporating the fact that the input rainfall events have volumes following an exponential distribution as shown in Equation (2.4), the average annual total volume of inflow into the trench, V_T (L, i.e., liters), can be derived and analytically expressed as:

$$V_T = \left(\frac{A\phi}{\zeta}\right)\theta \tag{2.7}$$

Additionally, the probability per operating dry period-rainfall event cycle that some overflow occurs [denoted as $G_p(0)$] is also derived and it can be expressed as:

$$\begin{aligned} G_p(0) = & \frac{\lambda(A + A_{IT})}{[\lambda(A + A_{IT}) + \zeta G][\psi(A + A_{IT}) + \zeta G]} \\ & \times [\psi(A + A_{IT}) + \zeta G e^{-\zeta B/(A+A_{IT}) - \psi B/G}] \end{aligned} \tag{2.8}$$

where B (in liters) is the amount of the total void space in the storage reservoir of an infiltration trench, G (L/h, i.e., liters per hour) is the infiltration or groundwater recharge rate facilitated by the infiltration trench which is equal to the design infiltration rate of the soil multiplied by the surface area over which infiltration occurs. The probability of no overflow per operation cycle can then be calculated as [1 - $G_p(0)$].

Building on the previously described derivation results, the average annual total volume infiltrated in the trench V_i (L) is derived and it can be expressed as:

$$V_i = \frac{A\theta(r+1)}{r\zeta}[1 - G_p(0)] \tag{2.9}$$

The runoff reduction rate R is calculated by dividing the average annual total volume infiltrated, V_i (L), by the average annual volume of runoff into the trench, V_T (L), i.e.,

$$R = \frac{V_i}{V_T} = 1 - G_p(0) \tag{2.10}$$

Equations (2.8) and (2.10) provide an analytical way of estimating runoff reduction rates and they form the basis of the APA for infiltration trenches. Compared to continuous simulations, the APA is much more computationally efficient. Guo and Gao (2015) verified that APA can provide accurate enough results for almost all possible design cases whereas it requires much less calculation than continuous simulations. In this research, the APA developed by Guo and Gao (2015) is used to calculate the runoff reduction rate for each individual design cases satisfying different sizing standards.

2.2.3. Sustainable Technologies Evaluation Program's LID Practices Costing Tool

The Sustainable Technologies Evaluation Program (STEP) is a multi-partner program that was developed to support sustainable initiatives and technological developments in Canada (Toronto and Region Conservation Authority, 2019). STEP is also a verifier for the Environmental Technology Verifier Process (EVP) which provides independent evaluation of new technologies to validate environmental claims so that users, developers, regulators and other parties can make informed decisions about purchasing, applying and regulating innovative technologies (Toronto and Region Conservation Authority, 2019). STEP has created a specific program in Microsoft Excel for determining the cost of LIDs such as bioretention, enhanced grassed swales, green roofs, infiltration chambers, infiltration trenches, permeable interlocking concrete pavers, and rainwater harvesting, which is referred to as the *Low Impact Development Practices Costing Tool* (hereafter referred to as STEP tool) (Toronto and Region Conservation Authority, 2019). The costing tool is available on the STEP program's web site for all to use and is free of charge (Uda et al., 2013).

The main purpose of this tool is to examine the capital costs of a LID project in Ontario, but it also assesses the cost for a life cycle of 50 years (Uda et al., 2013). For the purposes of this research, only the capital cost will be considered since the overall objective is to analyze the cost of a stormwater management control measure and its overall capture efficiency based on different sizing criteria. Qualitative benefits such as public health benefits, improved air quality, and improvement to aesthetics are not accounted for in the STEP costing tool, but it should be recognized that these are all advantages with any type of LID. The tool permits users to input parameters of a proposed design and check to see an approximate estimate of what the capital cost may look like. It also allows the opportunity for comparison of different proposed designs and cost variance between different forms of LID. Overhead costs may also be considered which include 4.5% for construction management, 2.5% for design, 0.5% for small tools and 0.3% for clean-up (Uda et al., 2013). In our analysis, a common total overhead of 10% is used in the costing process to account for the situation where a general contractor is in fact retained.

The tool provides an in-depth and complete procedure for estimating the cost of construction of LIDs in Ontario. The construction of each LID in the tool takes into account the construction sequence, construction methods and information regarding pre-construction tasks such as geotechnical testing. These construction processes and requirements are included and stipulated according to the *LID Guide* (2010). The costs of labour, required equipment and delivery were obtained from the RSMeans database and these costs do not include sales taxes. The assumption applied by STEP for the program was that there would be no general contractor for the potential construction project and Standard Union labour costs were used. With respect to general construction site assumptions, STEP assumed that all LIDs are for a large development; therefore mobilization and demobilization costs were neglected and that there is room on site for excavated soil to form a stock pile. Although the tool enlists prices from 2010, there is an option to enter an inflation rate on each LID capital cost spreadsheet. This option was not employed for this research because it does not affect the relationship between cost and runoff capture efficiency. It is not so much the overall cost that is essential to the work completed, but rather the increase in cost per millimeter of rainfall increased for design. Multiplying the calculated costs by the inflation rate between 2010 and 2019 in Canada would adjust the projected costs to 2019 rates. The relationship between cost and sizing criteria would be the same, just the prices would be greater.

The STEP tool divides the capital costs into three main categories: pre-construction, excavation, and materials and installation. The pre-construction section contains four items which are test pits, infiltration tests, stakeout of utilities, and erosion and sediment controls. The tool accounts for two test pits, two infiltration tests and one site visit to stakeout utilities. In Ontario, Ontario One Call is the service that must be contacted to set-up a visit to mark where utilities are underground prior to construction commencing. The related costs are automatically generated once the inputs are entered. Erosion and sediment control devices such as a silt fence, directing runoff away from the proposed facility are quantified per linear meter.

In the excavation section, there are five tasks which include topsoil salvage and haul to stockpile, excavating trench with trench box, loading, hauling and safety fencing (Toronto and Region Conservation Authority, 2019). Costs related to topsoil salvaging, hauling to stockpiles, and excavating trench box are measured in cubic meters for the volume of soil that is to be dealt with for each task. Loading is taken as 15 % of the overall excavation cost, the number of hours allocated to hauling is automatically generated and one week of a rental of a construction safety fence are indicated. There is an option to remove any of the previously mentioned items by use of a drop-down menu at the preference of the designer.

The materials and installation section are where the majority of the costs are produced. Four-inch diameter maintenance hole and inlet attachment, roof to system attachment, hydrodynamic separator, overflow attachment, and monitoring wells are all priced individually. Geotextile (Polypropylene filtration fabric) and line pipe with expandable rings are both priced per square meter. The 300 mm diameter perforated pipe is priced per linear meter of pipe required. Costing for placing and compaction of 50 mm clear stone and fill are based on both per balk cubic meter and per compacted cubic meter. Included in the placing and compaction tasks are compaction tests, one proctor test and four nuclear density tests (Toronto and Region Conservation Authority, 2019).

There are two tables within the STEP tool section for infiltration trenches, one for the design of the trench and the other one for calculating its capital cost. The design table contains fields where the user can enter the roof and road drainage area to calculate the catchment total area. The tool generates values for many other design parameters and an overall cost. However, the option to revise many of the automatic parameters is available. The infiltration rate of the subgrade, safety factor, void ratio, drawdown time, inlet locations, rainfall captured, depth, width and length of trench are all features that the user can modify to change the design and cost of a proposed infiltration trench. There is also an option to adjust sizing of the infiltration trench based on a ratio between drainage area to surface area of the trench. Finally, there are four fields that cannot be changed by the user and are generated by the tool itself. These are total drainage area, surface area of trench and water storage volume (Toronto and Region Conservation Authority, 2019). The STEP tool considers the cost of design (included in overhead), material, delivery, labour, equipment (rental, operating and operator costs), hauling and disposal (Toronto and Region Conservation Authority, 2019). For the purposes of this analysis, the constant parameter values in Table 2.3 are entered.

Table 2.3: Constant parameter values for infiltration trench cost

Constant Parameters for Obtaining Cost of Infiltration Trench	Value
Safety Factor	2.5
Void Ratio	40%
Drawdown Time	48 hours
Inlet Location(s)	1

The main input fields within the design table are catchment area, infiltration rate, rainfall captured, length, width and depth of trench, and the drainage area to surface area ratio. These fields are dependent on the catchment area and soil type chosen for each respective case. Based on the sizing criteria selected for use, these fields are all changed case by case, and the cost is calculated by this tool based on these inputs.

2.3. Results and Analysis

To assess the cost effectiveness of the current 25 mm sizing standard, for each of the selected catchment types and sizes, infiltration trenches are sized to satisfy different sizing standards. To assess the impact that the underlying soil's hydraulic conductivity may have on the cost effectiveness, infiltration trenches are also assumed to be situated in areas with either one of the previously described four soil types. For each combination of catchment size, catchment type, soil type, and design standard, the runoff reduction rate, i.e., capture efficiency, achieved by the trench is calculated using the APA, while its capital cost is estimated using the STEP tool. Comparisons are then made combining results from different groups of individual cases.

Figures 2.2–2.5 illustrate the resulting cost and capture efficiencies for four different soil types. For cases plotted in each of these four figures, the catchment area that the trenches are designed to serve is the same, also the same is the type of soil that underlies the trenches. The catchment type and area, and the type of soils of each group of cases are given in the titles of the figures. The factor that changes among the cases plotted in each figure is the sizing criterion. The sizing criterion that the trench is designed to satisfy is plotted on the horizontal axis of Figures 2.2–2.5. The runoff reduction rate that each case will provide is plotted with respect to the y-axis on the left, while the cost is plotted with respect to the y-axis on the right. Instead of plotting the actual costs for individual cases, we define the cost for the case where the 50 mm sizing criterion is satisfied as the maximum cost and then plot the ratio between the cost for satisfying one sizing criterion and the maximum cost. This ratio is referred to as the fraction of maximum cost. This way both y-axes represent dimensionless quantities ranging from 0 to 1. We also purposely make sure that both y-axes are measured at the same scale. The dots representing individual cases are connected to give the lines shown in Figures 2.2–2.5.

With a chosen sizing criterion, the total capital cost is mainly controlled by the catchment area. Specifically, with larger catchment areas, the costs for excavation and materials and installation would increase linearly as catchment area increases. That is why it is not necessary to use a figure to show how cost increases as catchment area increases or even treat catchment area as a variable in our analysis. However, as catchment area increases, additional monitoring wells may be needed and the increase in the cost of monitoring wells may not be linearly related to catchment areas. That is why three possibly encountered catchment areas were studied to ensure that our conclusions may be generally applied to common design cases.

