RUNOFF REDUCTION BENEFITS OF RETROFITTED ENHANCED OR EXTENDED-DEPRESSED TREE PITS OF THE BEASLEY AND LANDSDALE NEIGHBOURHOODS IN HAMILTON, ONTARIO

Exploring the Role of SWM Engineers in the SDGs

By

ROBERT JAMES MERRITT RAWLINS, B.Sc. (Hons)

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Abstract

This research explores the potential of retrofitting enhanced or extended-depressed tree pits (ETPs/EDTPs) around existing street trees to bolster pre-development hydrological processes in two Hamiltonian neighbourhoods to help satisfy their social, economic, and environmental needs and work toward the Sustainable Development Goals (SDGs). Using QGIS and openly available data to create catchment areas, establish the feasibility of a 20:1 catchment to pit area ratio, and investigate the performance of five available structured soil cells, the innovative Analytical Probabilistic Model (APM) for Bioretention systems was adapted to conduct a parametric sensitivity analysis and subsequently compute the Road Runoff Reduction Efficiency (RRRE) of the designs under different climatic scenarios. The catchment to pit area ratio, design storage depth, and final infiltration rate were found to have a significant impact on the RRRE while the average evapotranspiration rate did not. Based on a 75% efficiency cut-off, and assuming a 20:1 catchment to pit area ratio, the shallowest two depths were deemed ineffective in all final infiltration rate scenarios while the largest depth provided efficiencies greater than 75% runoff reduction even when faced with the lowest rate of 6 mm hr^{-1}. Comparing the RRRE during current climatic conditions to a simulated 2050s winter suggests that the RRRE of the deepest implementation is impacted only half as much as the shallowest; larger systems are more resilient. This research has reinforced the versatility and efficiency of the Analytical Probabilistic Model for modeling system performance of LIDs and ETPs, supports the prominent findings of the efficacy of enhanced tree pits to significantly contribute to urban stormwater management and re-establish more natural and sustainable hydrologic processes, and promotes them as a key to reaching the SDGs in Hamilton, Ontario.

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Abbreviations and Symbols

APM: Analytical Probabilistic Model for the Hydrologic performance of Low Impact Developments

ASCE: American Society of Civil Engineers

EDTP(s): Extended-Depressed Tree Pit(s)

ETP(s): Enhanced Tree Pit(s)

GI: Green Infrastructure

LID: Low Impact Development

NBLID(s): Nature-Based Low Impact Development(s)

Roadmap*:* The ASCE’s *5-year Roadmap to Sustainable Development*

SCM(s): Stormwater Control Measure(s)

SDG(s): Sustainable Development Goal(s)

SWM: Stormwater Management

SWS: Stormwater System

UN: United Nations

Declaration of Academic Achievement

I, Robert Rawlins, am the author of the contents found below. Edits have also been made by Dr. Yiping Guo and Dr. Altaf Arain. I declare that all information, statistics, and tools included in this thesis that were created by others are referenced and cited as deemed appropriate by the Office of Academic Integrity.

1. Introduction

In light of climate change, urbanization, and other trends requiring serious consideration, the UN has declared on numerous occasions that every sector of society must take immediate action if severe impacts are to be mitigated (Guterres 2018). The most substantial of these declarations are the Sustainable Development Goals (SDGs); seventeen comprehensive goals focused on establishing a more sustainable world by 2030 (Annan 2017). Responding to their unique role in establishing sustainable cities and infrastructure (SDG 9 and 11), ensuring resilient water infrastructure (SDG 6) in order to protect life on land (SDG 15) and receiving waters (SDG 14), and ultimately mitigate climate change (SDG 13), the American Society of Civil Engineers' (ASCE) *Five year roadmap to sustainable development* outlines the steps the profession must take to make it possible (Annan 2017).

The *Roadmap* is meant to inspire civil engineers to do the right project, do the project right, transform the profession, and communicate and advocate for sustainable development (ASCE 2018). One of the key concepts within the *Roadmap* is *Resilience;* the world's acknowledgement that traditionally static and isolated "Fail-safe" infrastructure engineering is unfit to sustainably cope with the uncertain and dynamic issues now facing the world (Dong, Guo, and Zeng 2017). Rather than measuring a system's sustainability as its ability to avoid failure under a static set of limited conditions, a resilient-sustainable system is one which promotes environmental, societal, and economic health under both "design" and "unknown" conditions (Dong, Guo, and Zeng 2017). The modern sustainable-resilient perspective in water resources engineering abandons traditional standards and assumes the environment *will* change and system failures are *inevitable*

(Dong, Guo, and Zeng 2017). Therefore, Sustainable-Resilient Stormwater Management aims to effectively manage failures and floods when they inevitably occur, while acknowledging the impacts the Stormwater System (SWS) has on the societal, environmental, and economic systems it is inextricably linked to (Razavi et al. 2016; Willuweit and O'Sullivan 2013; Zhou 2014).

While theoretically a straightforward answer to the dynamic nature of reality, the implementation of "resilience" in the real-world of water resources engineering has encountered difficulty (Birgani, Yazdandoost, and Moghadam 2013). As detailed by the ASCE, since Stormwater Management (SWM) resilience is an integrated and integrative concept dependent on numerous social, environmental, and economic factors, it requires equal consideration of all these aspects and the collaboration of the representative stakeholders to be truly resilient (ASCE 2018). Secondly, the resilience of a system increases as its scope of integration and collaboration does (Hussam and Akshat 2017). The better the interconnections of a system are understood, the better the impacts, and side effects can be modelled, planned for, avoided, and taken advantage of. Also highlighted in the *Roadmap* is the inherent elasticity and dynamisms of nature-based solutions (NBSs) which are incredible avenues to effectively add resilience to a SWS (WWAP and UN-Water 2018). Finally, despite "unrelenting expert advocacy for more than two decades," pointing to the benefits and resilience of Green Infrastructure (GI), Low Impact Development (LID), and Nature-Based Solutions (NBSs), uptake of these systems has been slow. As in many fields, there is a need for a strengthening of the link between academia and the public, theory and practice, expert and layperson (Dhakal and Chevalier 2017).

This research is therefore first and foremost an ASCE-directed response to the UN's call for action from every sector of society to do its part in implementing the holistic, integrated, resilient and cross sectoral solutions necessary to achieve the SDGs and realize a sustainable world by 2030. Driven by the *Roadmap's* insistence on nature-based solutions within the context of needs-based projects, and the need for the translation of concepts into decentralized and unique realities, this investigation focused on following the ASCE's *Roadmap* to guide a needs-based investigation two low-income neighbourhoods in Hamilton Ontario with the goal of estimating the potential stormwater capture efficiency found in retrofitting already-available street trees with enhanced tree pits, acknowledging the cross-sectoral costs and benefits and involving the community in the research process. This research followed the ASCE's Sustainability Framework's advice to "choose the right project and do the project right," by selecting a topic that was relevant to Hamilton in light of climate change, urbanization, and the city's focus on urban forestry, selecting a neighbourhood that was both relevant to the researcher's life and in exceptional need of investment and research, seeking out cross-sectoral collaboration and community member engagement, and by acknowledging and discussing the integrated impacts of enhanced tree pits beyond their stormwater resilience (ASCE 2018).

One of the most important aspects of this research was the "already-available" Analytical Probabilistic Model (APM) for evaluating the hydrologic performance of Bioretention Systems established by Shouhang Zhang (2014). Compared to several deterministic hydrologic models, the APM ultimately selected to evaluate the stormwater capture efficiency of retrofitted Enhanced tree pits (ETPs) within the Hamilton neighbourhoods of Beasley and Landsdale.

2. Methods

2.1 The ASCE's 5-year Roadmap to Sustainable Development

This research was directed by the four guidelines proposed by the ASCE's *Five-Year Roadmap to Sustainable Development*:

1. "Doing the *Right* Project". The *Roadmap's* first key stresses the necessary shift from thinking about the product to the needs being addressed. This need-focused approach will inspire new ways of tackling issues that rely less on building "new 'hard' infrastructure by reducing or eliminating the need," taking advantage of "Nature-Based systems that can accomplish the same outcome." (ASCE 2018). ASCE points to traditional SWM as an example of forgetting to ask, "what am I trying to accomplish and why?" and suggests new projects should be decided based on economic, social, and environmental sustainability as key requirements, while ensuring a focus on the use and application of available resources.
2. "Doing the Project *Right"*. The second priority stresses the irrelevance of current prescriptive standards focused on "conditions of stationarity", and a requirement for new process- and performance-based protocols. The concept of resiliency is highlighted as key to producing truly sustainable infrastructure. Projects should significantly improve environmental, economic, and social performance while integrating resiliency by acknowledging changing operating conditions.
3. "Transform the Profession". The profession needs to acknowledge that, "designing infrastructure based on [historical] standards and methods without knowing whether those standards really apply is inherently risky and leads to the commoditization of civil engineering." (ASCE 2018). Civil engineers need to enlist new approaches to

problems and new processes for design. Ultimately, civil engineers need to become an integration of, “master builders, environmental stewards, innovators, risk managers, and public policy leaders,” and build the relationships necessary to be trusted advisors.(ASCE 2018).

4. “Making the case”. Finally, citizens within and outside the engineering profession must understand the importance of and come to “demand environmentally, economically, and socially sustainable infrastructure that meets the needs of human welfare equitably and enables healthy communities.” (ASCE 2018) Understanding the importance of the shift towards sustainable infrastructure development, engineers have a responsibility to use their voices of influence and connections with all aspects of society to bring sustainable development into the centre of the public forum (ASCE 2018).

2.2 A Roadmap-inspired Research Methodology

While the *Roadmap* is directed at practicing engineers, this research explored the applicability of its guidelines in the context of engineering research. With a broad initial scope of building resilience in Hamilton’s Stormwater Management system, the ASCE’s recommendation to ask, “what am I trying to accomplish, and why?” was a great way to establish a more detailed, yet still overarching motivation for the project.

2.2.1 Establishing the Needs

To answer this question and ensure the *right* research project was conducted, a thorough investigation of the “needs being addressed” in the context of Hamilton was conducted. This investigation consisted of three sections:

1. The first, and more substantial component was a literature review focused on establishing an understanding of Climate Change and Urbanization, the UN's SDGs - as well as a more detailed review of their impacts on stormwater management engineering, the concept of resilience and the emergence of nature-based solutions as opportunities to bolster resilience.
2. The second, and more Hamilton-specific component of the investigation was several meetings and interviews with various organizations and relevant municipal departments which provided invaluable insight into the needs and circumstances of the city.
3. While standard practice would be to focus on the product before the location, the ASCE's suggestion to determine the needs *first* and then develop a solution was the motivation behind the third component. A multi-dimensional GIS-based investigation of different Hamilton neighbourhoods was conducted to establish an understanding of specific neighbourhoods and the needs that require attention within each. The second and third recommendations of the *roadmap* acted as encouragement to think outside the normative box of SWM engineering and adopt a more holistic perspective. Therefore, stormwater figures were not the only metrics considered; Quality of social spaces, air quality, vulnerable populations, and community resilience are just a few of the multi-dimensional characteristics explored to develop a comprehensive understanding of the needs of the project areas.

This initial investigation produced three clearly defined needs within the downtown Hamilton neighbourhoods of Beasley and Landsdale: a revitalization of the areas, a reduction of rainfall runoff and Hamilton Harbour pollution in the context of Climate Change and Urbanization, and the establishment of a healthy urban forest.

2.2.2 Making use of available resources

Inspired by the *Roadmap's* insistence to make use of already-available resources, every effort was made to explore and centre this research on the natural infrastructure, computational tools and engineering technology, data sources, and human resources already available.

2.2.2.1 Making use of available natural infrastructure

Centred on these needs and following the ASCE's suggestion to use what was already available, the benefits of retrofitting street trees with enhanced tree pits in the highly urbanized Hamilton neighbourhoods of Landsdale and Beasley were explored. With this decided, the literature was revisited to glean information on urban forests, street trees, and the many social, environmental, and economic benefits they promote, focusing on the processes of interception, infiltration, and evapotranspiration that make trees hydrologically invaluable.

2.2.2.2 Making use of available computational tools and engineering technology

Further encouraged to utilize what is already available while not being afraid to abandon traditional static engineering practices, a variety of current techniques used to accurately model the impacts of low impact developments (LIDs) in urban watersheds stormwater benefits of enhanced tree pits were investigated. After reviewing several options, the Analytical Probabilistic Model (APM) for LID implementations established by (S. Zhang 2014) was adopted to quantify the performance of extended tree pit-retrofitted street trees in the Landsdale and Beasley neighbourhoods.

Initially, a sensitivity analysis was conducted on several key implementation characteristics such as storage depth, catchment to implementation area ratio, infiltration rates, and evapotranspiration rates, to narrow in on the most impactful aspects of an ETP retrofit.

With an understanding of key components, a range of realistic implementations based on the characteristics of the Beasley and Landsdale neighbourhoods were tested. Results were examined to determine the most effective, realistic implementation scheme of retrofitted ETPs within the neighbourhoods.

Furthermore, with ETPs being an established technology, proprietary structured soil cell systems were investigated and utilized within the study in order to produce results with a foundation in a real-world implementation scenario.

2.2.2.3 Making use of and collaborating with available human resources

The second and third keys to sustainable development, as understood by the ASCE, highly recommend fostering and capitalizing on as many collaborative relationships as possible. Inspired by this mandate, city departments, academics, and NGOs focused on environmental- and development-focused issues and initiatives within Hamilton were engaged in order to glean as much information as efficiently as possible.

2.2.3 Promoting Sustainable Development

Finally, the ASCE’s fourth guideline is a reminder to civil engineers and the academics of their unique role in establishing sustainable development. To fulfill this responsibility, this research project was completed with the goal of effectively disseminating SWM knowledge throughout the Hamilton community and promote broader conversations and investment into SWM issues and decisions relevant to sustainable SWM. With community-centred research a key theme of this study, municipal offices, NGOs, and highschool students of Pathways to Education who reside in the study area were engaged throughout the project to disseminate knowledge regarding our collective role in establishing SWM as part of the journey towards sustainable development. This collaboration did not only aid in data collection, but also offered an opportunity to engage the community in discussion around society's often forgotten absolute dependence on effective SWSs, provide the students with a practical example of integrated research, educate them about the potential of LIDs, and discuss the many cross-sectoral benefits of extended tree pit implementation. Once again acknowledging the aim of inspiring the Hamilton community to move toward sustainable development, these procedures offered a chance for the community to be a part of making their neighbourhood more sustainable. As part of this endeavour, this research was presented at the International Conference of Water Management Modelling (ICWMM), a WaterCRESS (Community Research Education & Sustainability Seminars) event, McMaster's Annual Three Minute Thesis (3MT) Competition, and during an open-to-the-public thesis presentation. Ultimately the report will be submitted to the City of Hamilton as a proposal, which at the very least is meant to promote dialogue surrounding sustainable development and encourage city employees to take steps to bringing it about.

3. Establishing the Needs

3.1 Understanding the Global 'Needs'

In following the ASCE's *Roadmap*, understanding the issues being addressed is fundamental to the success of a sustainable engineering project. Therefore, the aim of the first section of the literature review was to define the major issues of climate change and urbanization facing the infrastructure within every city around the world, including Hamilton's urban SWM system.

3.1.1 Climate Change

'Climate Change' refers to measurable variations in long-term temperature, precipitation, and global weather patterns (Madsen et al. 2017). However, what research has been highlighting since the mid 20th century is *anthropogenic* climate change; a period of global warming driven by green house gas (GHG) production inextricably linked to industrialized human activity (IPCC 2013; IPCC 2018).

The impacts of anthropogenic GHG emissions and the subsequent change of climate are profound (Sagoe-Addy and Appeaning Addo 2013; IPCC 2013; Semadeni-Davies et al. 2008; Gilbert 2009; Guterres 2018). From melting glaciers and rising seas to more intense storms and longer droughts, ocean acidification and forest fires, nothing and no one will go unaffected by the minimum 1.5-2 degree rise in global temperatures expected by the end of the 21st century (IPCC 2013; IPCC 2018). For the sake of perspective, there are now more people fleeing from their homes due to climatic factors than those fleeing from human and political conflict (Warner 2011).

Unfortunately, while awareness of the issue is growing, the Inter-Governmental Panel on Climate Change (IPCC) very recently released a report deemed by the UN Secretary-General Antonio Guterres as, "an ear-splitting wake-up call to the world" that, although "we have the tools to make our actions effective" what is still missing "is the leadership – from politicians, from business and scientists, and from the public everywhere…and the ambition to do what is needed." (IPCC 2018; Guterres 2018).

3.1.1.1 Climate Change and Stormwater Management (SWM)

The most serious impacts of climate change on SWM aside from coastal flooding - predicted to inundate cities around the world - are the increase in frequency and intensity of rainfall events (Razavi et al. 2016; IPCC 2013). As oceanic and atmospheric temperatures rise, the atmosphere's ability to "hold" water vapour increases (at a rate of 7%/°C), making larger releases of water possible (ECIU 2017; Sharma, Wasko, and Lettenmaier 2018). Significant research now firmly links the frequency and severity of real storms, including several 2018 storms, to Anthropogenic Climate Change (Mal et al. 2018). The straightforward outcome of an increase in storm intensity is increased flooding, which at the small urban scale, appears to be the case (Jenkins et al. 2017; Pitt and Voorhees 2010; Mo et al. 2017). With that said, it is important to note current research highlighting observed increased precipitation event frequency, volume, and intensity doesn't always result in an increase in flood event frequency, volume, and intensity (Sharma, Wasko, and Lettenmaier 2018). While research conducted by (Sharma, Wasko, and Lettenmaier 2018) does reinforce findings of a strong positive link between rainfall and flood events in small urban catchments, it is important to understand and acknowledge the plethora of variables including land-usage, antecedent moisture, snow cover and volume changes, and the size and shape of a catchment that can impact flood characteristics as much as, if not more than, the precipitation event characteristics (Sharma, Wasko, and Lettenmaier 2018).