As displayed in Figures 2.2-2.5, the capture efficiency, i.e., the performance curves always have a tendency to plateau after reaching a certain threshold point of the sizing criterion, while the cost always increases linearly as the sizing criterion increases. If the performance curves do plateau or the maximum capture efficiencies do reach one or a fixed maximum value, the most appropriate sizing criterion may be justified as the point where the performance curve reaches its maximum value. However, capture efficiency never reaches one or a maximum value no matter how high the sizing criterion is and the capture efficiency always increases as the sizing criterion increases. It is therefore still difficult to determine from the four figures where the most appropriate sizing criterion is.

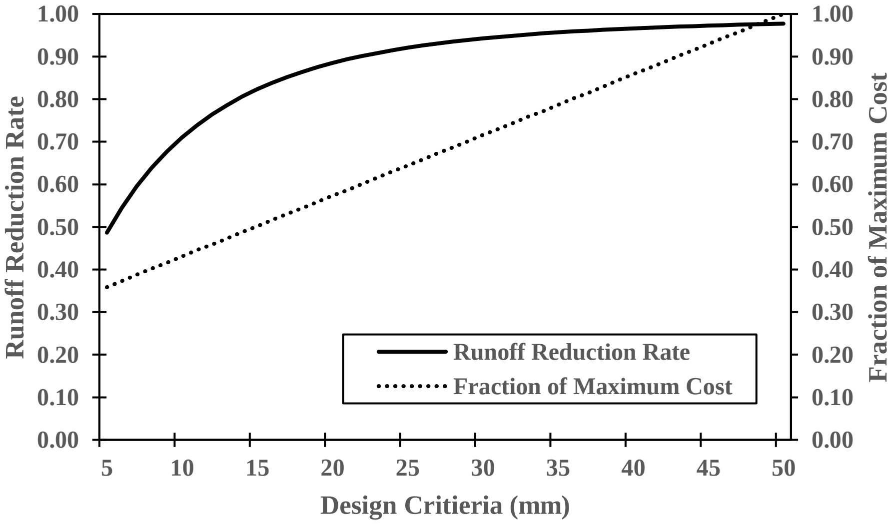

Figure 2.2: Cases with a catchment area of 10,000 m^2 containing both impervious and pervious areas and loam soils

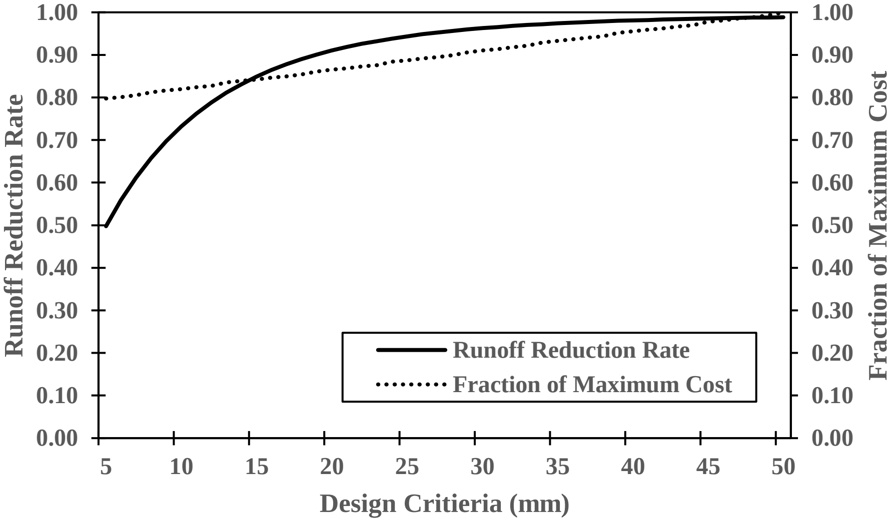

Figure 2.3: Cases with a catchment area of 4000 m^2 containing only impervious area and sand soil

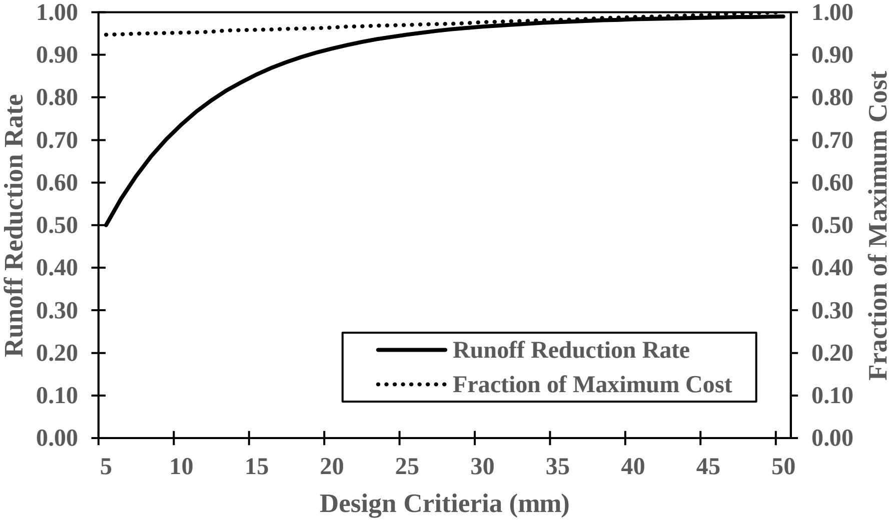

Figure 2.4: Cases with a catchment area of 10,000 m^2 containing only impervious area and coarse sand soil

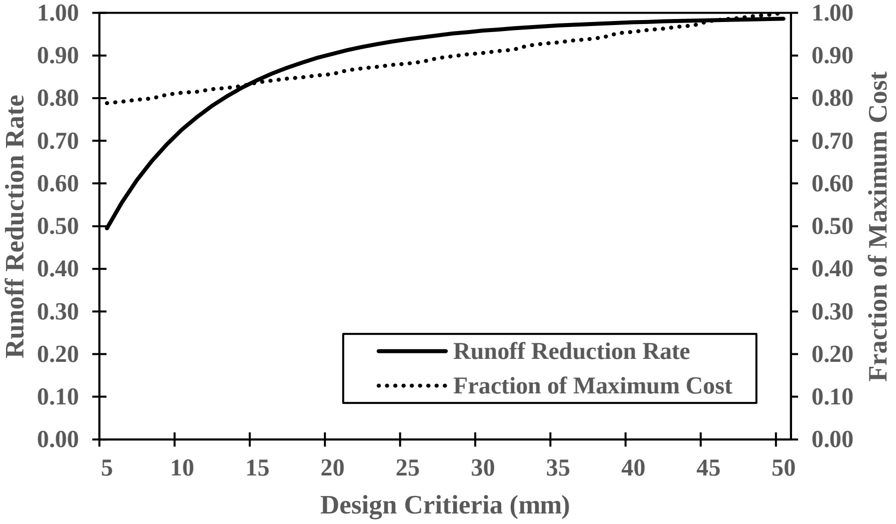

Figure 2.5: Cases with a catchment area of 2500 m^2 containing both impervious and pervious areas and loamy sand soils

If the benefit of reducing runoff volumes due to the installation of infiltration trenches can be assigned a monetary value based on the runoff volumes reduced, the benefit and cost of infiltration trenches may be directly combined and a more appropriate sizing criterion may be determined to maximize the net benefit. However, since no monetary value may be assigned to runoff volumes reduced, sizing criterion may not be chosen for maximizing benefit or minimizing cost. That is why other ways of seeking the economically more justifiable sizing criterion are needed. Our recommended approach is presented as follows.

2.3.1. Rate of Increase in Capture Efficiency Compared to Rate of Increase in Cost

We purposely plotted the y-axis representing the cost in dimensionless form and plot it at the same scale as we plot the dimensionless runoff reduction rates. The slope or gradient of the performance curve at each sizing criterion represents the rate of increase of performance as sizing criterion increases further from that sizing criterion; whereas the slope or gradient of the cost curve at each sizing criterion represents the rate of increase in cost as sizing criterion increases further from that sizing criterion. Since both performance and cost are measured using similar dimensionless measures at the same scale, their rates of increase may be compared directly. That is why we recommend that a straight line parallel to the cost line but tangent to the performance curve is drawn in each figure. The sizing criterion at which this parallel line touches the performance curve may be selected as the appropriate sizing criterion. This is because it is clear now that below this selected sizing criterion, the rate of increase in performance is always greater than the rate of increase in cost, so it is worthwhile to increase the sizing criterion until the selected sizing criterion. While exceeding this selected criterion, the rate of increase in performance is getting more and more smaller than the rate of increase in cost, so it is really not worth it to increase further the sizing criterion. Since performances and costs are measured using similar ratios, the above suggested methodology for selecting an appropriate sizing criterion may be justified.