The true threat posed by climate change to human systems - including SWM infrastructure - is the uncertainty it introduces. In the context of urban SWM, climate change is not only undermining the efficacy of current SWSs but is also shaking the once seemingly firm foundations of SWM design. SWSs are most often engineered utilizing design storms (Willems 2013). An x-year design storm is a theoretical storm of specific duration and intensity expected to be exceeded once every x-years. Design storms are founded on statistical analysis of historical rainfall data under the assumption that the frequency at which a storm with a certain intensity and duration occurred in the past will be the frequency at which it occurs in the future. Design storms are currently the standard “tests” for SWS design. In a stationary world, if a SWS can effectively manage a 100-year design storm now, given proper maintenance, it will in the future as well.

Naturally, climate change uproots the underlying assumption of stationarity that design storms are constructed on. In fact, research shows that the climate has already changed (IPCC 2018). In the case of Hamilton, Ontario, the city receives 9 mm less precipitation in the winter months and 29 mm more in the summer months compared to 40 years ago (Pierre, Amoroso, and Kelly 2018). In the city of Hamilton, along with many other cities around the world, millions of dollars worth of infrastructure have been and continue to be constructed, maintained, and retrofitted using out-dated design storms established with rainfall data from the mid-20th century; this is quite unfortunate when Hamilton is expected to receive more consecutive days of rain, more heavy precipitation days (above 20 mm), more rainy days, and more dry summer days in the 2020s, 2050s, and 2080s compared to current conditions (Razavi et al. 2016). Utilizing downscaled, continuous models of predicted future rainfall patterns is one method the research community has devised to address these issues theoretically; There are two main issues with doing so. Firstly, the high-uncertainty in these models creates the risk of either under- or over-engineering a SWS and therefore they are rarely used in SWS engineering practice. More significantly, the climate is expected to continue changing; creating a system that is suitable for 2080 may or may not be suitable for 2100. Any “updated” SWS will be as inherently flawed as the assumption of stationarity it is founded on.

Climate change has such large implications on the design of SWSs as it questions both the significance of the data used (i.e. the relevance of historical rainfall data in designing current and future structures) and the model itself (i.e. the validity of assuming climate is sufficiently constant to define probabilities to certain storms). To date, very few SWSs are built fully acknowledging the reality of climate change (Zölch et al. 2017; Depietri and McPhearson 2017).

While SWM doesn’t appear to contribute to climate change directly, traditional SWM uses a significant amount of concrete which is energy- and GHG-intensive. SWM is also a fundamental component of urban areas which are traditionally sources of environmental degradation and Green house Gasses (GHGs). SWM is therefore linked to climate change through the energy used in creating the physical components of the system and treating collected stormwater as well as the loss of carbon sequestering potential as a result of intentional runoff diversion from vegetation, among others. In light of this, SWM that takes advantage of nature-based solutions can reduce SWM’s climate change contribution by simultaneously reducing the sector’s energy requirements and bolstering the carbon-sequestering potential of an urban area.

Figure 1: Urbanization and its implications exemplified in a geologically-based 'before and after' rendering of Manhattan Island

3.1.2 Urbanization

Urbanization significantly impacts all aspects of society (Mo et al. 2017; Locatelli et al. 2017; Henderson, Storeygard, and Deichmann 2017). This is due in part because of the overwhelming portion of the population involved in the phenomenon; as of 2018, there were approximately 3.5 billion more people living in urban settlements than there were in 1950 (UN 2018). Highlighted by the strong positive correlation between urbanization and GDP, densely-populated cities have been and will continue to be “main centres of learning, culture and innovation” (Palanivel 2017). However, while cities can be the ideal environment for a new innovative idea or social movement to root, they also represent prime breeding grounds for issues of disease, poverty, and debilitating economic disparity (Palanivel 2017; Harari 2016). To understand the high economic cost of urbanization, research suggests the infrastructure required to meet the demands of rapid urban expansion will cost the world $57 trillion by 2030 (Palanivel 2017).

3.1.2.1 Urbanization and Stormwater Management

As of 2017, there were 700 million urban dwellers without access to proper sanitation, and a rough estimate is that 3 billion people will require new ‘homes’ by 2030 (Palanivel 2017). As mentioned, urbanization has created an incredible demand for effective infrastructure to support these billions of additional urban lives. Some of the most fundamental questions that arise in the discussion of infrastructural demands of urban areas surround the hydrologic regime of urban areas; how can a city sustainably secure clean drinking water for millions of additional members? Where will the inevitable increase in wastewater go and how will it be treated? How will natural groundwater reservoirs be recharged?

Perhaps urbanization’s most significant impact on the hydrologic regime has been the introduction of vast “hardscapes”; the conversion of pervious natural areas with impervious surfaces such as roads, sidewalks, parking lots, buildings, and other structures viewed as necessary to support the many lives within a city. For perspective of the impact of urbanization in this regard, during its great period of expansion - the 20th century - the USA used 4.4 gigatons, or 4.4 billion metric tons, of cement to create concrete for buildings, roads, and bridges (Smil 2014). While this number depicts the impacts of hardscape introduction, the rapid increase in urbanization can be understood in that China used 6.4 gigatons of cement in the span of only three years from 2011 to 2013: enough cement to pave the entire Big Island of Hawaii with a concrete parking lot (Smil 2014).

Interestingly, with the goal of traditional SWM being the efficient exportation of rainfall and runoff from the city-centre, this “sealing” of urban areas with impervious surfaces was traditionally understood as beneficial (Madsen et al. 2017; T. D. Fletcher et al. 2015). Of course, decades of research now accurately highlight the detrimental hydrologic reality of urbanization, including increased runoff volumes and larger peak discharge rates, and decreases in infiltration, ground water recharge, and evapotranspiration rates (Yazdanfar and Sharma 2015). These significant water-cycle alterations lead to a host of long-term issues including stream erosion, habitat destruction, increased water treatment costs, and receiving water contamination (Locatelli et al. 2017; Ashley et al. 2007; Madsen et al. 2017; McDonald et al. 2014; N. Zhang et al. 2010; Pumo et al. 2017; Dong, Guo, and Zeng 2017; Garcia et al. 2016). Acknowledging the importance of hydrologic processes in virtually every living system on earth, it is important to understand the seriousness of these issues and the threats they pose. An example of the lack of proper respect for these issues within Canada is that despite federal and provincial policies, Canadian municipalities released well over 1 trillion litres of raw sewage into natural receiving waters from 2013 to 2017 with no obligation to publicise the events. Furthermore, instead of collecting real data, municipalities are only required to estimate annual overflow volumes using computer simulations which have been shown to underestimate (Zupanic 2018). Estimates are often not even completed; in 2016, Environment Canada received overflow estimations from only 159 of 269 municipal water systems obligated to report (Zupanic 2018). In the context of Ontario, a 2018 Environmental Protection Report produced by the Environmental Commissioner of Ontario highlighted that between 2017-2018, in Southern Ontario alone, untreated sewage was discharged into receiving waters 1,327 times (Saxe 2018). When asked to comment on the situation, the Environmental Commissioner, Dianne Saxe, proclaimed that it was, “unbelievable that in 2018, the government allows this much filth into our lakes and rivers,” into places “Ontarians spend time with their families, where they swim and fish," adding that, "These shorelines and waters are home to Ontario's rich biodiversity, and to us." (Zupanic 2018).

3.1.3 Urbanization and Climate Change Feedback Loop

Finally, it is also necessary to acknowledge research that has highlighted the positive feedback loop that exists between urbanization and climate change (N. Zhang et al. 2010; Henderson, Storeygard, and Deichmann 2017). Most often, the pervious area being replaced with impervious materials is carbon-sequestering green space (Wang et al. 2014). Therefore, when occurring on the scale that it is, urbanization contributes to climate change by re-introducing carbon back into the atmosphere if the removed vegetation is burned and by reducing the land's capacity to sequester carbon in the future. Furthermore, in response to climate change-induced variability in growing seasons, an increasing number of rural-dwellers are fleeing their lives of self-subsistence in search of the seemingly dependable sources of necessities that cities represent (Bounoua et al. 2015; Henderson, Storeygard, and Deichmann 2017). Naturally, "making room" for these influxes of people requires further degradation of the environment and increased impervious surfaces, leading to further climate change and in turn, urbanization.

3.2 Understanding the Local Needs

Having reviewed the two substantial issues of Climate Change and Urbanisation that require immediate and global attention, and in response to the call-to-arms to engineers found in the SDGs and ASCE's roadmap to focus on *collaborative* and *resilient* utilization of *already-available*, *nature-based solutions*, an investigation into adding resilience to the urban stormwater system in Hamilton, Ontario was conducted, keeping aware of the inevitable impacts an integrated project such as this would have on other city sectors. In further accordance with the *Roadmap,* rather than focusing on "fitting" a great solution within this specific environment, this research focuses first on establishing an understanding of the needs of a specific environment and only then creating a solution which is realistic and available in that specific context.

With this research conducted at McMaster University, the selection of Hamilton, Ontario as the area of interest was natural. The city of Hamilton is uniquely positioned on the westernmost tip of Lake Ontario. The city is boarded on the North by Hamilton Harbour and flanked to the south by the UNESCO World Bioreserve-designated Niagara Escarpment. Over the past centuries, these admirable features helped Hamilton establish itself as one of Canada's great industrial centres, coming to be known as Canada's 'Steel Town'. While incredibly productive economically, decades of discharging factory sludge, along with sanitary waste, into Lake Ontario bore substantial social and environmental repercussions that are still major challenges today; Hamilton Harbour is one of 30 internationally (North American) recognized Environmental Areas of Concern (EAC) and is in desperate need of pollution reduction measures (Bay Area Restoration Council 2017); with aging infrastructure and the fastest growing population in Canada, people living in the downtown core face less than ideal circumstances, especially considering the goal of Hamilton to be, "the best municipality to raise a child and age successfully" in (A. Fletcher 2017); Finally, while being acknowledged as a step to dealing with the above issues effectively, the rejuvenation of Hamilton's urban forest needs to be completed in a sustainable, cost-effective, and equitable manner.

3.2.1 A Cleaner Hamilton Harbour

Hamilton’s rejuvenated investment into sustainability is continuously encouraged by several active municipal and non-governmental organizations (NGOs) including the Bay Area Restoration Council (BARC), Environment Hamilton (EH), the Royal Botanical Gardens (RBG), and the Hamilton Naturalist Club (HNC) which are involved in creating a more sustainable Hamilton. While each of these organizations has a different area of expertise, analysis of their overlapping jurisdiction and campaigns speaks to the sector’s general areas of concern for the city of Hamilton; the health of Hamilton Harbour is by far the greatest focus of these NGOs and other city departments (Kariem 2018; City of Hamilton 2016; Health Protection Division 2017; Ghbn 2010). Along with manufacturing plant effluent, Hamilton’s age means the downtown core is serviced by an outdated and outgrown combined sewer system (CSS) tasked with supporting an ever-increasing economy, urban area, and population (Arcand et al. 2018). Rather than modern sewer systems that transport collected stormwater runoff and wastewater in separate sewer systems, created for both construction convenience and to prevent sewage buildups, stormwater runoff and wastewater resulting from all human uses in Hamilton is collected in a single combined sewer. While originally presenting no issue, the combination of treatment regulations and the ever-increasing demands put on the treatment plant by the growing population create situations - most often during intense rainfall events - when the rate of treatment is overcome by the inflow rate. At this point, in lieu of allowing wastewater to back up and overflow the sinks and toilets of surrounding homes, the city allows the wastewater to bypass treatment and be discharged into the Harbour: this is called a Combined Sewer Overflow (CSO) event. Naturally, CSOs have the potential to deliver large amounts of human effluent and other toxins directly to receiving waters –

Hamilton Harbour in the case of Hamilton. In response to the devastating impacts of CSOs on the Hamilton Harbour ecosystem, from 1989 to 2015, the city of Hamilton constructed 9 CSO storage tanks which provide 314,000m^3 of additional storage to detain the polluted water until flowrates subside enough for the excess water to be reintroduced without overflowing the system (City of Hamilton 2016). While this $163 million investment has proven effective in inhibiting two billion litres of wastewater from entering the harbour every year, this unfortunately account for only half of CSOs contaminating the harbour annually (City of Hamilton 2016). Therefore, with the harbour being an international EAC that is still receiving billions of litres of untreated wastewater every year, and understanding that climate change is, and will continue to produce more frequent and intense storms, the city and its environmental NGOs are looking for ways to reduce these events more cost-effective and feasible than replacing the 600 kilometres of combined sewers currently servicing the city.

The most natural solution to overflowing storm sewers and polluted runoff reaching the Harbour is to reduce the amount of runoff reaching the combined system and introduce alternative methods to filter the runoff that is created. Therefore, one of the main “needs” of the Hamilton downtown core is an implementation that would reduce the amount of runoff reaching the central SWS and filter the runoff that does.

As discussed in detail above, LIDs, GI, and NBS are all designed to take advantage of natural hydrologic processes such as infiltration, groundwater recharge, and evapotranspiration to reduce the amount of runoff entering the sewer system and filter the water that does, thereby reducing the stress put on a city's water infrastructure and potentially reducing the pollution of Hamilton Harbour.

Figure 2: An outline of the studied neighbourhoods located in the core of downtown Hamilton: Beasley (Blue) and Landsdale (Yellow).

3.2.2 A Revitalized Downtown Core

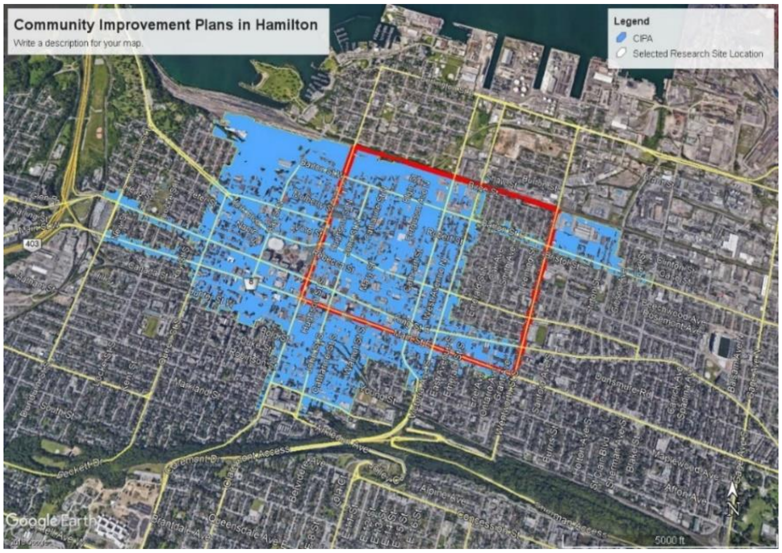

Figure 3: Map of Community Improvement Plan Applications (CIPAs) submitted to the City of Hamilton as of October 2018. As evident, many CIPAs are focused on the Beasley and Landsdale neighbourhoods.

While Hamilton is gaining recognition as Canada's "up and coming" city, there are neighbourhoods in the downtown core that aren't experiencing the benefits of the inflow of investment and attention the way the Locke Street Village is (Buist 2017; Arnold 2016). A review of local newspaper articles, invaluable discussions with members of Hamilton's Climate Change and sustainability departments, and analysis of the city's publicly available neighbourhood reports and data suggest that two neighbourhoods with a particular need for revitalization are the Beasley and Landsdale area (Carter 2017; Buist 2017; CBC News 2018). Utilizing GIS, these neighbourhoods were found to represent a combined area of 2.3 km^2 of Hamilton's downtown core, bordered by the TransCanada Railroad, Wentworth Street North, Main Street East, and James Street North, on the North, East, South, and West respectively, while Wellington Street North acts as the divide between the two neighbourhoods (*Figure 2)*.One of the main datasets that highlighted the needs of these neighbourhoods was that which mapped the Community Improvement Plan Applications (CIPAs) spatially. As seen in *Figure 3,* many of the CIPAs fall within the Beasley and Landsdale neighbourhoods, pointing to the sense of need in the area.

Openly available data from the city of Hamilton's INHALE project on air quality within the city (*Figure 4*) was also reviewed and clearly highlighted residents of the neighbourhoods of Beasley and Landsdale as being subject to the worst air pollution in the city and in need of cleaner air.

Furthermore, neighbourhood reports investigated to glean information on the socioeconomic factors of household income, population demographics, and health were additional signs of the incredible need for revitalization within these neighbourhoods; Single-parent homes are twice as likely in both Beasley and Landsdale when compared to Hamilton as a whole. Beasley is considered an "arrival city" with 14% of its residents being newcomers compared to the Hamilton average of 3% (Mayo, Klassen, and Bahkt

2012). Beasley and Landsdale struggle with poverty rates that are two and three times higher than the city average respectively, with 40% and 60% of residents living off incomes below the poverty line (Mayo, Klassen, and Bahkt 2012). And finally, while a retirement residence somewhat artificially increases Landsdale's life expectancy, Beasley residents have a life expectancy that is 3.3 years shorter than the city average, and residents of both Landsdale and Beasley are almost twice as likely to visit the emergency room than those living in other parts of Hamilton (Mayo, Klassen, and Bahkt 2012).

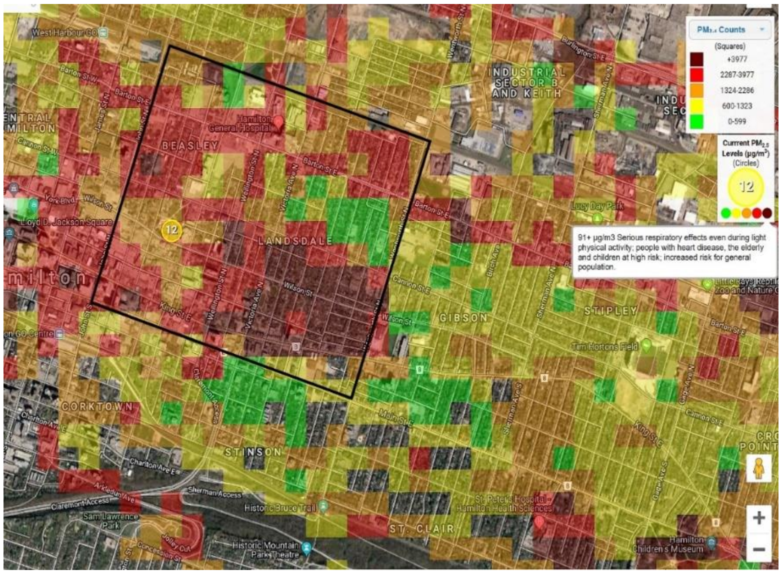

Figure 4: Hamilton's INHALE project provides geographically referenced, real-time air quality data. As in other metrics, the Beasley and Landsdale neighbourhoods were significantly worse-off than surrounding neighbourhoods and in need of cleaner air.