Example applications of the above methodology are illustrated in Figures 2.6 and 2.7. The more appropriate sizing criteria were found to both be 18 mm. The same method is completed for all the design scenarios and results are presented in Table 2.4

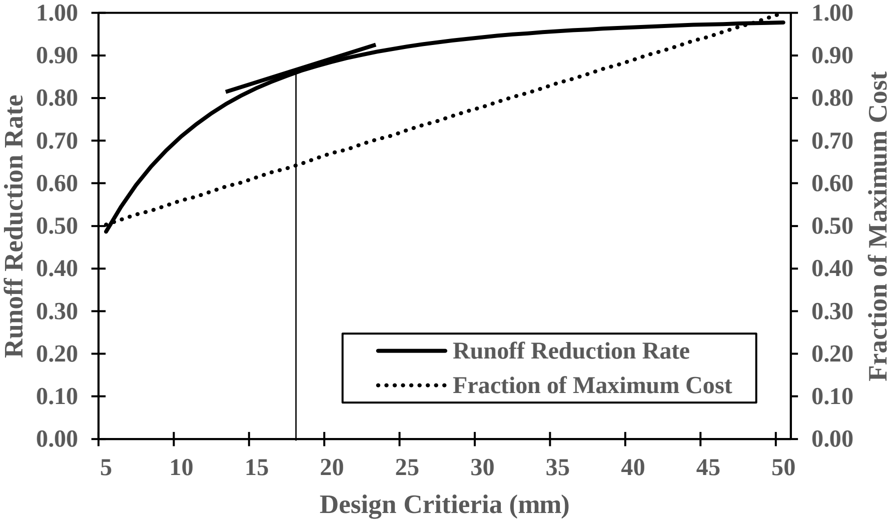

Figure 2.6: Appropriate sizing criteria for a loam catchment of 4000 m^2 (with both pervious and impervious areas)

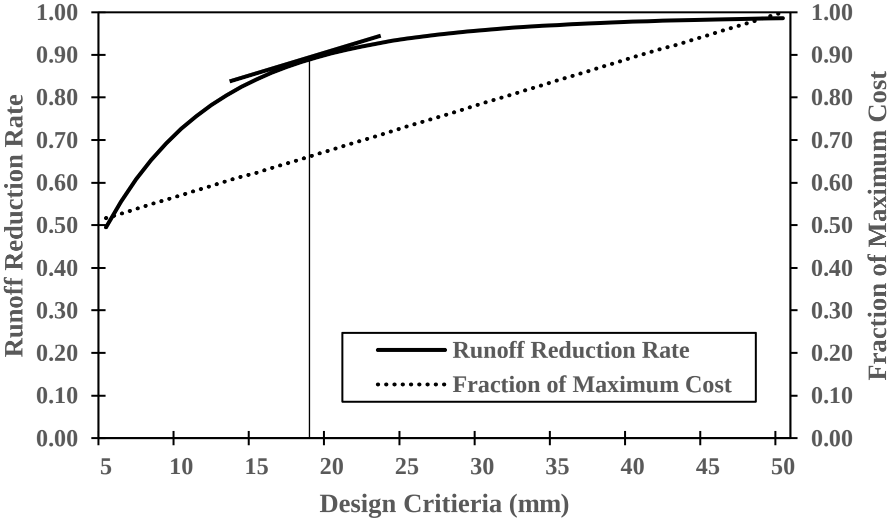

Figure 2.7: Appropriate sizing criteria for a loamy sand catchment of 10,000 m^2 (with an impervious area only)

Table 2.4: Selected sizing criteria for different catchment and soil combinations

Catchment Area (m^2)	Soil Type	Appropriate Sizing Target (mm)	Runoff Reduction Rate
Catchment Includes Pervious and Impervious Areas			
2500 m^2	Coarse Sand	37	0.99
	Sand	31	0.96
	Loamy Sand	24	0.93
	Loam	18	0.86
4000 m^2	Coarse Sand	35	0.98
	Sand	27	0.95
	Loamy Sand	24	0.93
	Loam	18	0.86
10,000 m^2	Coarse Sand	38	0.99
	Sand	25	0.94
	Loamy Sand	20	0.90
	Loam	16	0.84
Catchment Includes Impervious Areas Only			
2500 m^2	Coarse Sand	36	0.99
	Sand	28	0.96
	Loamy Sand	22	0.92
	Loam	18	0.86
4000 m^2	Coarse Sand	37	0.98
	Sand	26	0.95
	Loamy Sand	21	0.91
	Loam	16	0.84
10,000 m^2	Coarse Sand	38	0.99
	Sand	21	0.92
	Loamy Sand	18	0.88
	Loam	16	0.84

Using this method returned capture efficiencies ranging from 0.84 to 0.99. The larger sizing targets returned (i.e. greater than 25 mm) typically had a smaller spread in costs. This means that the cost increased from 5–50 mm was not significant. This was the case for some of the sand and coarse sand cases. Some of the other cases had large gaps between the minimum and maximum sizing criterion. However, it is shown that the majority of the results show a threshold point less than 25 mm while still achieving an acceptable amount of runoff reduced.

2.3.2. Volume of Runoff Reduced Per Millimeter Increase in Sizing Criterion

Even though standardization of both performance and cost make them to some degree directly comparable to each other, they are still two different things. That is why the above-suggested methodology for selecting the most appropriate sizing criterion may not be fully acceptable. Additional calculations were performed and useful statistics are presented to demonstrate further the validity of the proposed methodology. Taking advantage of the convenience of the APA, volume of runoff reduced per millimeter increase in sizing criterion was calculated for all the individual cases satisfying all possible design criteria.

The whole range of possible sizing criteria (from 5 mm to 50 mm) was divided into two sub-ranges: one below the selected criterion and the other above the selected criterion. The average runoff reduced per year per mm increase in sizing criterion is then calculated for the two sub-ranges simply by averaging the amounts obtained for each individual case belonging to the specific sub-range. To make sure the resulting two averages are more comparable to each other, the widths of the two design criteria sub-ranges were chosen to be equal for each groups of cases. Table 2.5 summarizes the calculation results. All runoff volumes in Table 2.5 are reported in the units of mm of water over the corresponding catchment area. This would make them comparable between groups of cases with different catchment areas.

As shown in Table 2.5, for different catchment areas and soil types, the average annual runoff reduced per mm of sizing criterion over the sub-range below the selected sizing criterion is about four times higher than that obtained over the sub-range above the suggested sizing criterion. This demonstrates again how little added performance may be achieved from further increases in sizing criterion above the suggested one. Also reported in Table 2.5 is the runoff reduction rate achieved for each group of cases with the selected sizing criterion. It can be seen that most of runoff reduction rates achieved vary from 0.84 to 0.96. Higher runoff reduction rates are achieved for groups of cases with sandy soils while lower runoff reduction rates are achieved for groups of cases with loamy soils. This highlights again that the infiltration capacity of the soils underneath infiltration trenches plays an important role and increasing the sizing criterion alone may not ensure satisfactory performance for all possible cases. Given that 0.84 to 0.96 can be viewed as satisfactory runoff reduction rates, the suggested methodology for selecting an appropriate sizing criterion seems to provide very useful results.

Table 2.5: Average annual runoff reduction contributed by every mm of sizing criterion

Catchment Area (m^2) & Soil Type	Selected Sizing Criterion and Resulting Runoff Reduction Rate *R*	Sub-range of Sizing Criteria below the Selected Criterion (mm) & Average Annual Runoff Reduced per mm of Sizing Criterion *V*	Sub-Range of Sizing Criteria above the Selected Criterion (mm) & Average Annual Runoff Reduced per mm of Sizing Criterion *V*
10,000 m^2 Loam with Impervious and Pervious Areas	16 mm *R* = 0.84	5–15 mm *V* = 716.90 mm	17–27 mm *V* =178.81 mm
4000 m^2 Loam with Impervious Area Only	16 mm *R* = 0.84	5–15 mm *V* = 1024.14 mm	17–27 mm *V* = 255.45 mm
2500 m^2 Loam With Impervious Area Only	18 mm *R* = 0.86	5–17 mm *V* = 926.98 mm	19–31 mm *V* = 191.45 mm
10,000 m^2 Loamy Sand With Impervious Area Only	18 mm *R* = 0.88	5–17 mm *V* = 954.94 mm	19–31 mm *V* = 181.81 mm
4000 m^2 Loam With Impervious and Pervious Areas	18 mm *R* = 0.86	5–17 mm *V* = 648.89 mm	19–31 mm *V* = 134.01 mm

2.4. Summary and Conclusions

Similar to many other jurisdictions in North America, the Ontario *LID Guide* currently requires that LIDs be sized to accommodate runoff from the 90th percentile rainfall event. In addition, there is a draft of updated LID standards in circulation to stakeholders proposing to increase further the current design target (Antoszek & Denich, 2018). In this study, the performance of infiltration trenches satisfying different design targets was compared to the overall cost for their design and construction. Analytical equations were used to determine the capture efficiencies of infiltration trenches and the STEP costing tool was used to estimate their total capital costs.

Results from this work show that the current 25 mm sizing target may already be too high. Only minor increase in capture efficiency would be gained if the trench is sized for a sizing target exceeding a specific threshold, but the total capital cost of the trench always increases linearly as the sizing target increases. The specific threshold of sizing target over which little increase in capture efficiency may be gained depends on the type of soil underneath the trench and the catchment area it services. To assist in selecting a more appropriate sizing target, almost all possible sizing targets were tested; the rate of increase in capture efficiency as sizing target increases was compared to the rate of trench cost increase as sizing target increases. The increase in runoff reduction rates per additional millimeter of sizing criteria were also calculated. Based on the outcomes of these calculations, the economically more justifiable sizing target was found to be in the range of 16–24 mm for most design cases of the different types of soils and catchments. Coarse sand showed results in the range of 35–38 mm which is slightly higher than the rest. However, coarse sands with an infiltration rate of 120 mm/h seldom occur in nature. For a jurisdiction of interest, the most possible soil types and catchment sizes may be narrowed down further in order to select a single sizing target.

It was confirmed in this research that a small increase in sizing criteria can lead to significant increases in costs. It is important to note that added cost of design and construction will also result in additional costs for operation and maintenance. Together this leads to considerably much more spending by the government on LIDs while more funds are actually needed for other integrated stormwater management practices. Instead of sizing to accommodate the 90th percentile storm regardless of the actual runoff reduction rate that can be achieved, it is more meaningful and useful to size trenches so that a uniform runoff reduction rate of, e.g., 80% or better, is achieved in each design case. Using the analytical equations, the runoff reduction rates for each design case can be easily calculated, ensuring that either under-design or over-design would not take place.

Recognizing that this is preliminary research, more comprehensive studies need to be completed to further reinforce the findings that 25 mm may not be the best choice as a sizing target. This work focuses on infiltration trenches, but additional studies focusing on other forms of LIDs such as permeable pavements, rainwater harvesting and bioretention cells can be conducted using the same techniques to evaluate the current runoff control volume target. Analytical probabilistic equations as opposed to continuous simulations may be used as a simpler method to estimate the runoff reduction rates of LIDs. Using the STEP tool or another estimating program of its kind can produce an approximated cost to compare to the capture efficiency provided by the LID. Moreover, carrying out this kind of work for more geographic locations of different climates can further explore what the most appropriate sizing target is for different regions.