Considering the air quality issues, low socioeconomic status, high crime rates, and plethora of CIPAs filed within the neighbourhoods, it is evident that Beasley and Landsdale would benefit greatly and are in need of an effort to revitalize the areas.

3.2.3 A Healthy Urban Forest for All

Following the lead of New York City, Hamilton has community-focused efforts such as the Trees Please program co-created by Environment Hamilton and the Hamilton Naturalists Club and the Forestry Department's Urban Forest Strategy (UFS). This program is focused on raising the city's urban canopy cover from 18% - last estimated in 2009 and visually represented in *Figure 6 which displays* inventoried trees within the Beasley and Landsdale area - to 30% by the year 2030 (HNC and EH 2017). This goal, shared by many municipalities around the world, stems from growing appreciation of the significant health, environmental, social, and economic ecoservices provided by healthy urban forests (Wild, Henneberry, and Gill 2017; Silvera Seamans 2013).

Figure 5: Hamilton's Tree inventory for the Landsdale and Beasley neighbourhoods. With the goal of reaching 30%, Hamilton's canopy coverage was last recorded to be approximately 18%.

In an ideal scenario, establishing an urban forest refers to preserving, implementing, and maintaining connected green spaces throughout an urban environment, allowing for natural processes to be preserved (Anderson and Piza 2018). While the concept of a large, healthy, and well-connected urban forest is admirable, as in any field, best intentions are often thwarted when faced with real constraints. Perhaps the largest constraint in the context of establishing a large and connected urban forest in major North

American urban areas is the little-to-no room designated for urban forests (W. Liu, Chen, and Peng 2015; Loperfido et al. 2014). Established decades ago with little thought of preserving natural areas, a combination of population growth, a growing desire to live in ultra-urban environments, and increasing property values has led to ever greater distortions of natural hydrologic regimes in ultra-urban areas through further densification of urban areas and the replacement of the few remaining natural areas with additional condominiums and retail spaces (Anderson and Piza 2018). In the case of Beasley and Landsdale, as displayed in *Figure 6,* the vast majority of the neighbourhoods is 'residential' which is more likely to experience further urban intensification and the accompanying reduction in pervious area than it is to be transformed into pervious 'park' land. This leads to the natural response to integrate trees and other vegetation in a more engineered method throughout the urban environment.

While distributed street trees is the natural answer, there are two main needs that require attention if this program is to be successful in Beasley, Landsdale, and Hamilton in general. Firstly, while ripe with benefits, there is also sufficient evidence highlighting the economic burden ill-planned and neglected urban street trees can be for municipalities (Mullaney, Lucke, and Trueman 2015). The seven- to ten-year average lifespan of trees planted in urban environments highlights this reality and suggests that urban forest implementation and maintenance requires more care than planting trees and forgetting about them (Mullaney, Lucke, and Trueman 2015). As laid out by Szota et al. (2019), the

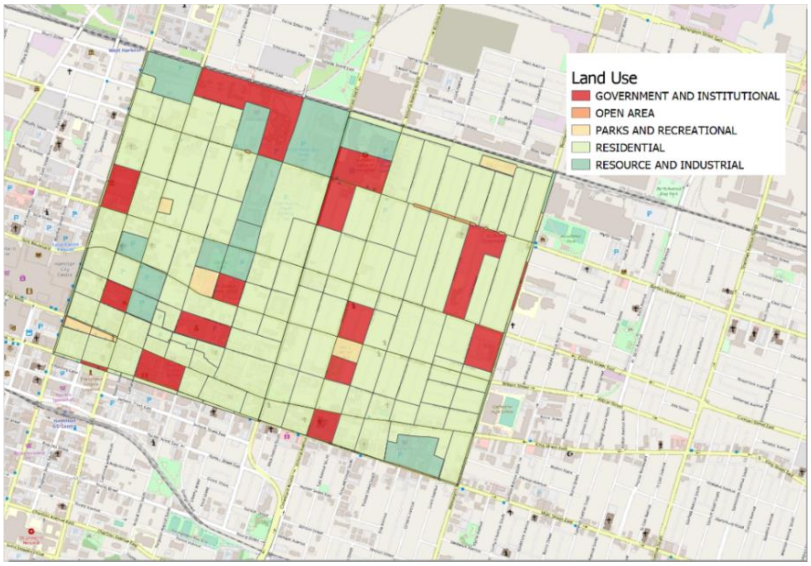

Figure 6: Land Use designations within the Beasley and Landsdale Study area. The neighbourhoods are primarily residential and contain very limited open areas or park spaces for the development of a healthy urban forest, necessitating a focus on street trees.

exposure to higher concentrations of pollutants, higher air temperatures, compacted soil, steep slopes, reduced infiltration and groundwater recharge rates, and most significantly, less water and vastly reduced rooting volumes all disrupt tree growth, lead to the staggeringly short average lifespan mentioned above, and reduce the tree's potential to provide their array of ecoservices (Close, Nguyen, and Kielbaso 1996; EPA 2016). Therefore, to establish a healthy urban forest, a solution is needed that most crucially, supplies trees with enough water and space for their roots to grow.

Furthermore, adopting the socio-economic perspective, the literature suggests that even when implementation is botanically (environmentally) successful, urban forest feature implementation is known to employ a "selective incorporation of ecological goals in the greening of urban" areas, while other canopy-focused programs often exacerbate social inequalities rather than reduce them (While, Jonas, and Gibbs 2004; Perkins, Heynen, and Wilson 2004). Considering the potential benefits of a successful Trees Please program in the context of the possible negative economic, environmental, and social consequences of erroneous urban forest implementation, a strategy is needed that will enable Hamilton's Trees Please program to not simply raise the overall number of trees in the city instantaneously but ensure the long-term health of already established trees in areas that require their ecoservices most.

3.3 Summarizing the Local and Global Needs

Therefore, the local and global needs of the downtown core of Hamilton, Ontario, introduced in the previous sections can be summarized as follows:

1. There needs to be **less urban runoff reaching Hamilton Harbour** both through treatment facilities and by way of runoff.
2. The runoff that does reach Hamilton Harbour needs to be **less polluted**.
3. Landsdale and Beasley residents require **cleaner air** to breath.
4. Landsdale and Beasley are in need of an implementation to **boost socio-economic conditions**.
5. For Hamilton's Trees Please program and Urban Forest Strategy to be effective, already-established street trees require **greater rooting volumes**.
6. Street trees are also in need of a **greater supply of water to their root systems.**
7. To mitigate the risk of urban forests exacerbating socio-economic divides within the city, **investments into the city's urban forest needs to be in neighbourhoods that truly need the help.**
8. The above needs need to be met with a solution sufficiently dynamic to stay relevant and effective in a world impacted by continued Climate Change.

4. Utilizing Available Resources

With a firm understanding of the need of Hamilton to address the global issues of climate change and urbanization while mitigating their negative impacts - including those within SWM engineering – and the local needs to address the pollution of Hamilton Harbour, rejuvenate the Landsdale and Beasley neighbourhoods, and bring sustainability to the city's Urban Forestry Strategy, research was conducted to establish a solid understanding of the resources available; from the most global concepts of sustainability and the sustainable development goals, to proprietary structured soil cells and the analytical probabilistic model for LID implementations.

4.1 Global Concepts and Frameworks

While the scale of climate change and urbanization make them extremely dangerous, their cross-sectoral nature also creates global awareness and discussion around potential solutions. Perhaps the most broad and far-reaching of these available solutions is the concept of *Sustainability*.

4.1.1 Sustainability and Sustainable Development

Introduced by John Evelyn in 1662, sustainability has become the overarching solution to the global issues of Climate Change, Urbanization and several other serious threats facing the world. Evelyn's insistence that, "Sowing and planting of trees has to be regarded as a national duty of every landowner, in order to stop the destructive over-exploitation of natural resources", has been captured in the current definition: "the practice of maintaining processes indefinitely – natural or human made – by replacing resources used with resources of equal or greater value without degrading or endangering natural biotic systems". Sustainability is the balancing of a community's environmental, social, and economic needs acknowledging the finiteness of resources, understanding the impacts humans have on each other and the environment, and agreeing that responsible management of resources requires collaboration.

Applying the above in the context of development, *sustainable development* is outlined by the United Nations as,

“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains with it two key concepts: The concept of ‘needs’, in particular, the essential needs of the world’s poor, to which overriding priority should be given; and the idea of limitation imposed by the state of technology and social organization on the environment’s ability to meet present and future needs” (WCED 1987).

In the same report titled, *Our Common World,* it was stressed sustainable development requires a fundamental shift from isolated industry development to thoughtful, integrated, and collaborative partnerships in which social and environmental impacts of the development process are always considered (WCED 1987).

4.1.2 The UN’s Sustainable Development Goals (SDGs)

Its holistic and integrated nature has positioned sustainable development at the centre of the United Nations’ (UN’s) framework for a better world by 2030 (United Nations 2015). The UN’s Sustainable Development Goals (SDGs) are 17 “integrated and indivisible” goals focused on ensuring the well being and health of all social, financial, and natural economies, built on the understanding that true, long-term, and equal progress in any of the 17 goals relies on the progress of all others (Annan 2017).

4.1.3 Resilience

Foundational to the SDGs, resilience can be understood as sustainability which acknowledges the non-stationarity of reality. While sustainability is justifiably founded on an integrated approach accounting for environmental, societal, and economic factors, it traditionally assumes stationarity. This assumption of “known”, or “design” scenarios encourages traditional engineering practice to erroneously label a system that is able to cope with current stresses as “fail-safe” or “sustainable”. (Dong, Guo, and Zeng 2017). The impact of this unfortunate reality is being revealed in the failures of such “sustainable” and “fail-safe” systems when tasked with responding to “unpredicted” stresses. Applying the principles of sustainability to the reality of a non-stationary environment, a resilient-sustainable system still accounts for “people, nature, and economies” but does so under the assumption that reality is far from a “static set of circumstances”, acknowledging that “a change in one system ripples through all others”, and that failure is inevitable (Kariem 2018). Therefore, a resilient-sustainable system is one which promotes the three aspects of sustainability – environment, society, economy - under both “design” and “unknown” conditions, whether through mitigation of initial impacts, or adaptation to failure.

4.1.4 The SDGs, Civil Engineers, and the ASCE

As discussed in detail in Chapter 2, while there is a call on every profession to work toward accomplishing the SDGs, as creators of the world’s infrastructure, civil engineers have a specific and sizable obligation to place the SDGs at the centre of their work. The American Society of Civil Engineers’ (ASCE) “*Five-Year Roadmap to Sustainable Development*” (*Roadmap*), acting as the foundation of this research project, is an acknowledgement of this responsibility. The *Roadmap* stresses the requirement for, “serious re-evaluation of current professional practice and standards” if, “challenging issues such as climate change and urbanization” are to be dealt with sustainably (ASCE 2018).

4.1.5 Sustainable-Resilient SWM

Water resources engineering is one field in transition to the more integrated, resilient-sustainable approach outlined in the ASCE's *Roadmap* (ASCE 2018). Traditional assumptions of a static environment and constant rainfall patterns leave little room to consider the impacts of inevitable upstream urbanization, ever-increasing usage rates, pollution sources, and imperviousness, or the reality of these changes being backdropped by a significantly altered, and continuously varying meteorology (Semadeni-Davies et al. 2008; Razavi et al. 2016; Dong, Guo, and Zeng 2017). This oversight can be seen in countless examples from around the world, including a number within Canada (Grahn and Nyberg 2017; Powers 2013; H. E. Lee and Kim 2017; Dhakal and Chevalier 2016; Roodsari and Chandler 2017; Nie 2015; Czajkowski et al. 2018). In contrast, the modern sustainable-resilient perspective assumes the environment *will* change and system failures are *inevitable* (Dong, Guo, and Zeng 2017). Instead of being focused only on resisting SWM failures and resulting floods, Sustainable-Resilient SWM aims to create a SWS which effectively manage failures and floods when they inevitably occur, while acknowledging the impacts the SWS has on the societal, environmental, and economic systems it is inextricably linked to (Razavi et al. 2016; Willuweit and O'Sullivan 2013; Zhou 2014).

4.1.6 Implications of Sustainable Development, Sustainable-Resilience, and the *Roadmap within* SWM Research

The movement away from traditional to Sustainable-Resilient SWM is important in establishing sustainability in the context of various systems. In fact, the direct link between water resources engineering and sustainable development is clear in several SDGs including providing safe and reliable water systems for all people (SDG 6), establishing resilient infrastructure (SDG 9), creating sustainable cities (SDG 11), mitigating climate change and its impacts (SDG 13), sustainably managing all aquatic life (SDG 14), and protecting all terrestrial ecosystems (SDG 15) (Annan 2017). Keying in on urban SWM, the Intergovernmental Panel on Climate Change's (IPCC's) latest report highlights the need to change the layout of cities and rely on green infrastructure in order to avoid the catastrophic consequences of climate change (IPCC 2018).

However, the above information is not novel. Introduced in the 1970s, Best Management Practices (BMPs) for SWM were practices and components put in place to reduce the pollution of runoff receiving waters. Soon after the establishment of BMPs, Low Impact Development (LID) acknowledged that the issues linked to stormwater runoff such as pollution and downstream flooding plaguing North American cities could be managed by ensuring development had as little impact on pre-development hydrologic processes (infiltration, evapotranspiration, groundwater recharge, depression storage) as possible. Of course, a logical method to protect natural processes is to conserve, re-establish, or take inspiration from natural components of the land; hence the well-established link between LID and the broader, cross-sectoral concept of Green Infrastructure introduced in the 1980s to tackle urban climatic challenges by "building with nature" (Depietri and McPhearson 2017). While there is considerable overlap between the concepts of LID, GI, and Nature Based Solutions (NBSs) (another common label), there has been a shift from initial BMP-LID practices of quantifiably mimicking pre-development peak flow values with end-of-pipe solutions like detention ponds, to a more holistic target of conserving hydrologic processes such as infiltration and evapotranspiration through on-site or conveyance stormwater control measures (SCMs) such as green roofs, rain gardens, enhanced tree pits (ETPs), and bioswales. Countless peer-reviewed articles outline the potential of GI and NBS to mitigate the impacts of traditional SWM and better deal with uncertain future operating conditions sustainably; significantly reducing both the amount of runoff reaching downstream receiving waters and the pollution levels within the runoff that does (Nie 2015; Wongsa et al. 2018; Eckart, McPhee, and Bolisetti 2017; W. Liu, Chen, and Peng 2014; Wild, Henneberry, and Gill 2017; Mal et al. 2018; Joksimovic and Alam 2014; Shannon and Weaver 1949; Trowsdale and Simcock 2011).

In a response to this need for SWM engineering projects that meet the demands of sustainability, the ASCE's *Roadmap's* first key to sustainable development suggests that the *right* project is not engineering yet another new solution to the same problem but ensuring the utilization of what is already available. In the context of SWM engineering *practice*, this means incorporating "already-available nature-based systems" rather than trying to solve flooding issues with the implementation of yet another overflow tank. In the realm of SWM engineering *research*, this means making use of already available research into these areas and established computational tools instead of re-writing the same conclusion for the "nth" time in a slightly different way.

Acknowledging the abundance of research supporting GI implementation and both the UN and ASCE stressing the immediacy with which action must be taken toward sustainable development, the *right* SWM research project is therefore not one that adds to the expansive theoretical knowledge-base, but one focused on the smaller-scale, more tedious work of transforming already-available theoretical genius on the benefits of already-available NBLID into real world, localized, and sustainable practices. This reality is echoed by experts in many fields including 2007 Nobel Peace Prize recipient Dr. Henry

Pollack who, in a conference presentation and subsequent interview suggested that if climate change is successfully dealt with, it will not be the result of more or improved technical research, but a result of more action; the translation of profound concepts into practical steps. Interestingly, yet not surprisingly, literature suggests smaller, local initiatives have been shown to be integral to widespread adoption of climate action (Damsø, Kjær, and Christensen 2016).

Finally, following the ASCE’s mandate, SWM engineers should not and can not feel exempt from the obligation to “use their voices of authority” to bring sustainable development into the “centre of the public eye” (ASCE 2018). In fact, being focused on the latest technologies and principles, the responsibility to educate government, industry, and citizens is even greater for the engineering *research* community.

4.2 Natural Infrastructure: Urban Forests

Cities around the world are becoming increasingly aware of the social, environmental, and economic costs of nature-devoid urban environments and the subsequent benefits – social, environmental, and economic – associated with reintroducing natural features into said areas (Ashley et al. 2013; Meerow and Newell 2017; Wild, Henneberry, and Gill 2017). By definition, and for the purposes of quantifying benefits, tracking growth, and scheduling maintenance, everything from residual natural forests to solitary road-side “street trees” are deemed part of a city’s *urban forest* (Kuehler, Hathaway, and Tirpak 2017).

Research into the environmental benefits of urban forests is well-established; they produce oxygen, sequester carbon, provide wildlife habitat, reduce UV radiation exposure, improve air quality, and reduce the urban heat island effect (Nowak 2015).