3. Proper Sizing of Bioretention Cells for Urban Stormwater Management Purposes

Abstract The Ministry of Environment and Climate Change (MOECC) establishes the sizing criteria for the design of Low Impact Development (LID) practices in the province of Ontario. The current design standards are based on the concept of the 90th percentile storm and require LIDs to provide enough storage capacity to store catchment runoff from a 25 mm rainfall event. This study examines the performance and cost of bioretention cells sized for alternative sizing standards ranging from 5–50 mm. Analytical probabilistic equations are used to determine the capture efficiencies of bioretention cells while the Sustainable Technologies Evaluation Program (STEP)'s LID Practices Costing Tool is used to estimate the overall cost. Two different catchment sizes and various soil types are included to broaden the analysis and make the conclusions more reliable. A design case including an underdrain is added to the work to encompass a larger scope. Results indicate that the current sizing standard of 25 mm is probably too high and not cost-effective. In fact, depending on the type of soil and LID, setting design standards based on depth of a rainfall event leads to little increase in performance, while there is a large increase in cost. A new methodology is proposed for sizing bioretention cells based on achieving a desired capture efficiency as opposed to a proposed depth. Use of an analytical probabilistic approach allows for the capture efficiency to be easily calculated and can aid in obtaining a more appropriate sizing target.

Keywords: Bioretention cells; Low Impact Development (LID); Probabilistic methods; Stormwater capture efficiency, Best management practices (BMP), stormwater management

3.1. Introduction

Bioretention cells are a form of low impact development practices (LIDs) and usually perform as a lot level control for stormwater management. The cells are excavated depressions that provide temporary storage for runoff. The cells also contain a filter-bed comprised of different sands, fines and organic matter, and has a thin layer of mulch near the surface and plants growing on it (CVC & TRCA, 2010). An overflow or bypass pipe is included in design to deal with extreme rainfall events. Stormwater runoff flows into the cell and is temporarily stored in the surface depression before infiltrating downward through the pervious media layer. Once the water passes through, it has less debris in it and is of much better quality. At this point it can either flow into a perforated pipe (if that is an option) and carry on to an outflow or keep percolating downward into the native soil. Figure 3.1 shows a schematic profile view of this process.

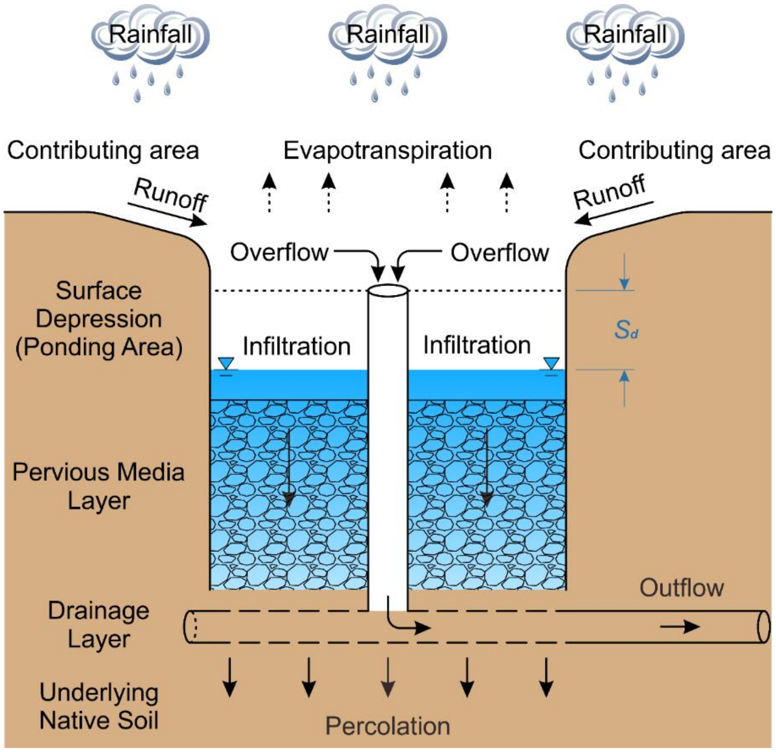

Figure 3.1: Bioretention cell profile

Bioretention cells are becoming a widely used stormwater control measure to meet increasingly stricter stormwater management regulations (Brown & Hunt, 2011). They are designed for three different scenarios: full infiltration, partial infiltration and filtration only (CVC & TRCA, 2010). Full infiltration requires no assistance of an underdrain, partial infiltration does require an underdrain and filtration only requires an underdrain and an impermeable liner to prevent water from infiltrating into the native soils (CVC & TRCA, 2010). In an effort to prevent clogging in the filter media, pre-treatment methods can be implemented to catch larger debris. These methods include the addition of a vegetated filter strip, a settling forebay, and a stone diaphragm (CVC & TRCA, 2010; Uda et al., 2013). It is also important that the plants chosen can withstand road salt and seasonal inundation (Uda et al., 2013).

As widely used and common as bioretention cells are, there are some concerns associated with their use. Some of these concerns include their performance during winter months, risk of groundwater contamination, standing water and mosquitoes, and foundations and seepage (Dietz, 2007; CVC & TRCA, 2010). During winter, considerable amounts of frost does accumulate in the cell, however studies have shown that there is no major decline in performance (Dietz, 2007). In other words, inflow is mostly infiltrated or evaporated (Dietz & Clausen, 2006; Dietz, 2007) and differences in retention time and lag time are not an issue (Dietz, 2007; Muthanna, Thorolfsson, & Viklander, 2013). There are practices that can be applied to counteract the winter cold to ensure the function of the cell is not compromised. Some of these tasks involve extending the underdrain pipe and filter bed below the frost line, choosing vegetation that is salt-tolerant and choosing to oversize the underdrain to reduce the odds of the pipe freezing (CVC & TRCA, 2010). To counteract the potential for groundwater contamination, cells should never receive runoff from heavy traffic areas where large quantities of de-icing salts are used during winter months, and rather give precedence to receiving runoff from areas that are less likely to have contaminants such as roofs, low traffic roads and small parking lots (CVC & TRCA, 2010).

To prevent the problem of mosquito attraction to standing water, cells are designed for a maximum allowable surface ponding time of 24 hours; this time is less than the time required for one mosquito breeding cycle (CVC & TRCA, 2010). In order to counteract seepage, bioretention cells should be set back 4 meters from building foundations (CVC & TRCA, 2010). It is important to consider other concerns when selecting a site for a potential bioretention cell to be located. Some factors to keep in mind are the proximity to wellhead protected zones, underground utilities, overhead wires, and water table (CVC & TRCA, 2010). Bioretention cells should be sized for areas that are between 100 square meters and 0.5 hectares, have contributing slopes from 1–5% and have 1–1.5 m of available head from the inflow point to the downstream invert if an underdrain is used (CVC & TRCA, 2010).

A bioretention cell's performance can be evaluated by monitoring or calculating the total amount of pollutants removed from the runoff captured over a long period of time. It is more costly and complicated to monitor or calculate the pollutants removed from the runoff, therefore the best surrogate measure of performance is the percentage of runoff infiltrated over the long term. This percentage ratio is referred to as the runoff reduction rate. This rate can be used to evaluate the overall performance of a bioretention cell. However, since the long-term average runoff reduction rate is also difficult to calculate, in many jurisdictions, the current practice is to size a bioretention cell so that it has enough storage space to store runoff from its catchment as a result of a storm with a specified depth.

For example, in Ontario, Canada, the Ministry of Environment and Climate Change (MOECC), together with the Credit Valley Conservation Authority (CVC) and Toronto and Region Conservation Authority (TRCA) require that, bioretention cells, similar to other types of low impact development practices (LIDs) must be able to provide enough storage for runoff from a 25 mm rainfall event. This quantity comes from the requirement that the LID should be able to accommodate the 90th percentile storm (CVC & TRCA, 2010; Uda et al., 2013; Aquafor Beech & EarthFX, 2016). The exact performance of bioretention cells is usually not assessed in detail.

The long-term average capture efficiency rate that a bioretention cell can deliver depends on sizing criterion that the cell must be sized to satisfy and local climate conditions. The time it takes for a bioretention cell to drain is usually required to be between 24 to 72 hours (ASCE et al., 2012; Zhang & Guo, 2014). This research examines the cost and performance of bioretention cells designed for alternative sizing criteria. A methodology that may be used for selecting more appropriate sizing criteria is developed. The appropriateness of the current sizing criterion used in Ontario is examined and alternative sizing criteria for Ontario are recommended

3.2. Methodology

The detailed design procedure used in Ontario is used in this study to obtain the required dimensions a bioretention cell serving a specific catchment and satisfying different sizing criteria. As opposed to using continuous simulations for evaluating the performance of LIDs, an analytical probabilistic approach (APA) is applied to determine the capture efficiency presented by individual bioretention cells. In Ontario, the Sustainable Technologies Evaluation Program (STEP) has created a LID Practices Costing Tool (hereafter referred to as the STEP tool), and it is used in this study to calculate the cost for the construction of bioretention cells (Toronto and Region Conservation Authority, 2019).

3.2.1. Detailed Sizing and Design Procedure

Sizing criteria ranging from 5–50 mm are considered. Three filter media types including coarse sand, sand, and sandy loam are investigated to include a wide range of sizing settings. The case with sandy loam soil and an underdrain is also considered. The infiltration rates, f_c of the filter media are shown in Table 3.1.

Table 3.1: Infiltration rates of different filter media

Parameter	Coarse Sand	Sand	Sandy Loam (underdrain included)
f_c (mm/h)	120	36	10.9

Catchment areas of 500 m^2 and 4,000 m^2 are included for the analysis of performance and cost of bioretention cells. It is assumed that the underdrain is a 200 mm diameter pipe and is of HDPE material as per MOECC standards (CVC & TRCA, 2010). With a given sizing criterion and following in accordance with the current Ontario LID design procedure, the total storage (S_T) provided by a bioretention cell is the first value that needs to be determined. Sizing criteria are also referred to as the Runoff Volume Control target (RVC_t) in Ontario; that is why a possible criterion from the range of 5–50 mm is denoted as (RVC_t).The total storage (S_T) that needs to be provided by a bioretention cell is calculated as the following

$$S_T = RVC_t \times A_c \times 10 \tag{3.1}$$

In Equation (3.1). A_c is the catchment area (ha) and 10 is the units correction factor (CVC & TRCA, 2010). Following that, the maximum depth $\left(d_{p,max}\right)$ (millimeters) that the bioretention cell can be is determined by using Equation (3.2)

$$d_{p,max} = f_c \times 48 \tag{3.2}$$

where 48 represents the time to drain or drawdown time (hours) (CVC & TRCA, 2010).

There is also a safety correction factor that the infiltration rate must be divided by in order to produce a conservative design. This factor is based on the ratio of the mean value at the proposed bottom elevation of the practice to the mean value in the least permeable soil horizon within 1.5 meters of the proposed bottom elevation (CVC & TRCA, 2010), and in this case it is 2.5. It should be noted that infiltration rates are high during the first stages of a storm because the soils are usually unsaturated. In this case, the infiltration rates are commonly greater than the soil's saturated hydraulic conductivity (Chahar et al., 2012; Guo & Gao, 2015). As a result, assuming a constant infiltration rate in the design stage ensures a marginally conservative design (Chahar et al., 2012; Guo & Gao, 2015), which is the reason why it is generally accepted in design practices (Maryland Department of Environment, 2000; Pennsylvania Department of Environmental Protection, 2006; Guo & Gao, 2015).

Once the total storage and depth have been determined, the surface area of the bioretention cell is calculated. The surface area (S_A) (also known as area footprint) is calculated in square meters (m^2) and is found using Equation (3.3).

$$S_A = \frac{S_T}{v_r \times d_{p,max}} \tag{3.3}$$

In the above equation, v_r is the void space ratio for filter bed and gravel storage layer which in Ontario, is usually assumed to be 0.4 (CVC & TRCA, 2010).

3.2.2. Analytical Probabilistic Approach for Estimating Capture Efficiency of Bioretention Cells

Given the characteristics and dimensions of the catchment area and the bioretention cell, the long-term average runoff capture efficiency of the cell can be estimated with continuous simulation that numerically models the operation of the cell under the input of an observed long-term rainfall record. The processes involved are modeled on a time step-by-time step basis. After each simulation run, the long-term average performance of the bioretention cell is obtained by averaging out the performance of it throughout the entire length of simulation. This is time consuming and is not recommended or used for regular design purposes. The analytical probabilistic approach (APA) is an alternative to continuous simulations. A similar analytical probabilistic approach for examining the rainfall-runoff transformation and streamflow estimation was first developed by Eagleson (1972). Eagleson (1972) demonstrated that using derived probability distribution theory, flood frequency distributions of small watersheds can be analytically determined taking into consideration local rainfall and catchment characteristics. This approach was expanded for use in urban stormwater management by Guo & Adams (1998a, 1998b); Zhang & Guo (2014), and many others. A brief introduction of this approach and how it was developed specifically for bioretention cells is explained below.

As an alternative to using directly the historical continuous rainfall series as input for computer simulation models, the APA first separates a continuous rainfall series into individual rainfall events according to a pre-selected minimum dry period known as the minimum interevent time (MIT) (Guo & Adams, 1998a, 1998b; Zhang & Guo, 2014; Guo

& Gao, 2015). The MIT is defined as the minimum time period without rainfall that separates consecutive rainfall events. Rainfall episodes that are separated by dry times shorter than MIT are considered as belonging to the same rainfall event. Each separated individual rainfall event is characterized by its volume, duration, and the interevent time preceding the occurrence of the event. It was discovered that, for many locations, exponential probability density functions (PDFs) fit well the observed frequency distributions of rainfall event volumes, durations and interevent times (Adams & Papa, 2000; Zhang & Guo, 2014; Guo & Gao, 2015).The PDFs of the exponential distributions are shown below.

$$f(v) = \zeta e^{-\zeta v} \tag{3.4}$$

$$f(t) = \lambda e^{-\lambda t} \tag{3.5}$$

$$f(b) = \psi e^{-\psi b} \tag{3.6}$$

In these equations, v is the rainfall event volume (mm), t is the rainfall event duration (hours), and b is the interevent time (hours); ζ, λ, and ψ are distribution parameters (Guo & Baetz, 2007; Zhang & Guo, 2012, 2014, 2015; Guo & Gao, 2015). Using the method of moments, the distribution parameters ζ, λ, and ψ can be estimated as, respectively, the inverse of the mean rainfall event volume ($\bar{v}$), the inverse of the mean rainfall event duration ($\bar{t}$), and the inverse of the mean of the interevent time ($\bar{b}$) for a location of interest.

The representative area chosen for this study is Toronto, Ontario, however this method can be used for other areas if data is available. Table 3.2 below shows the input parameters used for the PDFs for the city of Toronto which was obtained in the previous study by Guo and Adams (1998a).

Table 3.2: Input parameters for PDF

City	MIT (hours)	$\bar{v}$ (mm)	$\bar{t}$ (hours)	$\bar{b}$ (hours) (modified)	$\bar{b}$ (hours) (unmodified)	θ (number of events/year)
Toronto, ON	6	9.3	8	128	104.9	57.2

In Table 3.2, θ represents the average number of rainfall events per year. Rainfall periods that have a dry period longer than the IETD of 6 hours are considered separate rainfall events while those that are less than 6 hours are classified as the same event (Guo & Adams, 1998a).

The APA that can be used to estimate the runoff reduction rate provided by infiltration trenches was developed by Zhang and Guo (2014) where they also compared results from APA with those from continuous simulations. To derive the analytical equations that can be used to calculate the runoff reduction rate, Zhang and Guo (2014) analyze in detail the operation of a bioretention cell under a cycle of a dry period followed by a rainfall event. Both the dry period length and the rainfall event's volume and duration are treated as random variables following their respective exponential distributions. Knowing the PDFs of the random input rainfall event and dry period and the properties of the bioretention cell and its catchment, Zhang and Guo (2014) derived equations needed to probabilistically describe the operation and performance of the bioretention cell.

The stormwater capture efficiency of a bioretention system is the fraction of stormwater captured by the bioretention cell (Zhang & Guo, 2014). The equation used to calculate the capture efficiency (C_e) is

$$C_e = \frac{E(v_i) - E(v_o)}{E(v_o)} \tag{3.7}$$

where v_i is the volume of inflow into the cell, and v_o is the volume of overflow from the bioretention system during the current rainfall event, $E(v_i)$ is the expected value of the inflow into the cell and $E(v_o)$ is the expected value of the overflow from the bioretention system during the current rainfall event (Zhang & Guo, 2014). To determine these two expected values, the detailed operation of the bioretention cell over a random dry period and rainfall event cycle was analyzed. For this purpose, the rainfall event within the analyzed cycle is referred to as the current rainfall event, and the rainfall event preceding this event is referred to as the previous rainfall event.

The catchment area that the cell services is characterized as having a surface depression storage S_{dc} (in mm of water over the catchment) and runoff coefficient ϕ. The ϕ fraction of incoming rainfall exceeding S_{dc} is converted to runoff. According to this rainfall runoff relationship and taking into consideration that the input rainfall volumes follow an exponential distribution, (Zhang & Guo, 2014) showed that the expected value of inflow into the cell is

$$E(v_i) = \frac{[1 + r\phi \exp(-\zeta S_{dc})]}{\zeta} \tag{3.8}$$

where r (dimensionless) is the ratio between the contributing catchment's surface area (denoted as A_c) and the bioretention cell's surface area (S_A).

The amount of water contained in the surface depressions of a bioretention cell when the analyzed cycle starts or at the end of a previous rainfall event is denoted as S_{dw}. The expected value of S_{dw} (denoted as $E(S_{dw})$) is needed in order to determine $E(v_o)$. Zhang & Guo (2014) showed that $E(S_{dw})$ can be estimated as:

$$E(S_{dw}) = \frac{\lambda(r\phi + 1)^2}{\zeta[\lambda(r\phi + 1) + \zeta f_c]} exp\left[-\frac{S_{dc}(\zeta f_c + \lambda)}{f_c}\right]\left[1 - exp\left(\frac{\zeta S_d}{r\phi + 1}\right)\right] \tag{3.9}$$

In Equation (3.9), f_c is the infiltration rate of the filter media (mm/h), and S_d is the design storage capacity of the surface depression of the bioretention cell (in millimeters of water over the catchment). Water remaining in the surface depression during the dry period of the analyzed cycle is diminished by either evapotranspiration (ET) or infiltration. The average time for the cell to drain out entirely (denoted as t_d in hours) can be estimated as

$$t_d = \frac{E(S_{dw})}{E_a + f_c} \tag{3.10}$$

where E_a represents the average ET rate (in mm/h).

When the current rainfall event starts, the Horton's infiltration model was used to model more accurately the infiltration process. The volume of infiltrated water needed to wet the filter media layer so that the filter media would reach its ultimate infiltration capacity is denoted as F_{iw} (in mm). A filter medium's ultimate infiltration capacity is usually the same as its saturated hydraulic conductivity. The expected value of F_{iw}, $E(F_{iw})$, is required in order to calculate $E(v_o)$ and it was found to be:

$$E(F_{iw}) = \frac{Rk(f_m - f_c)exp(-\psi t_d)}{(\lambda + k)(\psi + Rk)} \tag{3.11}$$

where R is a constant ratio used in the Horton infiltration model to describe the recovery of infiltration capacities during dry times, f_m is the filter medium's maximum infiltration capacity and k is the infiltration capacity decay coefficient in h^{-1}(Zhang & Guo, 2014). The expected value of overflow was then derived, and it can be expressed in Eq. (3.12).

$$E(v_o) = \frac{(r\phi + 1)}{\zeta} C_1 C_3 [C_2 C_4 (1 - C_5) + exp(-\psi t_d)] \tag{3.12}$$

C_1 through C_5 are dimensionless constants implemented to simplify the formula for $E(v_o)$. The constants can be calculated when the bioretention system design, catchment area characteristics, and mean values of local rainfall event characteristics are distinguished (Zhang & Guo, 2014). The equations for constants C_1 through C_5 are shown below.

$$C_1 = \frac{\lambda(r\phi + 1)}{\lambda(r\phi + 1) + \zeta f_c} \tag{3.13}$$

$$C_2 = \frac{\psi(r\phi + 1)}{\psi(r\phi + 1) + \zeta(E_a + f_c)} \tag{3.14}$$

$$C_3 = exp\left\{-\frac{\zeta[r\phi S_{dc} + S_d + E(F_{iw})]}{r\phi + 1}\right\} \tag{3.15}$$

$$C_4 = exp\left[\frac{\zeta E(S_{dw})}{r\phi + 1}\right] \tag{3.16}$$

$$C_5 = exp\left[\frac{\psi(r\phi+1)+\zeta(E_a+f_c)}{r\phi+1}t_d\right] \tag{3.17}$$

The long-term average stormwater capture efficiency of a bioretention system can then be determined by substituting Equations (3.8) and (3.12) into Equation (3.7), the result is:

$$C_e = 1 - \frac{(r\phi+1)C_1C_3[C_2C_4(1-C_5)+exp(-\psi t_d)]}{[1+r\phi\exp(-\zeta S_{dc})]} \tag{3.18}$$

It is using this equation that the overall capture efficiency can be calculated to assess the performance of a bioretention cell sized to satisfy different sizing criteria. Some of the required inputs to the analytical probabilistic equations are shown below in Table 3.3. In comparison to continuous simulations, the APA is simpler and effective. Zhang and Guo (2014) verified that APA can produce accurate results for almost all possible design cases whereas it requires much less calculation than continuous simulations.