Research also highlights the social and health benefits for citizens and visitors that result from the above-mentioned environmental benefits. These include improved general attitudes toward life (De Vries et al. 2003), a reduction of negative reactions to acute stressful stimuli (van den Berg et al. 2010), lower susceptibility to crime (Kuo and Sullivan 2001), superior cardiovascular health (Donovan et al. 2013), a 15-35% reduction in extreme temperatures, valuable resources for wood products and fertilizer, and a more beautiful and pleasant urban experience (Nowak 2015). From an economic perspective, the many environmental and social benefits of urban forests result in a plethora of benefits including reduced air conditioning costs, greater consumer spending, and reduced public healthcare costs (Mullaney, Lucke, and Trueman 2015; Becker et al. 2019). While the rigour of these studies and the strength of their claims is periodically questioned (A. C. K. Lee and Maheswaran 2011), this has not dissuaded cities around the world from focusing on incorporating and maintaining urban forests within their boundaries in recent years. Initiatives such as MillionTreesNYC, Beijing's target of 45% urban forest coverage (Beijing 2017), Toronto's 40% urban canopy coverage target (Parks Forestry and Recreation 2012), and Hamilton's 30% canopy coverage target (HNC and EH 2017) are a few of the countless municipality plans prioritizing urban forests.

While urban forest campaigns are traditionally initiated based on their aesthetic value and air pollution-reducing potential, one of the most valuable and increasingly explored aspects of urban forests is their positive role in the hydrologic regime of urban areas. Well-established in the literature, urbanization and the replacement of naturally-pervious surfaces with impervious materials drastically alters the hydrologic regime- reducing infiltration, prohibiting groundwater recharge, eliminating countless storage areas and removing the potential for evapotranspiration to occur- which results in nutrient-poor soils, flood-prone areas, stream erosion, and either polluted receiving waters or high water treatment costs, if not both (L. M. Ahiablame, Engel, and Chaubey 2013; L. Ahiablame and Shakya 2016; W. Liu, Chen, and Peng 2014). Comprehensive reviews such as Berland et al. (2017) and Kuehler, Hathaway, and Tirpak (2017) highlight the capacity of urban forests to help re-establish pre-development hydrologic processes of infiltration, groundwater recharge and storage, interception, and evapotranspiration, thereby reducing risks of urban flooding, downstream erosion, and receiving water pollution, while also reducing the economic cost associated with water treatment (Mullaney, Lucke, and Trueman 2015; Nowak 2015).

4.2.1 Hydrologic Processes of Urban Forests

Urban forests provide these stormwater benefits through the three main hydrologic processes that naturally occur in, around, through, and because of trees: interception, infiltration, and evapotranspiration.

4.2.1.1 Interception

The “catching” of rain before it reaches the ground can be understood as the first impact of the urban forest on the hydrologic regime. Particularly during smaller storms and in the early stages of larger events, rain that falls on trees can be detained as canopy and stem storage (Xiao and McPherson 2002). Some portion of this stored water will be evaporated back into the atmosphere directly, while the rest will reach the ground by way of throughfall or stemflow and either infiltrate into the soil or be transformed into runoff. Promoting natural hydrologic mechanisms and losses of evapotranspiration and infiltration, both potential paths contribute to the goals of Low Impact Development (LID).

Even in the "worst-case" scenario in which water becomes runoff after being transported to the ground by stemflow, the water has been drastically slowed, carrying less potential to contribute to flash-flooding downstream.

While erroneously ignored in calculations of the hydrologic impacts of street trees (X. Liu and Chang 2019), there is no shortage of research on interception rates. This is most likely due to the incredible variability of interception rates produced within and amongst species and even within individual tree sampling.

Table 1: Modelled and observed interception rates from a range of sources found in the literature. The variability of interception rates based on species, size, health, environment, and weather conditions is evident.

Tree Species	**Interception values**	**Study**
Pear, *Pyrus calleryana* 'Bradford' (Deciduous)	15% total rainfall 100%	(Xiao et al. 2000)
Eucalyptus pauciflora	0.178 mm/unit-leaf-area	(Aston 1979)
Cork oak, *Quercus suber* (Evergreen)	27% total rainfall	(Xiao et al. 2000)
Eucalyptus maculata	0.032 mm/unit-leaf-area	(Aston 1979)
Broadleaved native forest	14-37% annual precipitation	(Iroumé and Huber 2002)
Douglas fir	22% over 26 months, 69% annual	(Iroumé and Huber 2002), (Huang et al. 2017)
Fagus sylvatica	16-23%	(Iroumé and Huber 2002)
Pseudotsuga menziesii	32-36%	(Iroumé and Huber 2002)
Pinus radiata	11-39%	(Iroumé and Huber 2002)

Conifers	34%	(Iroumé and Huber 2002)
Western Redcedar	75% annual	(Huang et al. 2017)
Norway Maple		(Huang et al. 2017)
Small Jacaranda mimosifolia	15.3% (0.8 m^3/tree)	(Xiao and McPherson 2002)
Mature *Tristania conferta*	66.5% (20.8 m^3/tree)	(Xiao and McPherson 2002)
Mature *Platanus acerifolia*	14.8% of 21.7 mm winter 79.5% of 20.3 mm summer	(Xiao and McPherson 2002)

As evident by the small sample of interception rates in Table 1, depending on the tree's species, size, health, leaf-area-index, as well as meteorological factors such as season, temperature, rainfall intensity and duration, windspeed, and air humidity, interception rates can be as low as 11% during a long and intense storm, or as high as, if not higher than 79% for short, less intense storms (Xiao and McPherson 2002). One study highlighted the impact of the species-derived variability by calculating the volume intercepted-per-storm values for *F. grandifolia* and *L. tulipifera* to be 500L tree^{-1} (21.5% of rainfall) and 650L tree^{-1} (27.8% of rainfall) respectively (Van Stan, Levia, and Jenkins 2015). While significant primarily for its offering of important interception data, the research did a great job of highlighting the impact of using different species for stormwater purposes; within a 12 ha catchment with a tree stand density of 225 trees ha^{-1}, the 150 L tree^{-1} storm^{-1} difference results in a significant 300 000 L difference of interception in an average rainfall event (Van Stan, Levia, and Jenkins 2015). Capturing the impact of interception in another way, each of Santa Monica's 29 299 street and park trees was found to intercept around 6.6 m^3 of rainfall over a given year, amounting to a total urban forest interception of 193 168 m^3 annually (Xiao and McPherson 2002).

As mentioned, the interception capacity of trees is highly dependent on species characteristics such as their being deciduous or coniferous, mature size, leaf smoothness, bark thickness and roughness, branch angles, leaf area, and leaf canopy structure and individual tree characteristics including canopy coverage, health, and planting density (Berland et al. 2017). Furthermore, independent of tree characteristics, meteorological factors such as rainfall intensity, interevent time, wind, and humidity, as well as seasonal factors which impact canopy density also play an important role in interception rates. For example, in smaller, shorter rainfall events, interception can result in interception rates above 90% (Elliott et al. 2018). Providing observed data on this topic, (Xiao and McPherson 2016) discovered that interception rates generally increased with rainfall intensity until 80 mm hr^{-1} before tapering off.

While additional research is always valuable, there is a strong consensus within the literature that urban forest interception can at the very least, significantly contribute to water pollution and quality control by reducing runoff volumes (Berland et al. 2017).

4.2.1.2 Infiltration

The second impact of trees on the urban hydrologic regime is the opportunity they create for water to infiltrate into the natural ground, naturally. Resulting from throughfall (falling onto the ground after travelling through the tree canopy (interrupted or uninterrupted)), stemflow (travelling down the trunk of a tree after being initially intercepted), or by falling on surrounding surfaces and travelling, intentionally or not, as runoff towards the base of trees, a tree's necessity for and therefore the inevitable presence of rooting soil provides a significant opportunity for rainfall to avoid the traditional sewer system and infiltrate naturally into the ground. For perspective on the exceptional efficacy of natural infiltration rates, while rainfall events can become incredibly intense, occasionally dropping rain at over 100 mm hr^{-1} (Phillips 2015), it is important to understand natural forests have infiltration rates ranging from 637 to 652 mm $hr^{-1;}$ infiltration rates that could handle the most extreme rainfall events quite adequately (Gregory et al. 2006). In contrast, with infiltration rates virtually eliminated, impervious surfaces such as roads, buildings, and parking lots have vastly limited capabilities to absorb any rainfall in storms of any intensity. One would assume therefore, that any remaining or newly-established area of soil would be incredibly beneficial for urban infiltration rates. However, as suggested by Gregory et al. (2006), the presence of open soil does not guarantee adequate infiltration. High pedestrian traffic and ignorant construction practices can lead to high rates of soil compaction in urban environments; the combination of which has been shown to reduce infiltration rates of soil by 70% to 99%, effectively turning soil into an impervious surface (Gregory et al. 2006).

The reality of soil compaction in combination with the knowledge of extremely high natural infiltration rates has led to considerable research into the quantification of tree-induced infiltration rates (Berland et al. 2017). One observational study found that the presence of trees, and specifically tree roots to be incredibly important for urban infiltration rates; the establishment of roots in the often compacted urban soil environment increased infiltration rates by 153% (Bartens et al. 2008). It should be noted however that tree roots don't provide a guarantee to uncompacted soils. While (Alizadehtazi et al. 2016) observed infiltration rates of 162 mm hr^{-1} for guarded tree pits, these rates were four times greater than the 36 mm hr^{-1} rate observed in unguarded pits. Therefore, while an infiltration rate of 162 mm hr^{-1} provides further evidence for the power of street trees to establish adequate infiltration regimes in urban environments, 36 mm hr^{-1} suggests that the same variability and multi-dimensional characteristics found in interception rates of street trees are present in infiltration rates as well.

Table 2: A selection of observed tree-induced infiltration rates categorized by type of plantation studied. As with interception, the variabiliy in infiltration rates is high and dependent on a variety of characteristics.

Feature Studied	**Infiltration Value (Compacted)**	**Study**
Natural Forest	377 to 634 mm hr^{-1} (8 to 175 mm hr^{-1})	(Gregory et al. 2006)
Planted Forest	637 to 652 mm hr^{-1} (160 to 188 mm hr^{-1})	(Gregory et al. 2006)
Tree Pits	162 mm hr^{-1} (Guarded) (36 mm hr^{-1} (Un-gaurded))	(Alizadehtazi et al. 2016)
Pasture	225 mm hr^{-1} (23 mm hr^{-1})	(Gregory et al. 2006)
NYC Tree pits	0.01 to 0.67 cm min^{-1}	(Elliott et al. 2018)

The variability of tree pit infiltration rates and their reliance on soil compaction was also a main finding of an investigation of forty street trees in New York City (Elliott et al. 2018). Researchers found that using soil compaction was significantly more effective at explaining the incredible variation found within the samples of infiltration rates than the presence of mulch or ground cover planting, the elevation of the pit, and even tree diameter and pit surface area. Observed variability was such that infiltration rates as low as 8 mm hr^{-1} and as high as 175 mm hr^{-1} were found (Elliott et al. 2018; Gregory et al.

2006). With all this said, it is important to consider the potential held in even the lowest of these infiltration rates to mitigate runoff pollution and volume. For example, within the Greater Toronto Area, a 15-min, 100-year storm has a rainfall intensity of about 120 mm hr^{-1} (Coulibaly et al. 2015).

This contextualization makes it quite clear that, similar to the process of interception, it is erroneous to 1) not take advantage of infiltration processes when designing stormwater management systems, and 2) assume their impact is negligible during modeling; a tree with uncompacted soil would facilitate a significant infiltration rate even in the context of the most extreme rainfall events and should therefor not be ignored. Furthermore, the key to effective infiltration rates and the stormwater benefits they produce is uncompacted soils; maintaining naturally separated soils is fundamental to reaping optimal infiltration benefits.

4.2.2.3 Evapotranspiration

Trees rely on the process of transpiration, or evapotranspiration (ET) of water from their leaves to facilitate the transportation of vital nutrients from the soil to the tips of their branches and leaves. From a hydrologic perspective, ET is one of, if not the fundamental source of precipitation losses, accounting for significant losses of total rainfall in urban environments; A recent study of ET rates in the Greater Toronto Area found annual rates of 210 mm to as high as 556 mm which accounted for 79% of the 698 mm that fell in the Kortright area that year (Delidjakova and MacMillan 2014).

While ET is significantly more impactful than infiltration or interception, it remains, especially in urban environments, quite understudied due to its inherent complexity (Berland et al. 2017) and variability (Pataki et al. 2011). One of the main issues is the scale at which ET is often measured. While the 500 mm yr^{-1} referenced above is valuable information, these annual ET rates provide little information on the impacts of ET during a specifically strong or weak, short or long storm event (Berland et al. 2017). This difficulty of estimation however should not lead to discounting of the research that has gone into ET data collection.

Table 3: Observed and modeled infiltration rates of different tree species found within the literature with note of the setting - urban or rural - of the trees studied. Despite the incredible variability, the overall impact of evapotranspiration is significant.

Species	**Setting**	**ET Rate (mm hr^{-1} assuming 9.3 m^2 canopy)**	**Study**
Acer saccharum (Sugar Maple)	Urban	*10.4 – 63.4 g m^{-2} hr^{-1}* (0.04 mm hr^{-1})	(Vrecenak and Herrington 1984)
Acer platenoids (Norway Maple)	Urban	6.8 – 55.5 g m^{-2} hr^{-1} (0.035 mm hr^{-1})	(Vrecenak and Herrington 1984)
Deciduous Landcape Trees	Urban	94 – 113 097 g hr^{-1} (6.09 mm hr^{-1})	(Vrecenak and Herrington 1984)
Pinus canariensis	Urban	$3.2 \pm 2.3\ kg\ tree^{-1}\ d^{-1}$ (0.014 mm hr^{-1})	(Pataki et al. 2011)
Platanus hybrida	Urban	$176.9 \pm 75.2\ kg\ tree^{-1}\ d^{-1}$ (0.79 mm hr^{-1})	(Pataki et al. 2011)
Brachychiton populneus	Urban	$< 5.0\ X\ 10^3\ kg\ tree^{-1}\ yr^{-1}$ $12.7 \pm 10.4\ kg\ tree^{-1}\ d^{-1}$ (0.06 mm hr^{-1})	(Pataki et al. 2011)
Gleditsia triacanthos	Urban	$(2.5 \pm 1)\ X\ 10\text{^}4\ \ kg\ tree^{-1}\ yr^{-1}$ $89.9 \pm 23.6\ kg\ tree^{-1}\ d^{-1}$ (0.40 mm hr^{-1})	(Pataki et al. 2011)
Douglas Fir	Forest	$4.9\ to\ 23.6\ kg\ tree^{-1}\ d^{-1}$ (0.06 mm hr^{-1})	(Black, Nnyamah, and Tan 1980)

As displayed in *Table 3*, like interception and infiltration, the species, canopy coverage, LAI, health, and size of the tree as well as meteorological considerations including wind speed, rainfall intensity, soil moisture, solar radiation, humidity, cloud cover, and a number of others impact the evapotranspiration occurring in any given instance (Xiao and McPherson 2016; Berland et al. 2017). The incredible variability resulting from such an extensive list of factors was demonstrated by research on Los Angelos' urban forest, which found the *Pinus canariensis* transpired 3.2+/-2.3 kg tree^{-1} day^{-1} while the *Platanus hybrida* transpired 176.9+/-75.2 kg tree^{-1} day^{-1} (Pataki et al. 2011). Naturally, rapidly growing deciduous have larger maximum ET rates than the more slowly growing coniferous trees.

Tree-induced ET should not be discussed without mention of the Leaf Area Index (LAI) measurement of a tree. Much more important than the tree's canopy or stem diameter, is the amount of leaf surface area present within that canopy area providing the opportunity for transpiration to occur. This is quantified simply as the one-sided area of leaves per land area under the tree canopy. LAI can be understood as a density of leaves or transpiration opportunity per canopy area. LAI can be less than one while in other situations greater than ten, if there are many layers of leaves over the projected canopy area. Observational and computational research conducted by Vrecenak and Herrington (1984) demonstrates the impact of LAI on transpiration rates, suggesting a change in LAI from a value of 1 to 6 can impact the transpiration rate of a tree with a constant canopy diameter by an order of magnitude.

Soil moisture is another of the largest predictors of ET rates, as a greater supply of water to the tree facilitates greater transpiration (Vrecenak and Herrington 1984). This is especially relevant in urban settings which are known to provide trees with extremely dry soils (Church 2015; Grey et al. 2018b). On a more positive note regarding urban environments and trees however, trees planted in less dense numbers have been shown to elicit up to three times the amount of ET than their densely-planted counterparts (Hagishima, Narita, and Tanimoto 2007), which is one of many benefits of using trees in urban settings.

The plethora of research described above focusing on the interception, infiltration, and evapotranspiration of rainfall facilitated by trees in urban areas points to the significant evidence describing trees as capable components of SWM regimes. Although their dynamic and non-static characteristics are complex and seemingly difficult relative to traditional dykes, pipes, and culverts, non-stationarity is exactly what is required for solutions to be effective in non-stationary circumstances (Dong, Guo, and Zeng 2017).

4.2.2 Potential of a healthy Urban Forest to satisfy the needs of Beasley and Landsdale

Recalling the list of eight key needs of Beasley and Landsdale outlined in Chapter 3 in conjunction with the above discourse regarding the benefits of healthy urban forests, one can understand how the needs detailed above actually work to satisfy themselves if given the opportunity. For example, the needs for runoff volume and Hamilton Harbour pollution reduction (Needs 1,2) can be satisfied by directing runoff to already-established street trees. By doing so, not only would Needs 1 and 2 be met, but can meet Need 6- the need of street trees for better water supplies in urban environments (Szota et al. 2019). If runoff were to be redirected towards the street trees, both the tree’s requirement for water and the city’s need for a less stressed treatment plant and polluted harbour would be satisfied. In the same way, the health of street trees is often hindered by a lack of rooting volume.

The simple procedure of providing the tree with additional rooting volume would allow the tree to flourish (Need 5) while also providing the city's SWM network with additional storage and resilience (Need 1,2,8). The resulting increase in urban forest health in Beasley and Landsdale would reduce other negative impacts associated with urbanization as well; heat island effect would be reduced and more CO_2 would be sequestered, urban runoff would be filtered thereby reducing the levels of pollution reaching Hamilton Harbour, and taller, healthier trees would contribute to the socio-economic boost the areas requires, improving the moods and attitudes of residents and visitors alike, lowering crime rates, improving air quality, increasing commercial activity, reducing energy costs, and enhancing natural habitats (Need 3,4,7). Perhaps the most important aspect of this focus on trees as stormwater control measures is their natural ability to grow; A fully-mature tree is more drought-resistant and can use an order of magnitude more water than a young tree. This suggests that as the impacts of climate change inevitably worsen in the coming decades, these nature-based control measures hold the potential to grow with the problem, rather than becoming obsolete (Need 8).

4.3 Extended-Depressed or Enhanced Tree Pits

It is in this context - a growing requirement for additional and discretized stormwater management implementations, growing awareness of the importance of larger, healthier urban forests, and the issues most urban street trees face due to a limited access to rooting volume and water - that the ingenuity of enhanced tree pits (ETPs) and extended-depressed tree pits (EDTPs) can be fully explored.

Enhanced Tree Pits (ETPs) are a form of Nature-Based Low Impact Development (NBLID) that, as the name suggests, offers trees enlarged rooting volumes filled with engineered, permeable soil layers designed to meet the needs of urban trees; magnifying the ecoservices provided, while also taking advantage of the increased rooting volume, infiltration, evapotranspiration, and interception rates to provide excess storage and filtration for stormwater runoff (Grey et al. 2018b). A number of studies have demonstrated the ability of bioretention cells, including ETPs, to significantly reduce the peak flowrate and volume of water entering the system and reduce the seemingly inevitable downstream pollutant loading (Shrestha, Hurley, and Wemple 2018); natural hydrologic processes are restored, street trees flourish, urban stormwater management improves, and multiple additional ecoservices are amplified (Berland et al. 2017; Grey 2018; Ow and Ghosh 2017; Szota et al. 2019). One comprehensive and observational study focusing on the hydrologic impacts of bioretention areas- including their impact on flow rates, flow volumes, and pollution reduction capacities, highlight their potential. Of the 121 real storms observed, 31% of them were fully captured by the bioretention systems, including one 39.4 mm event and every event up to 25 mm (Shrestha, Hurley, and Wemple 2018). Furthermore, contrary to popular belief, this study observed the significant impact bioretention areas have on large events (> 25 mm), showing a mean volume reduction of 70% and significant peak delays (Shrestha, Hurley, and Wemple 2018). While not complete solutions in isolation, these impacts provide valuable redundancy to the SWM system, allowing for the already-established sewer system to better deal with the volume, flow rate, and pollutant load of large events.

In addition to Enhanced Tree Pits, a simpler, SWM-focused option available is the implementation of Extended-Depressed Tree Pits (EDTPs). A less intrusive, and therefore less costly alternative to ETPs, rather than directing the runoff into a sub-surface soil cell, in the context of an EDTP, the runoff is held in a ponding area on the surface of the pit created as a result of the extension and depression of the already-available tree pit. This can be accomplished by simply removing the hardscape – often sidewalk – surrounding the existing pit. This process creates the opportunity for ponding to occur, allowing for both the storage and infiltration of water.

While EDTPs do present a lower initial economic cost option relative to ETPs, it is important to consider the multi-dimensional limitations of EDTPs in relation to ETPs. While EDTPs do provide the tree with an increased supply of water, as Chapter 3 suggests, exposed topsoil isn't always enough. As discussed, typical urban street tree implementations present potential issues of prolonged inundation of the roots due to an inability for the runoff to infiltrate into and exfiltrate from the soil, insufficient rooting volume which prohibits healthy root and tree growth, reducing the potential of cross-sectoral ecoservices such as air quality improvements, street beautification, reduction of urban heat island effect and crime rates, stormwater runoff retention, and downstream pollution reduction.

With all things considered, ETPs and EDTPs are two options available that hold the potential to enable municipalities to take better advantage of already available street tree pits. While ETPs are more costly and complex, they meet a more holistic set of needs that extend far beyond SWM. While EDTPs are more focused on the potential of street trees to contribute to the SWM regime, they are much simpler and more cost-effective. Both these options were explored in this research.

4.3.1 ETP Design

While a niche concept, similarities between all NBLIDs and the particular potential of ETPs has resulted in an abundance of simulation- and field-based research into either observing the impacts of coincidentally or intentionally different pit designs (Grey et al. 2018b; Stovin, Jorgensen, and Clayden 2008; Grey et al. 2018a; Armson, Stringer, and Ennos 2013). Furthermore, based on demonstration projects, there are several municipality-created design guides, including that put forward by the Credit Valley Conservation Authority (CVC) proposing different methods and considerations to be aware of while implementing ETPs such as tree species and size, pit sizing, appropriate soil characteristics, and the necessity of additional features such as liners or underdrains to connect the tree pits to the traditional SWS (Grey et al. 2018b).

Pit Size

As is suggested in the literature at large, the availability of rooting volume is vital for tree growth, health, and therefore stormwater management performance (Lindsey and Bassuk 1992). While Lindsey and Bassuk (1992) suggests a minimum of 5 m^3 of rooting volume for a medium sized tree, there are a number of factors that have led other sources to suggest pits with dimensions of 5 x 0.6 x 2 m (L x W x D), suggest minimums of 12 m^3, and even others that claim some trees require “at least 34 m^3” (Lukes 2010). One of the richest resources available regarding LIDs is the Low Impact Development Stormwater Management Planning and Design Guide, available at https://wiki.sustainabletechnologies.ca/wiki/Main_Page and developed collaboratively by the Toronto and Region Conservation Authority (TRCA), the CVC, and the Lake Simcoe Region Conservation Authority (LSRCA). It suggests that a tree should be given at least

1000 mm of rooting depth which is an important consideration when calculating the total storage depth provided by an ETP (TRCA 2018). Relevant to EDTPs is the Design Guide's suggestion that pits are designed to allow at least 300 mm of ponding to occur on the surface (TRCA 2018). However, the exploration of ETPs utilizing structured soil cells within this research prevents additional ponding to occur on the surface.

Soil

In addition to the pit size, a plethora of literature as well as demonstration projects completed by the TRCA and the CVC have also explored the importance of soil characteristics in the context of ETP performance. In the collaborative Design Guide, it is suggested that the 1000 mm of rooting volume mentioned above is filled with a filter media. While filter medias can be implemented in a wide range of fashions, the CVC insists the soil should be an engineered mixture of 85-88% sand (2.0 to 0.05mm), 8-12% fines (<0.05mm) and 3-5% organic matter (Lukes 2010). The 3-5% organic matter has been suggested to be crucial to plant growth and nutrient filtration and is therefore virtually mandatory in the situation of ETP implementations (Page, Winston, and Hunt III 2015). In addition to the filter media, typical bioretention implementations have a storage layer consisting of stones. It should be noted that a sand-based filter media and a stone storage layer as described above can both be assumed to have void ratios of 0.4. In the context of ETP implementation, the void ratio is crucial in determining the total depth of storage and the infiltration rates provided by the system. With this in mind, as discussed in detail above, the precise composition of the soil, while important, isn't the only factor involved in infiltration rates. Both the presence of tree roots and the density or compaction of the implemented soils are equally important in ensuring optimal system performance.

As EDTPs utilize the soil already in the tree pit, the above factors don’t apply in their situation. However, based on research exploring the variability of infiltration rates in urban environments, such as that conducted by Elliott et al. (2018) on the infiltration rates of established tree pits in New York City, it is very important that when designing specific EDTPs, that specific measurements of infiltration are completed to ensure proper depth design.

Tree Characteristics

As detailed above, the many benefits associated with street trees and urban forests are conditional upon two main factors: the health and species of the tree (Rahman, Armson, and Ennos 2015). Similarly, different tree species are impacted differently by the same stress; Research exploring the different cooling abilities and growth rates of different tree species found differences in growth rates and stress tolerances of over 100% and depending on factors such as salt, pollution, and drought resistance, proper tree species is very important (Rahman, Armson, and Ennos 2015). Regarding the size of the tree implemented, while the CVC suggests deciduous trees have a calliper of at least 60 mm, and coniferous trees are at least 175 cm tall (Lukes 2010), it is important to note the long-term benefits of retrofitting ETPs in the vicinity of any tree. While young and smaller trees will not produce the same benefits right away, the presence of larger, uncompacted rooting volumes and more consistent access to adequate water supplies will help trees of all native species grow more quickly, and therefore enable each member of the urban forest to more effectively deal with stormwater runoff. It should also be reinforced that different tree species of different sizes will contribute very differently to the SWM and hydrologic regime; a mature tree can intercept and transpire orders of magnitude more water than its younger counterpart (Nagendra and Gopal 2010; Xiao and McPherson 2002; Xiao and McPherson 2016).

Overflow Infrastructure

While the CVC only briefly mentions drainage infrastructure, research conducted points to the potential of underdrain installation to double tree growth rate (Grey et al. 2018a). With an intricate setup including a passive street tree, a storm-water directed street tree, an un-drained sandy tree pit, a drained sandy tree pit, and a parallel sandy tree pit, the study shows that the ability for underdrains to maintain optimal soil moisture greatly reduced tree stress and increased tree growth, while un-drained sandy pit trees exhibited poor growth or even died due to extended waterlogging within the same environmental conditions (Grey et al. 2018a). The research highlights the uncertainty of relying on what was deemed the “highly disturbed urban soil landscape” as the trees in the sandy pit groups experienced an incredible range of exfiltration rates from 1 mm hr^{-1} to 68 mm hr^{-1} while only metres away from each other (Grey et al. 2018a). This calls for a high-degree of pre-implementation research to justify a lack of underdrain. Other than the underdrain, implementing a parallel soil pit provides an additional method to prevent waterlogging of trees. In this specific study, an engineered soil pit with high infiltration rates was installed 1.5 metres laterally from the tree. Theoretically, this would provide the tree with access to a reservoir of water without the risk of inundating the roots. Quite naturally, while it did provide benefits to water storage and tree health, it did not provide street trees with access to water as effectively as the underdrain group (Grey et al. 2018b). While concessions are expected in retrofitting scenarios, the researches highlighted that this lack of performance was due in part, to both the youth of the trees and the short period of the study. It could be surmised that the trees were not given enough time to extend their roots into the reservoir. Therefore, if given time, the tree would in fact have better access to the water and be provided with and provide more significant benefits (Grey et al. 2018b).

For both ETP and EDTP implementations, the inclusion of an underdrain depends on the type of installation. If completing a new project, the cost of an underdrain is rarely counted as not worth it. However, in the context of non-intrusive tree pit retrofits, the most practical solution to overflow is to allow it to re-enter the streetscape “system”. While obviously not ideal, the justification can be based on the reality that prior to the retrofit, the water had no chance of exiting the streetscape; that some runoff re-enters the system should not be seen as a negative consequence as no water is actually being added to the street.

Fundamental ETP Implementation Considerations

Research suggests that the most influential factors in determining tree growth and runoff retention rates are the pit to catchment area ratio and the exfiltration rates of the underlying soil (Grey 2018). In their research, Grey et al. (2018b) provides a table detailing the relationships between pit and catchment area, runoff retention and runoff days, as well as exfiltration rates found in their study. For example, to meet the target retention figures of 77-93% and only 15 days of runoff a year, a pit with an exfiltration rate of 1 mm hr^{-1} would require a pit area of 3.7 m^2. Note this is significantly higher than the 1.1 m^2 pit required assuming a 34 mm hr^{-1} exfiltration rate (Grey et al. 2018b). Of course, the actual pit areas are less important than the pit to catchment area ratio. In line with similar studies, the findings of Grey et al. (2018b) suggest pit to catchment areas of <1% are most-often ineffective at retaining significant runoff volumes if not compensated by obscenely high exfiltration rates, and that pit areas should represent at least 2.5% of the catchment area, with the most ideal and feasible ratio in their specific study area being 8% (Grey et al. 2018b).

5.1.6 Structured Soil Cells

The importance of pit area and soil exfiltration rates in ETP effectiveness makes structured soil cells incredibly useful. In highly-trafficked urban areas, structured soil cells allow for the use of very pervious soils throughout larger areas, protect against future soil compaction and therefore reduction of ETP performance, and present an economic positive, requiring none of the often-valuable store-front or Right of Way (ROW) surface area. Evidence of the benefits of using structured soil cells can be seen in findings of 37% greater tree growth relative to trees planted in normal soils and significant reductions in the total suspended solids (TSS), total Phosphorus (TP), total Nitrogen (TN), and other common pollutants within the system outflow (Ow, Ghosh, and Mohamed Lokman Mohd. 2018). Several proprietary structured soil cells are available to the public. Two main providers of structured soil cells are DeepRoot which manufacture and sell what they refer to as *SilvaCell 2*, and GreenBlue Urban which offer the *RootSpace* system. Both systems have been installed several thousand times around the world while also boasting impressive results in several prominent projects within Ontario. Both systems claim environmental consciousness, being fabricated from recycled plastics, provide the structural support required to support sidewalks, and remove the usually-necessary process of underlying soil compaction, allowing for optimal tree growth.

Being proprietary systems, each is produced in prefabricated sizes. The *SilvaCell 2* comes in three sizes – small, medium, and large, with total depths of 424, 784, and 1092 mm. The *RootSpace* comes in two sizes- the *600* and *400,* which are 600 mm and 400 mm deep respectively. GreenBlue Urban claims a “void area” of 92% for their systems, suggesting that 92% of the cell can be filled with soil. As seen in *Table 4,* applying this value to each size of both systems produced the total depth available for the installation of a fill media. While from a stormwater management standpoint it can be argued that leaving the cells fully empty would produce the largest amount of storage for the system, soil must be present within the cells if any filtration is desired, and even more rudimentarily, soil is still required to provide the street tree roots with some level of support. Assuming a void ratio of 0.4 as assigned above to sandy fill medias, the storage depths provided by each size were also calculated and displayed in *Table 4.*

Table 4: Calculated storage depths provided by different sizes of SilvaCells and RootSpace systems. These values were calculated based on a non-structural ratio of 0.92 and a fill media void ratio of 0.4 for each system suggested within a number of LID design guides.

Structured Soil Cell System	**Cell Depth (mm)**	**Total Soil Depth (mm)**	**Storage Depth (mm)**
RootSpace 400	400	368	147
RootSpace 600	600	552	220
Small SC	424	390	156
Medium SC	784	721	288
Large SC	1092	1004	401

As displayed in *Table 4*, the five effective storage depths offered by the five systems range from 147 mm to 401 mm.

4.3.2 The Evidence-based Case for Retrofitted ETPs

Inspired by the ASCE’s insistence that engineers “make use of what is already available” and the potential held in structured soil cells suggested above, rather than focusing on the installation of new ETPs (Grey et al. 2018a), research has highlighted the significant benefits for tree growth and runoff retention available in enhancing the tree pits of the millions of *already-established* street trees in urban areas around the world (Szota et al. 2019; Grey et al. 2018a). This “use-what-is-available” approach of ETPs avoids the costs and risks of removing established trees from the ground, while still providing extra rooting volume and access to additional water, promoting a healthy, long-lived urban forest and amplifying the many ecoservices provided. In a demonstration study of this practice, Szota et al. (2019) found infiltration pits- or adjacent EDTPs- installed as far as 1.5 m from established trees achieved average runoff retention figures of 22.8% for sandy soils and 13.3% for clay sites. While these figures are lower than those of tree pits and other SCMs, it is important to note that high variance was recorded between sites. For example, while the least effective trench retained an insignificant 5.2% of runoff, one trench achieved an overall runoff retention of 43.7% (Szota et al. 2019). Furthermore, while the tree pits were most effective at retaining smaller rainfall events, there was a situation where 50% of a large event (>10 mm) was retained (Szota et al. 2019). While Grey (2018) found under-drained ETPs to promote tree growth more effectively than pits adjacent to the tree, it was suggested that the 18-month study was perhaps too short to judge the long-term growth benefits of adjacent ETPs as roots were not given an adequate growth period. Furthermore, Grey et al. (2018a) determined no significant difference between tree pit design in retaining runoff; instead, soil exfiltration rates and tree pit to catchment area ratios were highlighted as the key determining factors (Grey et al. 2018a). Two notes regarding this should be considered. While tree transpiration was found to have an insignificant role of 4%, the trees implemented in this study were small relative to other studies which have found transpiration to be responsible for as much as 72% of runoff retention (Grey et al. 2018a). Furthermore, this (lack of) interaction is amplified for adjacent ETP installations as tree roots require additional time to grow into the extended pit, reap the growth-benefits of the extra water and rooting volume, and improve runoff retention through higher evapotranspiration and infiltration rates.

While the evidence supporting Enhanced Tree Pits is clear, that supporting Extended-Depressed tree pits is less overwhelming. Perhaps the largest hurdle to their success is the reliance on the already-available urban soils. While ETPs present new engineered soils for tree roots to grow into, EDTPs abandon the subsurface regime, thereby providing the trees with no extra rooting volume, and run the risk of providing little to no additional water to the roots depending on the compaction status of the rooting and topsoil. As mentioned in Chapter 3, soils in “normal” tree pits have been found to have infiltration rates as low as 6 mm hr^{-1} (Elliott, Shetty, and Culligan 2018; Elliott et al. 2018).