Table 3.3: Input parameters for analytical probabilistic equations for a bioretention cell

Input Parameter	Coarse Sand	Sand	Sandy Loam (underdrain included)
f_c (mm/h)	120	36	10.9
S_d(mm)	200	200	200
S_{dc} (mm)	2.7	2.7	2.7
E_a(mm/h)	0.11	0.11	0.11
k(h^{-1})	3	3	4
R(fraction)	0.014	0.014	0.005
f_m(mm/h)	360	127	101.9

3.2.3. Sustainable Technologies Evaluation Program's LID Practices Costing Tool

The Sustainable Technologies Evaluation Program (STEP) is a multi-partner program that was developed to support sustainable initiatives and technological developments in Canada (Toronto and Region Conservation Authority, 2019). STEP is also a verifier for the Environmental Technology Verifier Process which provides independent evaluation of new technologies to validate environmental claims so that users, developers, regulators and other parties can make informed decisions about purchasing, applying and regulating innovative technologies (Toronto and Region Conservation Authority, 2019). STEP has created a specific program in Microsoft Excel for determining the cost of LIDs such as bioretention, enhanced grassed swales, green roofs, infiltration chambers, infiltration trenches, permeable interlocking concrete pavers, and rainwater harvesting, which is entitled *Low Impact Development Practices Costing Tool* (hereafter referred to as the STEP tool) (Toronto and Region Conservation Authority, 2019). This costing tool is available on the STEP program's web site for all to use and is free of charge (Uda et al., 2013).

The main purpose of the STEP tool is to not only examine the capital costs of a LID project in Ontario, but also assess the cost for a life cycle of 50 years (Uda et al., 2013). For the purposes of this research, only the capital cost will be considered since the overall objective is to analyze the cost of a LID and its overall capture efficiency based on different sizing criteria. Qualitative benefits such as public health, improved air quality, and improvement to aesthetics are not accounted for in the STEP costing tool, but it should be recognized that these are all advantages with any type of LID (Uda et al., 2013). The tool permits users to input the parameters of a proposed design and check to see an approximate estimate of what the capital cost may look like. It also allows the opportunity for comparison of different proposed designs and cost variance between different forms of LIDs. Finally, overhead costs considered include 4.5% for construction management, 2.5% for design, 0.5% for small tools and 0.3% for clean-up (Uda et al., 2013). However, in the spreadsheet for each respective LID, a common overhead of 10% is used in the costing process to account for a situation where a general contractor is in fact retained.

The tool provides an in-depth process for estimating the cost and construction of LID in Ontario. It takes into account the construction sequence, construction methods and pre-construction tasks such as geotechnical testing. The construction process and requirements are included and stipulated according to the *LID Guide* (2010). The costs of labor were obtained from RSMeans database and these costs do not include sales taxes. With respect to general construction site assumptions, STEP assumed that all LIDs are for a larger development; therefore mobilization and demobilization costs were neglected and that there is room on site for excavated soil to form a stock pile (Uda et al., 2013). Although the tool enlists prices from 2010, there is an option to enter an inflation on each LID capital cost spreadsheet. This option was not employed for this research because it does not affect the relationship between cost and runoff capture efficiency. It is not so much the overall cost that is essential, but rather the increase in cost per millimeter of sizing criterion raised.

The STEP tool includes two separate tables for determining the design and cost of a proposed bioretention cell. General assumptions made by the tool are that the bioretention cell is rectangular in shape, pre-treatment occurs through stone diaphragms at curb inlets (not by vegetated filter strips or a settling forebay) and that the design is a new construction and not a retrofit. These tables are separated into two distinct categories: design and capital costs. The design table requires the user to enter three required fields before it can generate a cost. These fields are drainage area (m^2), native soil infiltration rate (mm/h) and design type. Design type refers to whether or not the cell requires an underdrain for support of the process. This is distinguished by the infiltration rate of the soil. Table 3.4 shows how the design types are classified according to the STEP tool.

Table 3.4: STEP tool bioretention cell design type conditions

Design Type	Condition
Full Infiltration	Infiltration rate ≥15 mm/h
Partial Infiltration	Infiltration rate <15 mm/h; requires underdrain
No Infiltration	Used when there are high water tables, contaminated soils, or other constraints to infiltration. Requires underdrain and impermeable liner.

There are several other fields that the tool calculates, but the user can modify to suit their own design needs. These fields include drainage period (h), ponding depth (m), safety factor (unitless), void ratio (%), filter media depth (m), mulch depth (m), pea gravel depth (m), gravel storage layer depth (m), length of bioretention cell (m), width of bioretention cell (m) and an option to size the cell according to the drainage area to surface area ratio (Toronto and Region Conservation Authority, 2019). The constant parameters entered in the table are shown in Table 3.5. Once all the inputs are entered into the STEP tool, the capital cost table generates prices for each corresponding task. These fields are readily available to be changed on a case by case basis depending on the sizing criteria of the proposed bioretention cell.

Table 3.5: Constant parameter values for bioretention cell cost

Constant Parameters for Obtaining Cost of Bioretention Cell	Value
Safety Factor	2.5
Void Ratio	40 %
Drawdown Time	48 hours
Inlet Location(s)	1

3.3. Results and Analysis

In order to review the cost efficiency of the current 25 mm LID sizing standard, bioretention cells of different sizes that receive runoff from different catchment types are sized to meet several sizing standards. It is assumed that bioretention cells are located in areas with one of the aforementioned three soil types. The STEP tool is consulted to estimate the cost of construction of a bioretention cell for a specific design case and the capture efficiency is calculated using the APA proposed by Zhang and Guo (2014). Results from the specific design cases are reviewed and analyzed.

Figures 3.2 and 3.3 show the results of capture efficiencies from the analytical equations and cost ratios achieved from using the STEP tool. Each of the figures represent different soil types. The catchment area is specified in the figure title. It should be noted that the case where an underdrain is used is stated. The horizontal x-axis shows the sizing criterion to size the bioretention cell for, which ranges from 5–50 mm. Along the traditional y-axis on the left side of each figure, the capture efficiency attained for each design case is plotted ranging from 0 to 1. On the secondary y-axis on the right side of the figure the cost ratio is plotted. The individual costs for each design case were calculated for this study, however the cost differences between different soil types and catchment sizes were large. As opposed to plotting these actual costs calculated for each individual sizing case, a cost ratio is calculated instead. This is done by setting the cost for the case where the 50 mm sizing criterion is satisfied as the maximum cost and taking a ratio between the cost of a case satisfying a different sizing criterion (ranging from 5–49 mm) and the maximum cost. Hereafter, this ratio is referred to as the fraction of maximum cost. The rationale behind implementing this instead of plotting actual costs is to ensure that both of the y-axes have dimensionless units from 0 to 1. Along with this tactic, the scales on both of the y-axes are measured the same. The smooth lines in the figures show the capture efficiencies and the dotted lines represent each of the individual cases' fraction of maximum cost.

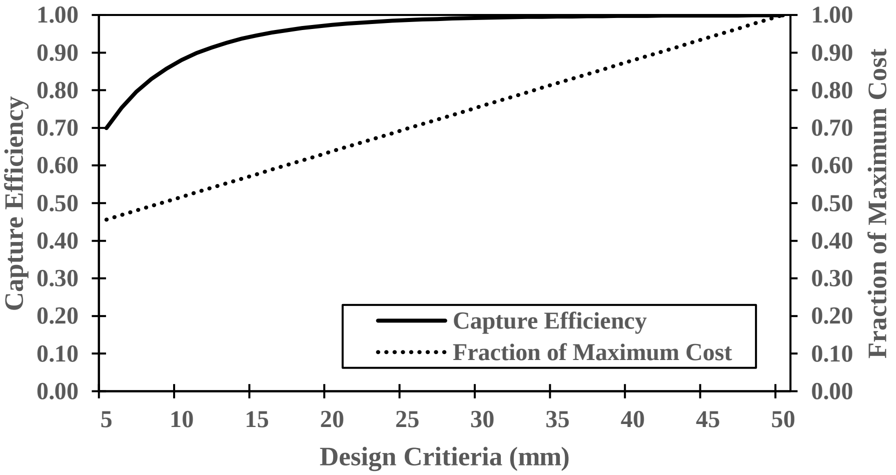

Figure 3.2: Cases with a catchment area 500 m^2 and filter media containing sand soil

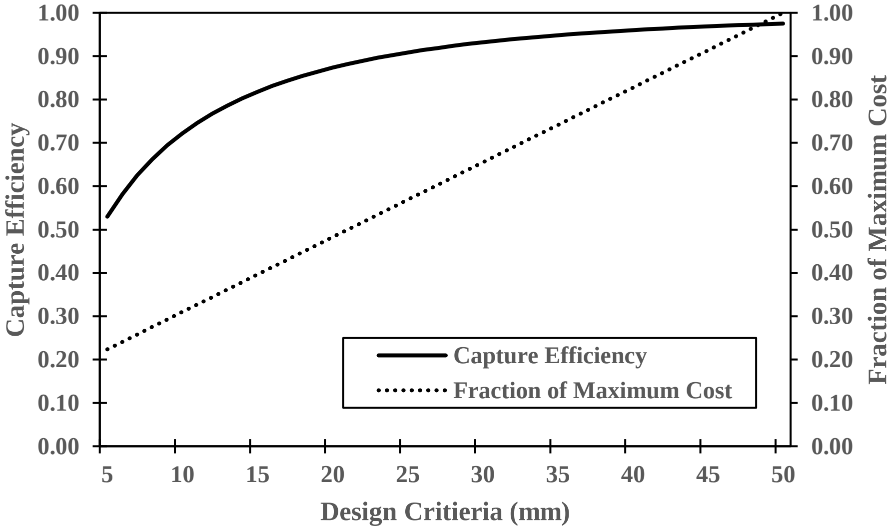

Figure 3.3: Cases with a catchment area 4000 m^2 and filter media containing coarse sand soil

Results show that the cost is mainly controlled by catchment size, although soil type does bear influence also. The costs for excavation and materials and installation increase when the catchment area is increased. As catchment areas are increased, the costs increase as well in a linear manner. Based on these observations, it is not essential to consider catchment area as a variable in this study. According to the STEP tool, additional monitoring wells need to be included as catchment area increases. However, this is dependent on specific catchment size and soil type so it is not able to be categorized as linearly related. In an effort to draw a conclusion from a range of design cases, two catchment areas are included for this study. In order to provide a wider scope of the research, a catchment area with sandy loam soils that has an underdrain included is also considered. It is observed in Figures 3.2 and 3.3 that both capture efficiency curves begin to plateau after a certain threshold point and show minimal amounts of improvement as the sizing criteria are increased further. Beyond the threshold point, the cost of the bioretention cell still increases linearly to varying degrees depending on catchment area size and soil type. The capture efficiency will never reach one or a maximum value no matter how high the sizing criterion is raised. Therefore, the criterion can continually be raised but the gain in performance is not substantial after the threshold point, the cost however still increases linearly. This can end up being much more money spent on minor increase in performance of the bioretention cell. It is therefore important to decide on a more suitable sizing target.

It is not possible to allocate a monetary value to runoff capture efficiency provided by a bioretention cell. Therefore, it is not possible to frame an optimization problem to either minimize the total cost or maximize the total benefit of bioretention cells. This study recommends an alternative method to sizing bioretention cells. This method is described below.

3.3.1. Rate of Increase in Capture Efficiency Compared to Rate of Increase in Cost

Plotting the maximum fraction of cost and capture efficiency in the same format on the y-axis and at the same scale was strategic. The gradient of the performance curve at each sizing criterion represents the rate of increase of performance as sizing criterion increases further from that sizing criterion. Since the capture efficiency curve and fraction of maximum cost are plotted in the same units and the exact same scale, they can be directly compared. This study is proposing that a straight line that is parallel to the cost line and is tangent to the capture efficiency curve is added to each figure to help identify a more suitable sizing criterion. The position on the capture efficiency curve where the parallel line touches is the most suitable sizing criterion to recommend. The sizing criteria below this point are the range where the rate of increase in cost is less than the rate of increase in capture efficiency; the sizing criteria above this point are the range where the rate in cost increase is greater than the rate of capture efficiency increase, which demonstrates that it is not really worth it to size a bioretention cell larger than the selected threshold point. Since there is a consistent ratio and scale between capture efficiency and fraction of maximum cost (cost ratio), this methodology may be justified as a process for choosing a suitable sizing criterion.

Examples of the approach recommended above are shown below in Figures 3.4 and 3.5. Applying the methodology recommended, the economically more justifiable sizing criterion for each case shown in the figures was 14 mm and 11 mm respectively. The same method is completed for all the design scenarios and results are presented in Table 3.6.

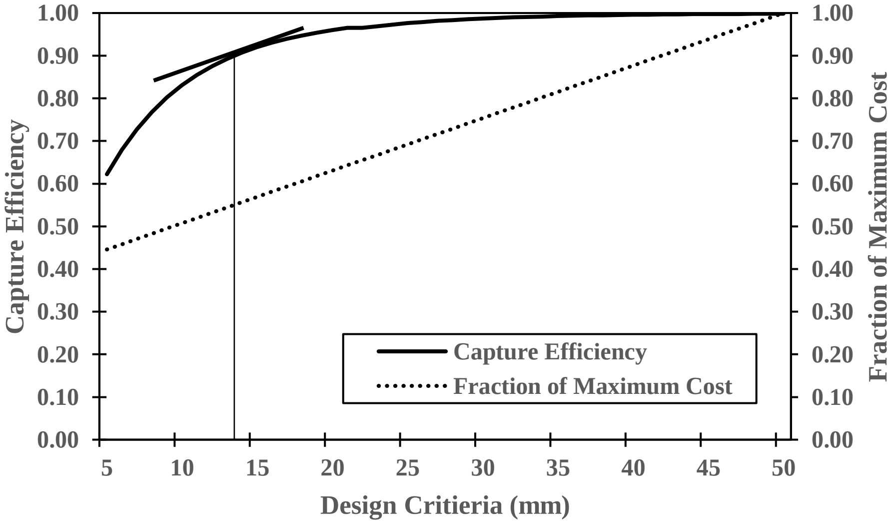

Figure 3.4: Appropriate sizing criteria for a catchment of 500 m^2 containing sandy loam filter media with the inclusion of an underdrain in the bioretention cell design

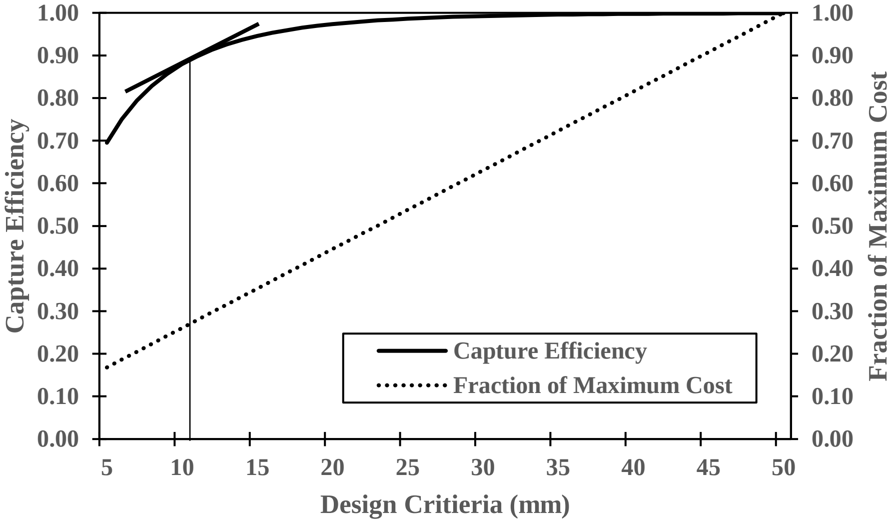

Figure 3.5: Appropriate sizing criteria for a catchment of 4000 m^2 containing a sand filter media without the inclusion of an underdrain in the bioretention cell design

Table 3.6 shows the appropriate sizing target accompanying capture efficiency for the rest of the design situations for a bioretention cell.

Table 3.6: Appropriate sizing targets and accompanying capture efficiencies for bioretention cell design

Catchment Area (m^2)	Soil Type	Sizing Target	Capture Efficiency
500 m^2	Coarse Sand	21	0.91
	Sand	13	0.92
	Sandy Loam + underdrain	14	0.90
4000 m^2	Coarse Sand	14	0.83
	Sand	11	0.90
	Sandy Loam + underdrain	12	0.88

The other design scenarios had similar graphs; the most appropriate sizing criteria found are all under 25 mm. The capture efficiencies achieved with the selected sizing criteria are almost always above 88%. If this level of performance is indeed the desired level, the proposed methodology seems to be suitable for selecting more appropriate sizing criteria

3.3.2. Volume of Runoff Reduced Per Millimeter Increase in Sizing Criterion

The methodology recommended above standardizes capture efficiency and cost of bioretention cells to make them comparable to each other. While this is useful for calculations, these two variables are different, and it is important to provide further support for this methodology of selecting appropriate sizing criteria. Additional statistical calculations are performed to further test the acceptability and validity of this sizing methodology. The volume of runoff reduced per millimeter of sizing criterion increased were calculated for all the individual cases included in this study. The sizing criteria range of 5–50 mm was divided into two sub-ranges: the sub-range below the selected sizing criterion and the sub-range above the selected sizing criterion.

Table 3.7: Average annual runoff reduction contributed by every millimeter of sizing criterion for bioretention cells

Catchment Area (m^2) & Soil Type	Economically More Justified Sizing Target and Reduction Rate *R*	Sub-range of Sizing Criteria below the Selected Criterion (mm) & Average Annual Runoff Reduced per mm of Sizing Criterion *V*	Sub-range of Sizing Criteria above the Selected Criterion (mm) & Average Annual Runoff Reduced per mm of Sizing Criterion *V*
4000 m^2 Sandy Loam with underdrain	12 mm *R* = 0.82	5–11 mm 388.78 mm	13–19 mm 177.60 mm
4000 m^2 Coarse Sand	14 mm *R* = 0.83	5–13 mm 1476.34 mm	15–23 mm 603.83 mm
500 m^2 Sandy Loam with underdrain	14 mm *R* = 0.88	5–13 mm 507.23 mm	15–23 mm 227.08 mm

Table 3.7 shows that the average annual runoff reduced per mm of sizing criterion over the sub-range below the selected sizing criterion is approximately two times higher than that obtained over the sub-range above the suggested sizing criterion This demonstrates that further increasing in sizing criteria beyond the selected ones would be only half as efficient in runoff reductions as compared to what the cells have already been sized for according to the selected criteria. If 80% of runoff reduction is enough for water quality control purposes, the proposed methodology can help provide more appropriate sizing criteria.

3.4. Summary and Conclusion

Ontario currently requires that all LIDs be able to capture and store runoff from a 25 mm rainfall event. In this study, an analytical probabilistic approach was used to determine the capture efficiency of bioretention cells based on a sizing target range of 5–50 mm. The Sustainable Technologies Evaluation Program (STEP)'s *Low Impact Development Practices Costing Tool* was used to estimate the approximate cost of design and construction of bioretention cells. Outcomes demonstrate that the current design standard of 25 mm may be too high for sizing LIDs. The cost increases linearly in most cases as sizing criteria are increased, however capture efficiency of a bioretention cell does not follow this pattern. Beyond a case specific threshold sizing criterion, minor gains in performance may be obtained. This threshold sizing target is case specific and is dependent on the soil type and the catchment size. The increase in capture efficiency per additional millimeter of sizing criteria were also calculated to support further the proposed methodology of comparing the performance and cost curves' gradients for the selection of sizing criteria.

This research reinforces the concept that a small increase in sizing criteria can lead to significant increases in capital costs. It is important to note that added cost of design and construction will also result in additional costs for operation and maintenance. A practical way to size bioretention cells is to propose a uniform capture efficiency, e.g. 80%–90% or better, and each specific design case is required to achieve the specified uniform capture efficiency. This will greatly reduce the probability of over-design and under-design.