A few key conclusions can be drawn from the review of literature on urban forests and the potential of retrofitted ETPs and EDTPs to optimize the ecoservices they provide. Firstly, while sufficiently extended and depressed EDTPs can potentially contribute greatly to providing additional water storage within urban environments, their inability to provide trees with additional rooting volume or significant amounts of additional infiltrated water suggest that EDTPs should be seen as a runoff-volume-focused SWM control measure rather than the holistic and vital component to a sustainable urban environment. On the other hand, research suggests ETPs do have the potential to significantly promote the sustainability of urban environments. Firstly, among a plethora of cross-sectoral ecoservices, the processes of interception, infiltration, and evapotranspiration facilitated by urban trees have a particularly significant ability to reduce stormwater runoff volumes, pollution levels, and peak flow rates. Secondly, Nature-Based LIDs (NBLIDs), in particular ETPs, have the ability to augment these benefits. Thirdly, despite this potential, being naturally-based, a myriad of possible environments, weather patterns, soil properties, and tree species and characteristics among other factors make it difficult to make broad statements regarding the performance of specific installations. This inevitable variability introduces higher costs and doubt within the professional community which work together to hinder wide-spread uptake of NBLID technologies. The main questions that require answering therefore are, “Given the inherent variability found within NBLIDs, what design standards or guidelines should be used in *this* instance?” More importantly, “What benefits will be produced by *this* implementation in *this* environment?”

4.4 Modelling Programs

Despite the industry-sourced skepticism mentioned above, the serious and intensifying challenges in urban stormwater management described previously have propelled a push for Nature-Based LIDs (Collentine and Futter 2018). This emphasis on NBLID implementation in combination with the site-specific parameters required for efficient LIDs and the incredible site-specific variability inherent in natural features has given rise to several government and non-governmental software-based water management models aimed at making LID design and implementations such as ETPs more economically, environmentally, and socially effective. With the *Roadmap’s* suggestion to take note of the resources already available, a review of several of the well-established water management models capable of estimating the impacts of retrofitting enhanced tree pits or extended-depressed tree pits to existing street trees was conducted.

4.4.1 Deterministic Models

A review of the literature and available resources made it clear that there are a number of event-based or continuous simulation models available to explore the impacts of LID implementations. The US EPA's latest Stormwater Management Modelling (SWMM5) software has preprogrammed LID options to aid users in the design process; the EPA has also designed a green infrastructure design tool titled Green Infrastructure Flexible Model (GIFMOD) for more detailed simulations and experimentation. Computational Hydraulics International (CHI) also has LIDs, including Infiltration pits and bioretention areas, incorporated into their SWMM-based PCSWMM hydrologic modelling software. For the USA, the EPA has created the web-based National Stormwater Calculator (SWC) to help "urban planners, developers, landscaper, and even homeowners" properly plan LID projects to deal with the estimated "10 trillion gallons of stormwater" that result from impervious areas each year (EPA SWC 2017). Perhaps the most authoritative software for modelling the characteristics and impacts of trees is the EPA's i-Tree suite. i-Tree is a suite of web- and desktop-based software programs dedicated to estimating the various ecoservices and benefits of trees. *i-Tree Eco* "quantifies the structure of, threats to, and benefits and values provided by forest populations globally", including everything from canopy interception and air pollution reduction to habitat creation (Nowak 2015). *i-Tree Streets* focuses on modelling the ecoservices provided specifically by street trees in urban environments including energy conservation, air quality, property value increases, carbon sequestration, and stormwater management. Finally, *i-Tree Hydro* is a SWMM-based tool designed for both lay-users and designers alike to efficiently and effectively investigate the impacts of land-use changes on the hydrological cycle and potential benefits of maintaining and expanding the urban forest.

While these programs are self-reportedly aimed at different users, the recent emphasis on decentralized and smaller LID SWM projects has led to emphasis being put on the need for and creation of easier-to-use, yet still effective design tools for “lay people” now more likely to be involved. While one would assume that the increased accessibility of these new models is achieved at the cost of efficacy. A recent study comparing the efficacy of the EPA’s SWMM and SWC programs in describing the impacts of a street tree project in Mississauga, Ontario, revealed that the much more “basic” SWC software produced runoff reduction rates that were well within range of the “sophisticated” and more complicated SWMM software. This shouldn’t be surprising however, as Sakshi and Singh (2016) highlight the similar foundations of these models.

4.4.2 The Case for Probabilistic rather than Deterministic Models

As each of these tools has been created, tested, and affirmed by experts in their respective fields, there is little basis for questioning the efficacy of these tools in creating quality deterministic estimations of flow through NBLIDs based on continuous simulations. With this said, there is a strong case to be made for the use of probabilistic models in lieu of or alongside deterministic models.

Data Availability

The fact that one of the most intricate SWM software programs available produced similar results to a program meant for non-expert homeowners, reinforces an adage in the modelling community that, “a model is only as good as its data.”; SWC, like SWMM, for example, can be using Horton’s model of infiltration or the Penman-Monteith equation for evapotranspiration rates. That one program is running the calculations and not the other doesn’t significantly change the results of the model. What does impact the model results is the availability of quality data and the equations to effectively utilize that site-specific data. Taking this to be true, the complexity of modelling LIDs and ETPs can be further appreciated. As discussed in length above, NBLID systems deal with incredibly complex and variable hydrologic processes of infiltration, evapotranspiration, interception, rainfall patterns, runoff transformations, and several other processes, with each relying on incredibly unique parameter sets. To estimate, let alone replicate the movement of water through an LID implementation is nearly impossible. Furthermore, understanding the within-site variability of LID performance, the question can be raised whether the estimation of LID performance is worth the high cost to create the model.

Ultimate Purpose of the Model

This question is especially amplified when presented with the proven utility of probabilistic models to return accurate estimations of flows at a fraction of the parametric “cost” of deterministic models (Zhang and Guo 2014). If deterministically describing the flows in a specific situation is, at best, a gross estimation requiring large amounts of scarce data, then it can be suggested that a more valuable simulation goal would be to establish overall characteristics of a system’s performance. This is the focus of what are called probabilistic runoff models. As discussed by Zhang (2014), deterministic rainfall-runoff models rely on either continuous rainfall data or fabricated design storms that may or may not ever occur within the study area. The inherent variability throughout natural systems and in particular, rainfall and runoff processes provide a natural suggestion to adopt the “resource-efficient” probabilistic approach to modeling hydrologic processes within stormwater management in place of the more popular, yet “resource-hungry” deterministic models.

Proven Efficacy of Analytical Probabilistic Approaches to SWM

While unknown to many professionals in the SWM community, the computationally efficient and revolutionary probabilistic approach to SWM has already been applied to rainwater harvesting systems, permeable pavements, and most importantly for this research, bioretention areas by Zhang and Guo (2014), who demonstrated the ability of the Analytical Probabilistic Model (APM) for each of these LIDs to produce results well within range of those produced by a simulation created within the EPA's SWMM software, while, as mentioned previously, requiring a vastly reduced set of data and parameters (Zhang and Guo 2014).

4.5 The Analytical Probabilistic Model (APM) for LIDs

The Analytical Probabilistic Model (APM), like other analytical probabilistic approaches to simulations is founded on the derived probability distribution theory. This theory states that the frequency of occurrence (probability distribution) for dependent variables such as runoff volumes can be derived or accurately estimated if the frequency of occurrence (probability distribution) of the independent variable, such as rainfall volume, is known. Once again, in the realm of stormwater management, this theory suggests that if the probability functions of rainfall characteristics are known, then based on functional or mathematical relationships relating rainfall to runoff such as Horton's Model of Infiltration, the PDF of runoff volumes can be derived. In the case of LID implementations such as enhanced tree pits, this means that the PDFs of rainfall characteristics can be "transferred" through functional relationships describing rainfall-runoff, infiltration, evapotranspiration, and storage, so that the LID performance can be analytically determined (Zhang and Guo 2014); the resulting formulas are named Analytical

Probabilistic Models (APMs). Therefore, in keeping with the ASCE's guideline to "use the resources that are already available", the APM for bioretention areas already established by Zhang and Guo (2014) was utilized to estimate the impacts of extending the tree pits of already-established street trees in Beasley and Landsdale neighbourhoods of Hamilton, Ontario.

To be clear, the ASCE doesn't encourage using already-available yet ineffective tools. The APM for LIDs was selected for this investigation with confidence based on previous research outlining its effectiveness in reproducing (to within 7%) SWMM simulation results regarding the stormwater capture efficiency (SCE) of bioretention areas in Boston, and perhaps more importantly, replicating the observed runoff reduction rate of green roofs in a study conducted in Portland, Oregon to within 4% (Zhang 2014). While the APM is not perfect, no model is, and utilizing the APM requires a fraction of the time number of the resources required to run continuous simulation models (Zhang 2014).

4.5.1 Stormwater Capture Efficiency (SCE) to Quantify ETP Performance

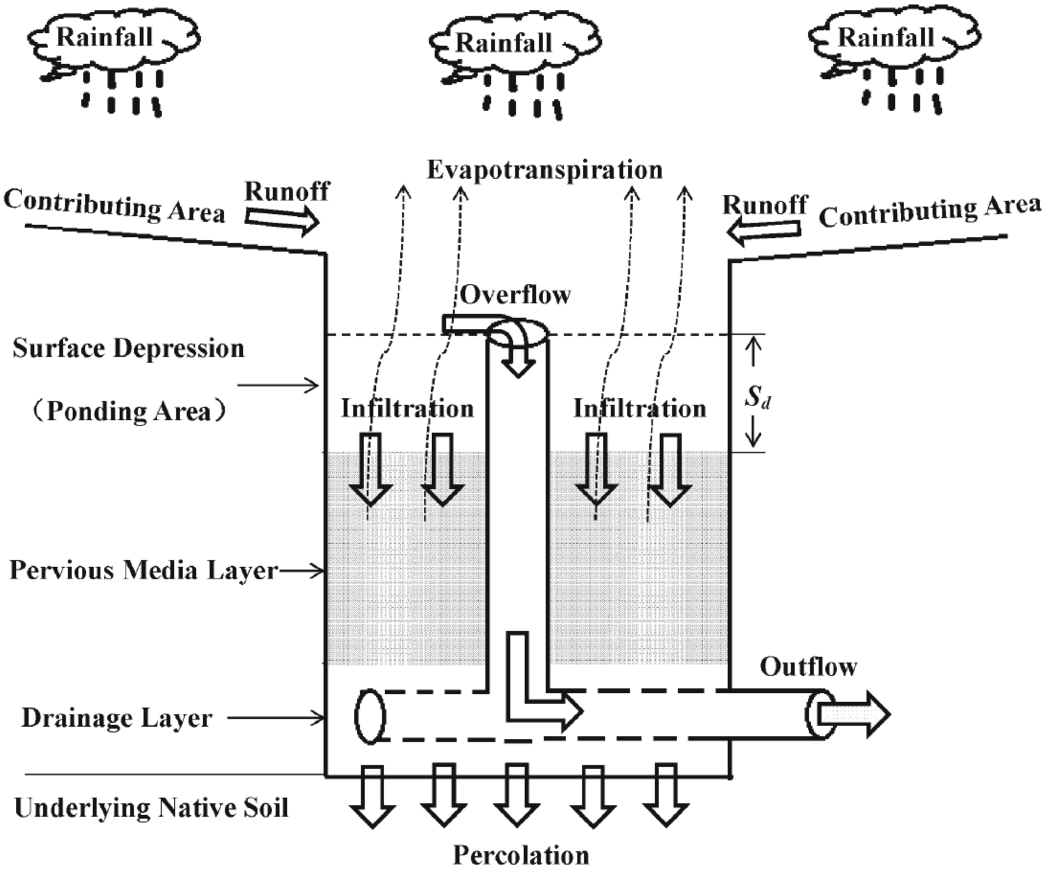

Figure 7: Schematic of the hydrologic processes occurring in, around, and through bioretention areas conceptualized by (Zhang and Guo 2014). While not physically identical, theoretically and conceptually, ETPs work very similarly to bioretention areas.

While ETPs produce an array of multi-dimensional and multi-sectoral ecoservices, within the realm of SWM, the performance of ETPs and EDTPs, like that of other bioretention systems, can be understood as their ability to disturb the hydraulic efficiency established by traditional stormwater management systems. As seen in *Figure 7,* by simultaneously storing water and providing the time, media, and vegetation required for interception, infiltration and evapotranspiration processes to occur, ETPs reduce the volume and contamination levels of water entering the sewer system, thereby reducing treatment costs and risks of combined-sewer overflows (CSOs), while creating a healthier environment for trees and re-establishing natural hydrologic processes such as groundwater recharge and evapotranspiration (Zhang and Guo 2014). For this reason, the hydrologic performance of bioretention systems is often quantified as the portion of runoff generated from the bioretention system catchment area that is prohibited from reaching downstream receiving waters or catch basins (Zhang and Guo 2014). This metric, detailed in equation (1) and known as the Stormwater Capture Efficiency (SCE), has been shown to accurately predict the ability of LIDs to contribute to stormwater quantity and quality control (Zhang and Guo 2013).

$$C_e = \frac{E(v_i)-E(v_0)}{E(v_i)} \tag{1}$$

Where $E(v_i)$ is the expected depth of runoff inflow to the system and $E(v_0)$ is the expected depth of outflow from the bioretention system per rainfall event.

It is important to highlight that while the APM was originally conceived for the purposes of quantifying the performance of open bioretention systems as seen in *Figure 7* and is therefore perfectly suited to model EDTPs. With that in mind, careful consideration has been made to ensure that the model is accurate and effective at modelling the performance of closed ETP systems as well; a few assumptions make this possible. Firstly, while the APM is designed to depict and model a bioretention area with an exposed storage depression where water is stored and eventually evaporated from, infiltrated into the system's soil, or removed through the overflow pipe, it can also be used to describe the storage within a closed structured soil cell, describing the pore space available under the soil, and the maximum and final infiltration rates of the subsurface soils underneath the system responsible for the final exfiltration of the water from the system. This is because it is assumed that in both situations, it is assumed that runoff in either an EDTP and ETP can instantaneously reach the storage area. While obvious for an EDTP, this assumption can be made for ETPs based on the use of highly engineered soil layers within the pit which allows for sufficient infiltration rates which, in comparison to the exfiltration rate at the barrier between the storage layer of the ETP and the underlying soil, is insignificant. In fact, literature is now pointing to the exfiltration rates of LIDs as significant contributors to system performance (Grey et al. 2018b; Y. and Darko 2019). This is why the APM applies to both open EDTP and closed ETP systems.

4.5.2 Theory of derived probability distributions and derived analytical equations

While the equation for C_e above is straight forward, the methods of producing values for $E(v_i)$ and $E(v_0)$ are more complicated. It is first important to understand that the entire APM for bioretention areas and other LIDs put forward by Zhang and Guo (2014) are founded on the assumption that the probability of rainfall event characteristics can be described by the exponential expressions seen in equations (2) through (4):

$$f(v) = \varsigma e^{(-\varsigma v)}, \qquad v \geq 0 \tag{2}$$

$$f(t) = \lambda e^{(-\lambda t)}, \qquad t \geq 0 \tag{3}$$

$$f(b) = \psi e^{(-\psi b)}, \qquad b \geq 0 \tag{4}$$

Where *v, t* and *b* are rainfall event volume, rainfall event duration, and the inter-event dry period, respectively, and *ς, λ, and ψ* are the distribution parameters which are inverse to the mean values of event volumes ($\bar{v}$), duration ($\bar{t}$), and inter-event dry periods ($\bar{b}$).

Once again, the significance of statistically characterizing rainfall events is that they can now be subjected to the derived probability distribution theory. This theory suggests that if the probability of an event is known, then the probability of any other variable that is related to the first variable through functional relationships can be derived as well. Therefore, based on the probability of occurrence of the three rainfall characteristics above, the probability of outputs such as system overflows, and the Stormwater Capture Efficiency (SCE) can be derived based on the functional relationships linking rainfall, runoff, and losses like infiltration and evapotranspiration.

For the purposes of this study, two main equations derived by Zhang and Guo (2014) are required for estimating the SCE of the system. The SCE (C_e) of a bioretention system can be expressed by equation (5):

$$C_e = 1 - \frac{(r+1)C_1C_3[C_2C_4(1-C_5)+e^{(-\psi t_d)}]}{[1+re^{(-\varsigma S_{dc})}]} \tag{5}$$

Where C_1 through C_5 are shorthand expressions defined as:

$$C_1 = \frac{\lambda(r\emptyset+1)}{\lambda(r\emptyset+1)+\varsigma f_c} \tag{6}$$

$$C_2 = \frac{\psi(r\emptyset+1)}{\psi(r\emptyset+1)+\varsigma(E_a+f_c)} \tag{7}$$

$$C_3 = exp\left\{-\frac{\varsigma[r\emptyset S_{dc}+S_d+E(F_{iw})]}{r\emptyset+1}\right\} \tag{8}$$

$$C_4 = exp\left\{\frac{\varsigma E(S_{dw})}{r\emptyset+1}\right\} \tag{9}$$

$$C_5 = exp\left\{-\frac{\psi(r\emptyset+1)+\varsigma(E_a+f_c)}{r\emptyset+1}t_d\right\} \tag{10}$$

In which f_c is the final infiltration capacity of the soil (mm hr^{-1}), S_d is the design storage depth of the system (mm), S_{dc} is the depression storage of the entire catchment (mm), $E(S_{dw})$ is the expected depth of water within the bioretention system left over from the previous rainfall event (PRE) at the onset of the current rainfall event (CRE) (mm), $E(F_{iw})$

is the analytically expected depth of water required to wet the fill media layer (mm), E_a represents the average ET rate during the interevent time (mm hr^{-1}), ∅ is the catchment runoff coefficient (unitless), r is the catchment-to-pit area ratio (unitless), and t_d, shown in equation (11), is the time required to completely drain the system (hrs).

$$t_d = \frac{E(S_{dw})}{E_a + f_c} \tag{11}$$

This definition of t_d (drying time) is logical as it is a matter of how quickly the expected amount of water in the system [$E(S_{dw})$] can be depleted by the processes of ET (E_a) and infiltration (f_c).