This research specifically examines bioretention cells, but future works can apply this methodology for sizing other LIDs such as rainwater harvesting and permeable pavements to analyze current sizing criteria. This method can be applied for many different geographic locations as well. More comprehensive applications need to take place to further support the idea that sizing LIDs for 25 mm may not be the economically more justifiable choice. Analytical probabilistic equations provide a convenient method to determine runoff capture efficiencies. They allow engineers to perform quick calculations for the estimation of the performance of proposed bioretention cell design.

4. Conclusions

This study concentrated on Ontario's Low Impact Development practices' sizing criteria. The suitability of the current sizing criterion of 25 mm representing the 90th percentile rainfall event was investigated to see if this is universally suitable for all types of sites. The overall cost of construction of LIDs was estimated to determine the cost effectiveness of sizing criteria setting at different levels.

Two types of LIDs, infiltration trenches and bioretention cells, are used to assess the current sizing requirement. The range of sizing criteria tested in this work is 5–50 mm to fully assess all possible sizing levels. In addition, several catchment areas and soil types are considered to increase the generality of results and consider different site conditions that LID could potentially be constructed upon.

An analytical probabilistic approach is used for both LIDs to calculate their capture efficiencies. Sustainable Technologies Evaluation Program's (STEP's) Low *Impact Development Practices Costing Tool* is used to calculate the cost of construction for each LID based on a specific sizing criterion. To standardize costs, the cost of each case is divided by the maximum cost of the case satisfying the 50 mm sizing criterion. This value is referred to as the fraction of maximum cost. This value and the capture efficiency are both plotted on the vertical y-axis at the same scale and the sizing criterion is plotted on the horizontal x-axis for figures used to help select more appropriate sizing criteria.

A new methodology is proposed for the selection of proper sizing criteria. This methodology includes three steps. First of all, sizing criteria, capture efficiency and fraction of maximum cost for each catchment size and soil type are plotted in a figure. Secondly, using a line that is parallel to the linear of the cost line, obtaining the point on the performance curve where the cost line is tangent to the performance curve. This point becomes the threshold point where it is ideal for both performance and cost. Thirdly, after obtaining the threshold point, the volume of runoff reduced per millimeter of sizing criteria increased is calculated. This is done by choosing two sub-ranges on the graph; one below the threshold point and one above the threshold point. Each sub-range must be the same in size in order to calculate the average runoff reduced per millimeter prior and after the threshold point.

Infiltration results confirm that this methodology is reliable and demonstrate that after the threshold point, performance is not improved very much while cost still rises. It is discovered that in the case of infiltration trenches, four times the amount of runoff is reduced prior to the threshold point rather than beyond it. Results indicated that coarse sand can contain the most runoff while loam is not as effective. Bioretention cells showed similar design outcomes.

In closing, this research recommends that engineers design LID on a case specific basis with a designated capture efficiency to achieve as oppose to a depth of runoff from a rainfall event. Using the new methodology can achieve this sizing goal, for example attaining a capture efficiency above 80%. By designing on a case-by-case basis, sizing can take into consideration the size of the catchment area and the underlying soils that the LID will be constructed in. This will give more efficient and realistic sizing targets while also saving money on the construction of a LID because this method will significantly reduce the possibility of over-design and under-design.

5. Future Work

This research is in the preliminary stages and leaves plenty of opportunity to test this methodology out further. Future research can apply and assess this method by applying it to other LIDs such as permeable pavement, vegetated filter strips and grassed swales. In addition, it would be useful to try different design cases in different geographic locations to observe how it performs in more severe weather that is different from Toronto. A full life cycle analysis can be performed since the STEP tool has the capability to estimate for cost and operations and maintenance.

6. Contributions

The research presented in this thesis proposes a new point of view for sizing LIDs in the province of Ontario. As opposed to using a sizing target of 25 mm rainfall depth representing the 90th percentile storm, this new methodology focuses on choosing an appropriate sizing criterion from a desired runoff reduction rate.

Instead of using a traditional design storm method or continuous simulations for LID design, an analytical probabilistic approach is used. This method comprises of a few steps of simple calculations but can achieve comparable capture efficiencies just as continuous simulation modelling would. This methodology demonstrates how crucial it is to set a sizing target that considers catchment area and soil conditions. Through this study, it is shown that higher capture efficiencies are more difficult to achieve when catchment areas increase. It also demonstrates how much of a bearing soil conditions have on capture efficiencies. For example, no matter how high a sizing target is, loam soils will not achieve as good as a runoff reduction rate as coarse sand in a catchment of the same size. By aiming for a capture efficiency, specific site characteristics are taken into account which makes LIDs much more feasible and efficient.

References

Adams, B. J., & Papa, F. (2000). *Urban stormwater management planning with analytical probabilistic models*. New York: Wiley.

Antoszek, J., & Denich, C. (2018). *Addressing Stormwater in Ontario using Green Infrastructure : the New Ministry of the Environment and Climate Change Low Impact Development Stormwater Management Manual TRIECA*. Toronto: Ministry of Environment and Climate Change.

Aquafor Beech, & EarthFX. (2016). *Runoff Volume Control Targets for Ontario Final Report*. Toronto.

ASCE, EWRI (Environmental and Water Resources Institute), & WEF (Water Environment Federation). (2012). *Design of Urban Stormwater Controls*. New York: McGraw-Hill.

Brown, R. A., & Hunt, W. F. (2011). Evaluating Media Depth, Surface Storage Volume, and Presence of an Internal Water Storage Zone on Four Sets of Bioretention Cells in North Carolina. *World Environmental and Water Resources Congress 2011*, 405–414. https://doi.org/10.1061/41173(414)44

Buckley, M., Soulhas, T., & Hollingshead, A. (2012). *Economic Benefits of Green Infrastructure, Cheapeake Bay Region*. Retrieved from http://www.americanrivers.org/assets/pdfs/reports-and-publications/20498-chesapeake-final-2011-1213.pdf

Chahar, B. R., Graillot, D., & Gaur, S. (2012). Storm-Water Management through Infiltration Trenches. *Journal of Irrigation and Drainage Engineering*, *138*(3), 274–281. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000408

CVC & TRCA. (2010). *Low Impact Development Stormwater Management Planning and Design Guide*. *Vol. 1*.

Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution*, *186*(1–4), 351–363. https://doi.org/10.1007/s11270-007-9484-z

Dietz, M. E., & Clausen, J. C. (2006). Saturation to Improve Pollutant Retention in a Rain Garden. *Environmental Science & Technology*, *40*(4), 1335–1340. https://doi.org/10.1021/es051644f

Fach, S., & Dierkes, C. (2011). On-site infiltration of road runoff using pervious pavements with subjacent infiltration trenches as source control strategy. *Water Science and Technology*, *64*(7), 1388–1397. https://doi.org/10.2166/wst.2011.227

Guo, Y., & Adams, B. J. (1998a). Hydrologic analysis of urban catchments with event-based probabilistic models: 1. Runoff volume. *Water Resources Research*, *34*(12), 3421–3431. https://doi.org/10.1029/98WR02449

Guo, Y., & Adams, B. J. (1998b). Hydrologic analysis of urban catchments with event-based probabilistic models: 2. Peak discharge rate. *Water Resources Research*, *34*(12), 3433–3443. https://doi.org/10.1029/98WR02448

Guo, Y., & Baetz, B. W. (2007). Sizing of Rainwater Storage Units for Green Building Applications. *Journal of Hydrologic Engineering*, *12*(2), 197–205. https://doi.org/10.1061/(ASCE)1084-0699(2007)12:2(197)

Guo, Y., & Gao, T. (2015). Analytical Equations for Estimating the Total Runoff Reduction Efficiency of Infiltration Trenches. *Journal of Sustainable Water in the Built Environment*, *2*(3), 1–9. https://doi.org/10.1061/JSWBAY.0000809.

Innovyze Research Center. (2016). xpdrainage Help Documentation. Retrieved from https://help.innovyze.com/display/XDH2016v1

Klimas, R. (2009). *Design Criteria for Sewers and Watermains First Edition*.

Maryland Department of Environment. (2000). Maryland Stormwater Design Manual, Vols I and II.

Ministry of Transportation (MTO). (2005). ONTARIO PROVINCIAL STANDARDS

FOR ROADS & PUBLIC WORKS OPSD-3090.101 Foundation frost depths for Southern Ontario.

Muthanna, T., Thorolfsson, S., & Viklander, M. (2013, November 15). *Winter hydrology in a cold climate rain garden*. https://doi.org/10.13031/2013.20792

Odefey, J., Detwiler, S., Rousseau, K., Trice, A., Blackwell, R., O'Hara, K., … Raviprakash, P. (2012). *Banking on Green HighRes*. Retrieved from https://www.asla.org/uploadedFiles/CMS/Government_Affairs/Federal_Government_Affairs/Banking on Green HighRes.pdf

Pennsylvania Department of Environmental Protection. (2006). *Pennsylvania Stormwater Management Best Practices Manual*. Harrisburg, PA: Bureau of Watershed Management.

Siriwardene, N. R., Deletic, A., & Fletcher, T. D. (2007). Clogging of stormwater gravel infiltration systems and filters: Insights from a laboratory study. *Water Research*, *41*(7), 1433–1440. https://doi.org/10.1016/j.watres.2006.12.040

Toronto and Region Conservation Authority. (2019). Sustainable Technologies Evaluation Program (STEP).

Uda, M., Van Seters, T., Graham, C., & Rocha, L. (2013). *Assessment of Life Cycle Costs for Low Impact Development Stormwater Management Practices (Report)*. Toronto.

Warnaars, E., Veldt Larsend, A., Jacobsen, P., & Steen Mikkelsen, P. (1999). Hydrologic behaviour of stormwater infiltration trenches in a central urban area during 2 3/4 years of operation. *Water Science & TechnologyTechnology*, *39*(2), 217–224.

Zhang, S., & Guo, Y. (2012). Explicit Equation for Estimating Storm-Water Capture Efficiency of Rain Gardens. *Journal of Hydrologic Engineering*, *18*(12), 1739–1748. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000734

Zhang, S., & Guo, Y. (2014). Stormwater Capture Efficiency of Bioretention Systems. *Water Resources Management*, *28*(1), 149–168. https://doi.org/10.1007/s11269-013-

0477-y

Zhang, S., & Guo, Y. (2015). Analytical Equation for Estimating the Stormwater Capture Efficiency of Permeable Pavement Systems. *Journal of Irrigation and Drainage Engineering*, *141*(4), 06014004. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000810