One of the reasons that the APM produces results that are so comparable to SWMM continuous simulation runs is that the CRE is not treated like an isolated event as in design-storm based approach. Instead, the PRE and its impacts on the available runoff storage of the CRE is justifiably considered to provide a more accurate representation of the system (Zhang and Guo 2014). For this purpose, the "expected depth of stored water" within the LID at the end of the PRE ($E(S_{dw})$), was derived and can be estimated using equation (6):

$$E(S_{dw}) = \frac{\lambda(r\emptyset+1)^2}{\varsigma[\lambda(r\emptyset+1)+\varsigma f_c]} \exp\left[-\frac{S_{dc}(\varsigma f_c+\lambda)}{f_c}\right][1-\exp\left(-\frac{\varsigma S_d}{r\emptyset+1}\right)] \tag{12}$$

The expected depth of water required to wet the fill media layer E(F$_{iw}$) was also derived and is shown to be:

$$E(F_{iw}) = \frac{Rk(f_m-f_c)\exp(-\psi t_d)}{(\lambda+k)(\psi+Rk)} \tag{13}$$

5. Parametric Sensitivity Analysis of EDTPs and ETPs

Having reviewed the needs of Beasley and Landsdale including the global pressures of climate change, urbanization, and densification and the local needs of community revitalization, runoff reduction and downstream receiving water protection, and equitable and sustainable urban forest protection and promotion; acknowledging the available resources within the community, the current practices surrounding nature-based LIDs and narrowing in on retrofitted ETPs as the best option to meet the economic, environmental, and social needs of the community; and exploring the simulation options available and adopting Zhang (2014)'s Analytical Probabilistic Model (APM) for bioretention systems as the most effective tool; a site-specific investigation was conducted for the purpose of estimating the hydrologic impacts of retrofitting street trees within the Beasley and Landsdale neighbourhoods with ETPs or EDTPs.

As discussed in Chapter 4, the list of considerations and parameters that are involved in determining the rates and extents of the hydrologic processes occurring in ETPs is virtually impossible to fully conceptualize; from meteorological factors such as wind speed, humidity, cloud cover, and temperature; soil parameters such as hydraulic conductivity, porosity, compaction, and grain size; tree characteristics such as general health, species, age, canopy breadth, and the presence of other trees in proximity; as well as the complex interactions between these variables makes calculating the SCE of an ETP an uncertain process. This is clearly displayed in the incredible range of interception, infiltration, evapotranspiration, and runoff retention rates found in the literature and described in previous chapters.

However, while it is impossible to perfectly replicate reality with a model, it is both possible and valuable to describe the hydrologic situation accurately enough – through simplification – to glean information on general system characteristics and performance (Zhang and Guo 2013; Zhang and Guo 2014). Therefore, focusing on the system characteristics discussed in Chapter 4 to be the most impactful to system performance – catchment-to-pit area ratio, design storage depth, soil characteristics such as final infiltration rate, and average rates of evapotranspiration, a sensitivity analysis was conducted to better understand the range of possible impacts of retrofitting street trees in the Beasley and Landsdale neighbourhoods with ETPs. Combined with GIS data, this sensitivity analysis will allow for the establishment of realistic system dimensions and expectations of the specific system performance.

While the APM requires a drastically reduced set of data and parameters relative to continuous or event-based simulation models such as SWMM, it still requires some parametric data.

*Table 5: Parameters required and inputted to conduct calculations using the APM for Bioretention Systems. *Rainfall statistics derived previously for Toronto, Ontario.*

Parameter	**Value (units)**
Average rainfall event volume (v)	9.3 (mm)*
Average rainfall event duration (t)	8*
Average interevent time (b)	128 (hrs)*
Catchment Imperviousness (h)	0.9
Fill media ultimate infiltration rate (f_c)	36 (mm hr^{-1})
Horton's infiltration decay constant (k)	3 (hr^{-1})
Drying time (D)	4 (Days)
Pervious Catchment Storage (S_{dp})	5 (mm)
Impervious Catchment Storage (S_{di})	2 (mm)
Max infiltration rate of media (f_m)	150 (mm hr^{-1})
Average ET rate (E_a)	0.1 (mm hr^{-1})

Table 5 represents an example set of parameters required to run the APM effectively, including rainfall probability characteristics, imperviousness of the area, infiltration rates, storage depth, evapotranspiration rates, and drawdown time. The rainfall characteristics used in this study were determined for the City of Toronto based on rainfall frequency and probability analysis procedures outlined by Guo and Adams (1998) which describe the characteristics with exponential expressions (equations 2-4). While the 100 kilometres between Toronto and Hamilton suggest the use of Toronto precipitation data for a Hamilton study to be unrealistic, the benefit of the APM is that adjusting the rainfall characteristics in the future is incredibly efficient. While most of the parametric values were adapted from Zhang (2014), the pervious catchment storage was increased to 5 mm to account for the canopy storage provided by the trees, the catchment imperviousness was increased to 0.9 to represent the ultra-urban downtown

neighbourhoods of Beasley and Landsdale, the maximum infiltration rate was raised to 150 mm hr^{-1} to align with the findings of observational studies focused on ETPs in other cities outlined above, and the ultimate infiltration rate was set to three values – 6 mm hr^{-1}, 36 mm hr^{-1}, and 66 mm hr^{-1}, relating to the characteristics of three main soil types found within Hamilton, Ontario and found within the literature reviewed (Telis 2001).

5.1 Catchment to Pit Area Ratio

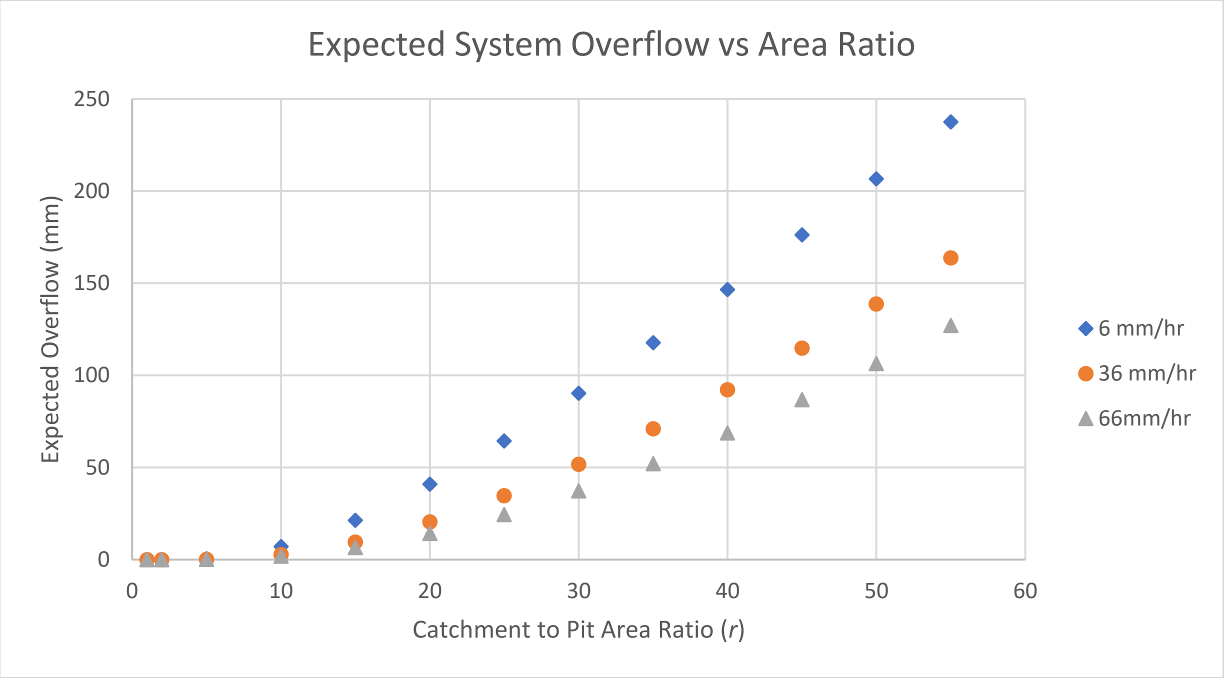

Figure 8: Expected system overflow depth in relation to catchment to pit area ratio of three systems with 150 mm of storage depth, but each implemented with and on three different soil regimes with varying final infiltration rates.

Detailed within many LID design guides and studies (T. D. Fletcher et al. 2015; Raymond et al. 2017; Lukes 2010; Dhalla and Zimmer 2010; Grey 2018), the first parameter explored was the catchment area to pit area ratio; more simply understood as the area of potential runoff-producing area the tree pit receives runoff from relative to its own area. Clearly displayed in *figure 8*, as the ETP deals with relatively larger catchment areas and coinciding runoff volumes, more overflow from the system occurs. It is important to note however, that unlike *figure 9* which speaks to the efficiency of the ETP, the results displayed in *figure 8* do not necessarily suggest the system is less efficient. The SCE of a system is focused on the proportion of rainfall captured, and with a larger catchment to pit area ratio, the pit is taking on proportionately greater depths of runoff; a 25 mm rainfall event over 0.5 km^2 creates 12 500 m^3 of potential runoff while collecting the water of the same 25 mm rainfall event from 1 km^2 would mean considering 25 000 m^3 of water. Therefore, it is possible that while overflow due to this event could be imagined to increase from 25 mm to 50 mm with the expansion of the catchment, the captured runoff also increases from 25 to 50 mm. In that scenario, despite the increase in runoff, the SCE of the ETP remained constant at 50%.

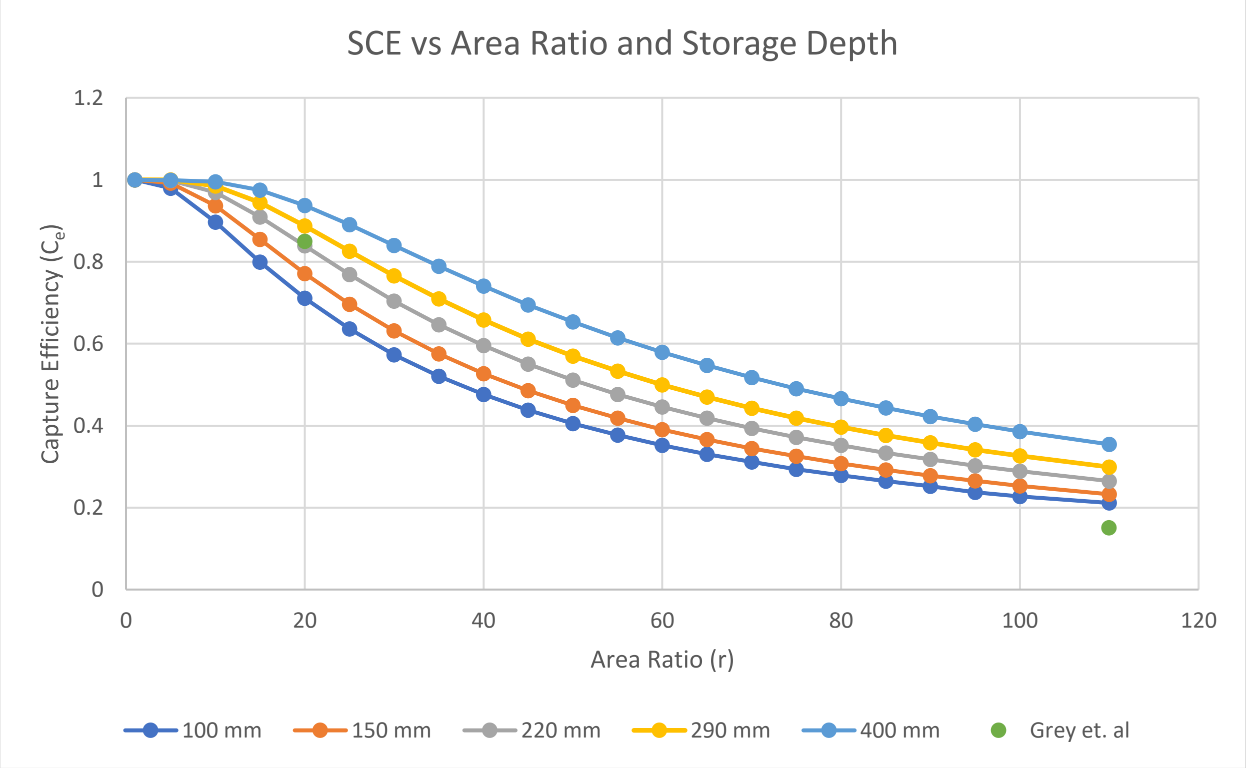

Figure 9: Impact of Area ratio on the Stormwater Capture Efficiency of Enhanced or Extended Tree Pits with storage capacities of 100 mm, 150 mm, 220 mm, 290 mm, and 400 mm relating to the storage depths provided by the three sizes of Silva Cells and two sizes of RootSpace systems; Two proprietary structured soil cell systems.

Figure 9 speaks to what *Figure 8* cannot: As the catchment-to-pit area ratio increases, the SCE does in fact decrease in somewhat of an exponential fashion. To demonstrate the efficient efficacy of the APM, note that the APM results align quite closely with the green dots which depict the results of an extensive continuous rainfall-runoff simulation-based study conducted by *Grey et al. (2018b)*.

Recalling the research of Grey et al. (2018a) highlighting a minimum ratio of 20:1 required to reach an overall runoff reduction rate of 75%, the similarity of the APM results can be appreciated. In fact, Grey et al. (2018a)'s findings (seen as a red data point in *Figure* 2) overlap with the APM model results that suggest a ratio of 20:1 leads to a capture efficiency (runoff reduction) of 76.8%. Furthermore, the findings within the same research suggesting the performance of ETP's with large ratios such as 50 or even 100, are also echoed by the findings of the APM outlining ETPs with ratios close to 100 producing capture efficiencies as low as, if not lower than 25%. With a generally-accepted goal of 75% capture efficiency, it is clear that the APM coincides with the recommendation of Grey et al. (2018a) and other studies to ensure ETPs cover around 5%, and at least 2.5%, of the catchment area (Lukes 2010; Sakshi and Singh 2016; Jia et al. 2016; Baek et al. 2015). Again, the APM suggests this ratio of 20:1 provides a SCE in the range of 77-93% given a reasonable subsurface exfiltration rate, while a ratio of 50:1 only provides a 45% reduction. As one can imagine, while *Figure 10* displays the near perfect efficiencies that can be achieved with 1:1 catchment-to-pit area ratios, retrofitting half of all impervious areas with ETPs would be expensive even if it were possible.

5.2 Design Storage Depth

Figure 9 also depicts the impact of storage depth on capture efficiency. The five storage depths chosen- 100 mm, 150 mm, 220 mm, 290 mm, and 400mm – represent not only realistic values for open EDTPs, but are also the five storage depths calculated in Chapter 4 coinciding with five sizes of proprietary structured soil cells to be implemented in ETPs.

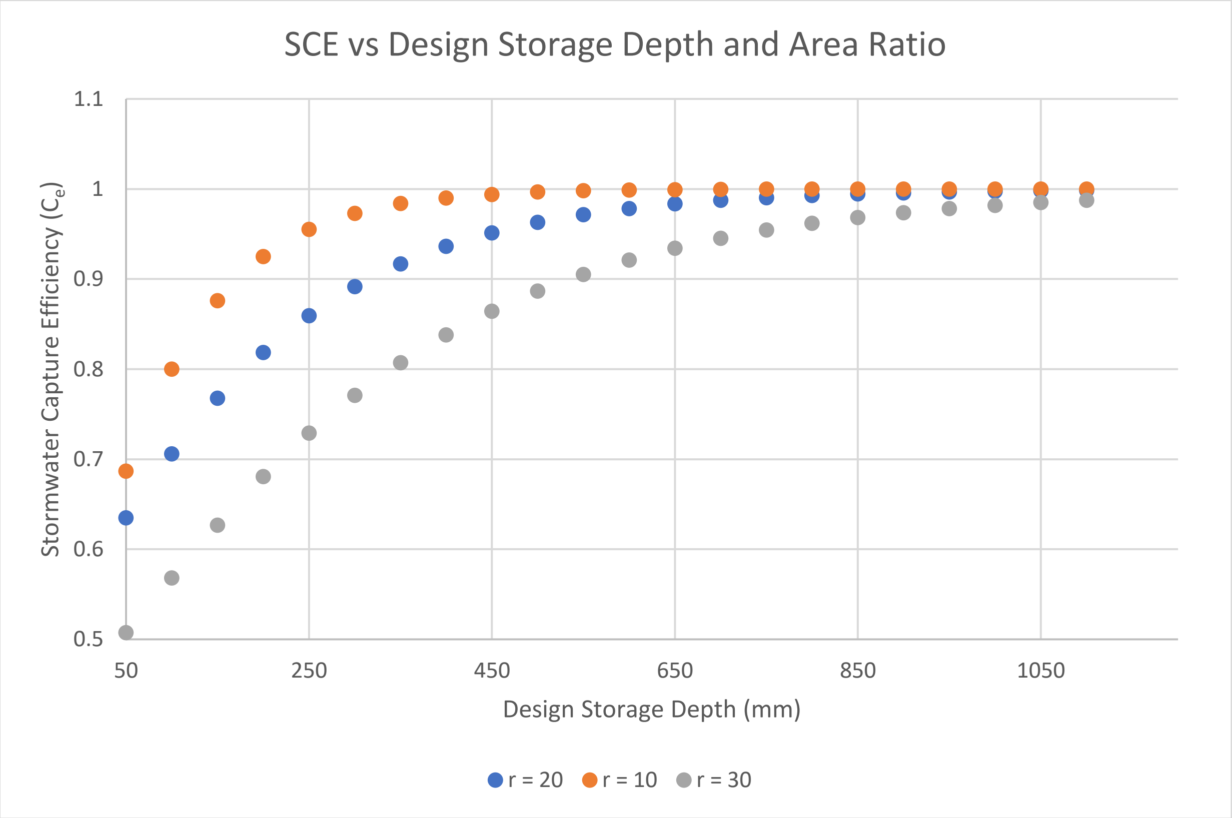

Figure 10: Capture efficiency of three area ratio implementations in relation to the design storage depth of the ETP. As evident, there are logarithmically characterised benefits to increasing the design storage depth of an ETP

Additional insights can be made by graphing the same parameters in alternative ways, as seen in *Figure 10*. While each of the three set area ratios provide decaying returns on increased investment, depending on the area ratio, a system of varying depth can produce drastically different SCEs. For example, a system with 650 mm of storage can sufficiently handle a variety of area ratios. However, this statement is not true for a system with 250 or 150 mm of storage depth. In fact, a 150 mm system can handle a 30:1 ratio about 60% as well as it can handle a 10:1 area ratio. Furthermore, changing the depth of storage from 10 centimetres to a metre increases the capture efficiency by 76%. Within the literature, and suggested by (S. Zhang 2014), the range of storage depths provided by different LID implementations and ETPs is wide. To explore this range of possibilities, a range of depths from 50 to 1100 mm was explored.

This representation of industry norms makes the APM's findings regarding Capture Efficiency of varying depths extremely relevant. As is evident, the steepest slope, and therefore largest relative change in capture efficiency due to depth is seen between systems with a depth of 50 mm compared to those with 250 mm. Directly applied to the structured soil cells, a structured soil cell implementation with a catchment to pit area ratio of 20:1 within the set rainfall conditions sees a change in capture efficiency from 70% to 87% when the smallest size is replaced by the largest.

5.3 Infiltration Rate

While both the maximum and final infiltration rates of the soil are required to run the APM, the APM's utilization of the Horton model of infiltration results in a rapid decay of the infiltration rate after the onset of rainfall events. In fact, the decay to the final infiltration rate occurs so quickly that Zhang (2014) safely assumes that as soon as the CRE begins, the final infiltration rate is reached.

This is why during this investigation of the soil infiltration rate, the final infiltration rate, initially explored in *Figure 8,* was investigated. As with other parameters and evident in the non-symmetric changes in overflow within the three infiltration rates explored in *Figure 8*, the relationship between final infiltration rate and the SCE is not linear. As seen in *Figure 11* below, the largest increases in the SCE come from changes in final infiltration rates from 0 mm hr^{-1} to about 15-20 mm hr^{-1}. Once again, the efficient efficacy of the APM is put on display. Industry standards as well as several case studies have highlighted 15 mm hr^{-1} as a standard cut-off when deciding whether an underdrain is required or not, which aligns well with the marked reduction in capture efficiency increase in systems with infiltration rates above 15 mm hr^{-1}.

With the final infiltration rate highlighted as the most important, it is important to make note of at what layer this final infiltration rate is referring to, in the context of both EDTPs and ETPs. In the case of EDTPs, the final infiltration rate refers to the infiltration rate of the tree pit's surface soil when saturated. On the other hand, with the storage occurring below ground in an ETP in highly permeable soil, the more important infiltration value is that of the sub-ETP soil (Grey et al. 2018b), and therefore the saturated sub-ETP soil infiltration rate, or ETP exfiltration rate, is what is being referenced when discussing final infiltration rates in the context of ETPs. This is safe to assume because the engineered fill media within ETPs have incredibly high infiltration rates that will rarely be the reason water entering the system is slowed. Making this assumption, the storage space within the ETP can be treated as simple depression storage, and the soil directly beneath the system can be treated as the soil layer.

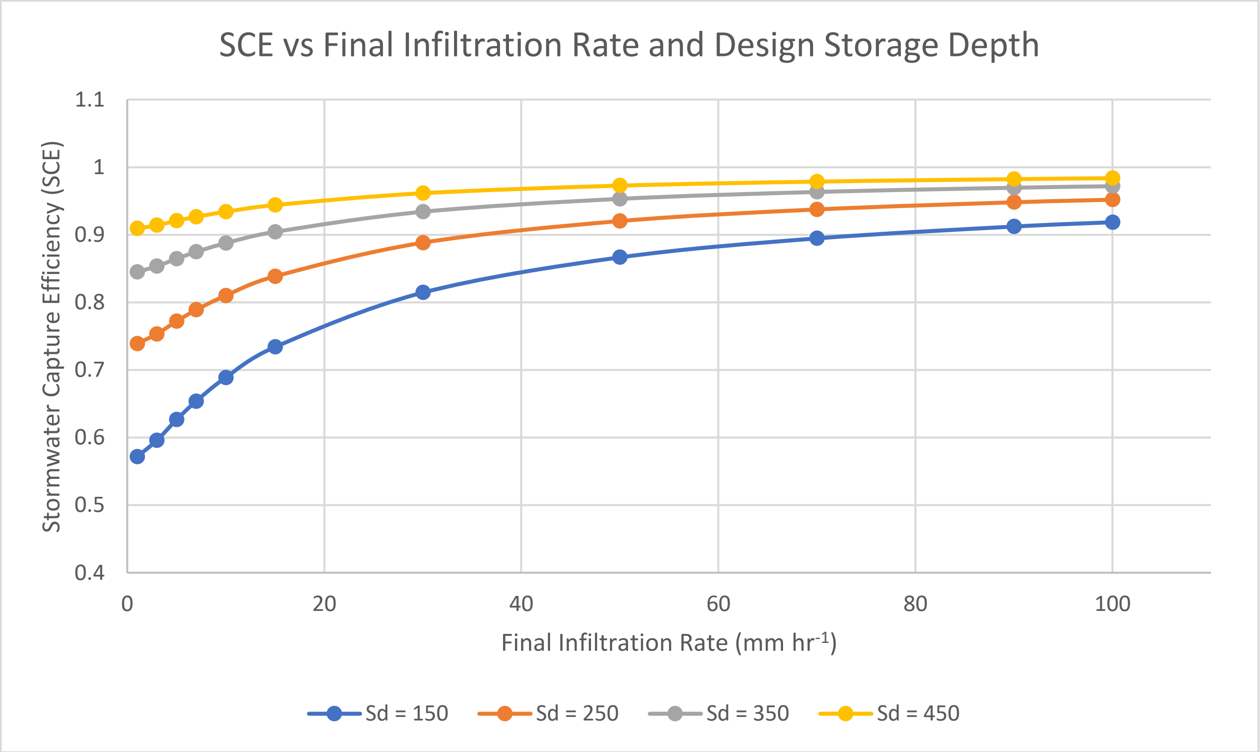

Figure 11: Stormwater Capture Efficiency of four storage depth systems in the context of a range of final infiltration rates.

Within most LID design guides, and especially those focused on the GTHA, 20 mm hr^{-1} is the threshold value for the necessity of overflow infrastructure (Lukes 2010; Palla and Gnecco 2015; Baek et al. 2015); if the final infiltration rate is lower than 20 mm hr^{-1}, the ETP requires an underdrain to ensure adequate drainage and healthy moisture levels for tree growth (Grey et al. 2018a). Interestingly, *Figure 11* shows a marked decrease in slope right around 15 to 20 mm hr^{-1}, putting the APM simulation in agreeance with design guides. In simpler terms, an increase of the final infiltration rates up until 20 mm hr^{-1} is significantly more beneficial to EDTP or ETP performance than the same absolute increase in infiltration rate from an initial rate that is greater than 20 mm hr^{-1}. With this said, it is important to note that this being a guideline, it should be considered as such. For example, an ETP installed in an extremely dry city could perhaps attain high efficiencies with an infiltration rate lower than 20 mm hr^{-1}, while in a tropical or more moist location, 20 mm hr^{-1} may not be enough. Multiple storage depths are also displayed in *Figure 11* demonstrating the different impact the final infiltration rate has depending on the depth of the system. As clearly evident in *Figure 11*, the shallower the system, the more a poor (low) final infiltration value will negatively impact it's performance.

5.4 Average Evapotranspiration

Naturally, the evapotranspiration rate of the ETP would be considered a significant sink of runoff and therefore prove important in stormwater capture efficiency. ET may be conceptualized as upwards infiltration; While infiltration allows water to bypass the sewer system by moving into surrounding soils, ET allows water to bypass the sewer system by moving into the surrounding atmosphere. This process contributes to the drying or emptying of the system between the previous rainfall event (PRE) and the current rainfall event (CRE) to provide the most storage as possible for the CRE. However, supported by research showing transpiration rates can be reduced by 85% by cloud cover (Young

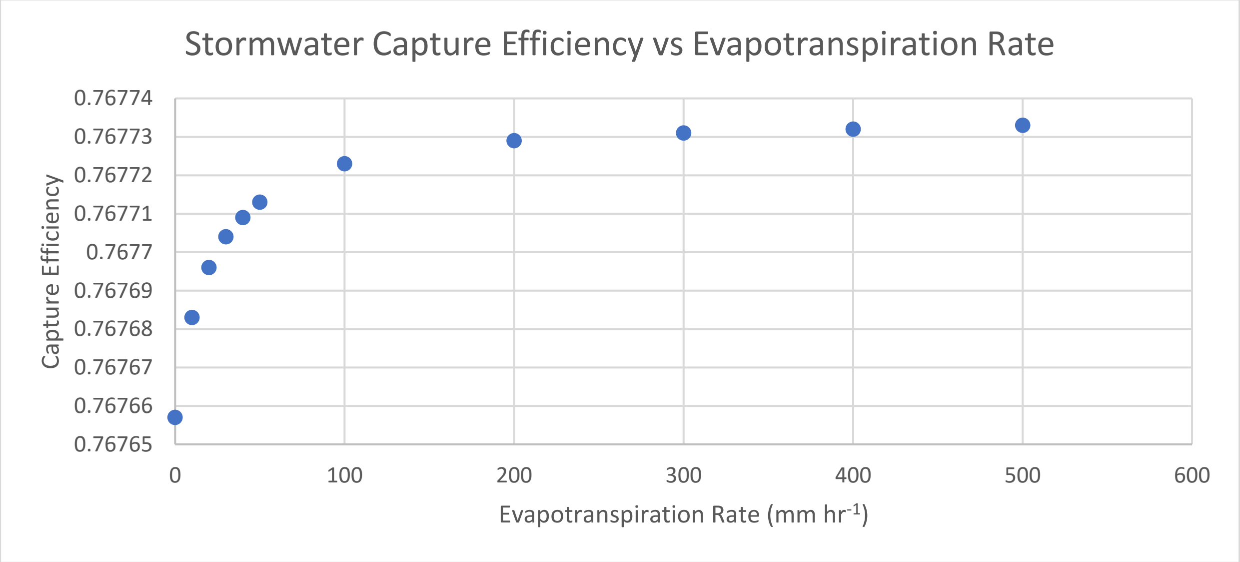

Figure 12: The impact of average evapotranspiration rate on ETP Stormwater Capture Efficiency. The APM suggests increases in ET have a logarithmic, yet negligible impact on SCE of ETPs.

and Smith 1983), the APM put forward by Shouhong Zhang and Guo (2014) assumes that ET does not occur during rainfall events. Therefore, as seen in *Figure 12*, the impact of ET on the SCE of ETPs in this climate are negligible. Only impacting the interevent drawdown time, according to the APM for ETPs, a change in the average rate of ET from 10 mm hr^{-1} to 500 mm hr^{-1} raises the capture efficiency by less than 0.001 percentile. While a low drawdown time is crucial to the efficiency of an ETP, it is situation-dependent. A low drawdown time reduces the impact of the PRE on the effective storage depth of the ETP for the CRE making the relevance of the drawdown time dependent on the interevent time. In this case, with an average rainfall volume of 9.3 mm and a final infiltration rate of 20 mm hr^{-1}, even with an ET rate as low as 10 mm hr^{-1}, the drawdown time of the ETP is only 1.4 hours. This suggests that even in the case of the ETP being at 100% capacity at the end of the PRE, only 1.4 hours will pass before the total design surface depression (S_d) is available to “service” the CRE. Considering again the 128-hour interevent time, one can see why lowering the 1.4-hour drawdown time further has a negligible impact on all but the rarest successive-event occasions.

It should also be noted that the evapotranspiration rates explored here are extremely high rates. As used by Zhang (2014), well represented in the literature, and laid out in Chapter 4, average evapotranspiration rates can be as low as 0.05 mm hr^{-1} and are rarely found to be greater than 10 mm hr^{-1} (Konarska et al. 2016; Ballinas and Barradas 2016; Young and Smith 1983).

5.5 Statistical Analysis and Sensitivity Analysis Conclusions

The sensitivity analysis on the independent impacts of area ratios, ETP/EDTP storage depth, final infiltration rates, and the evapotranspiration rates occurring on the ETP suggest that the catchment-to-pit area ratio has the largest independent impact on the SCE of ETPs. Investigating a range of ratios from 1% to 50%, the SCE was found to increase 296% from 0.25 to 0.99. The APM-based simulation also reinforces the conclusions of observational studies (Grey et al. 2018a) and LID design guides (City of Mississauga 2010; Lukes 2010; Wavin Plastics Limited 2002) highlighting the importance of final infiltration rate on the capture efficiency of enhanced tree pits. A 47.8% increase in SCE from 0.57 to 0.845 was observed when the infiltration rate was increased from 1 to 40 mm hr^{-1}. The design storage depth also had a large impact on the capture efficiency. Within the reasonable range of 100 to 600 mm of depth, the SCE increased 38.5% from 0.71 to 0.98. Finally, the final infiltration rate from 3 to 20 mm hr^{-1} resulted in a 28% increase in SCE from 0.59 to 0.74. While all other parameters had significant impacts on the SCE of the ETP, the average evapotranspiration rate seemed to have no significant impact on the SCE. While surprising, as described above, evapotranspiration rates are negligible during rainfall events and therefore have no impact during the event. With this said, they have been shown to provide significant precipitation losses between rainfall events and this can be seen in the drastic changes in drawdown times coinciding with different evapotranspiration rates, especially in situations with compacted soils (Zölch et al. 2017).

Using one-way analysis of variance (ANOVA) to explore the significance of different parameters on the SCE reinforced the findings outlined above. For example, analyzing the impact of three final infiltration rates- 6, 20, and 36 mm hr^{-1} in the context of five design storage depths- 147, 156, 220, 288, and 401 mm, revealed that while the differences were insignificant when comparing 6 to 20 mm hr^{-1} or 20 to 36 mm hr^{-1}, the difference between 6 and 36 mm hr^{-1} resulted in a significant Holm p-value of 0.042. Investigating the significance of storage depth on the SCE using the same sample populations and procedure provided a similarly significant Holm p-value of 0.045 between the smallest and largest design storage depths and therefore it can be suggested that storage depth has a significant role in altering the SCE of the system.

Using this same technique to investigate the impact of catchment to pit area ratios also reinforces the findings above and solidifies the area ratio as the most significant factor in SCE. While the difference between SCEs within pit area ratios of 1 and 5 and 1 and 10, every other comparison with a ratio of 1 was found to be highly significant with a p-value < 0.01.

6. QGIS-Based Beasley and Landsdale Implementation Scenarios

After establishing a solid understanding of the needs of the Beasley and Landsdale communities, exploring what was already available in the form of street trees and the literature on EDTPs or ETPs as an effective method to meet those needs, and using the APM for bioretention systems to confirm that adequate SCEs rely most heavily on the catchment to pit area ratio, the design storage depth, and the final infiltration rate, a GIS-based investigation into the details of the Beasley and Landsdale neighbourhoods was conducted. This model was used to explore the impacts of different ETP/EDTP sizing and climactic scenarios within the specific context of the Beasley-Landsdale Catchment study area.

6.1 Scenario Development and Configuration

The free, open-source QGIS Global Information System (GIS) application was utilized to explore the plethora of valuable data available to the public through Hamilton's open data initiative in order to estimate the SCE and runoff reductions attained by four different catchment-wide ETP retrofit schemes founded on the use of five different EDTP depression and ETP storage depths and area to pit ratios.

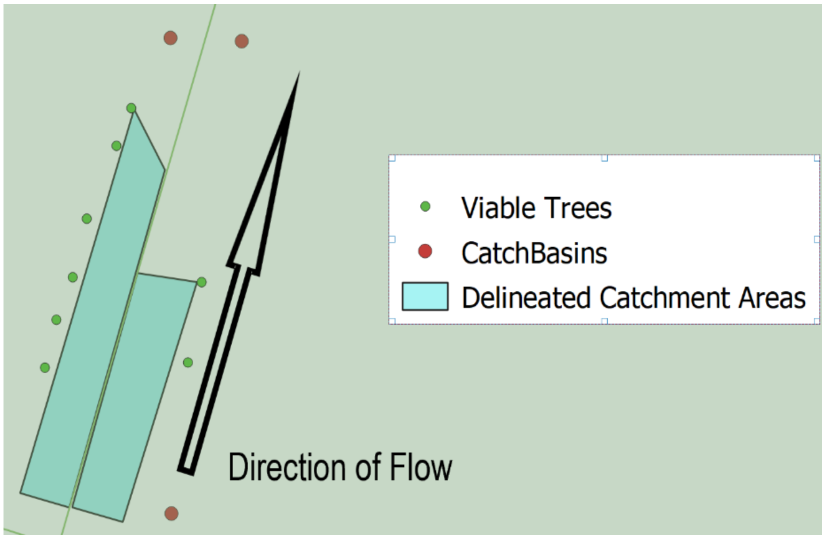

Figure 13: 2 of the 446 delineated subcatchments (blue) in the study area. Delineation was based on knowledge of street slope, location of catchbasins (red), the assumption of no potential of water to cross over street centre lines, and the vicinity of roadside trees (green).

Having already mapped Hamilton's tree inventory in QGIS while establishing the needs of the neighbourhoods in Chapter 3, according to the latest available data- collected in 2009- there are 1094 and 893 trees in the Beasley and Landsdale neighbourhoods respectively. Additional information gleaned from this process was the mean diameter of trees in each neighbourhood: 20.15 cm and 26.33 cm for Beasley and Landsdale respectively. Overlaying Hamilton's publicly available tree inventory on Bing's hybrid map in the proprietary PCSWMM computer program (available to students for free), proximity to the tree, estimations of street slope gleaned from knowledge of the area reinforced by a Digital Elevation Model (DEM) of Hamilton available through the McMaster Library, and the location of 931 catchbasins within the two neighbourhoods, 446 potential subcatchments were established in the two neighbourhoods. These potential subcatchments were created based on the assumption of grading away from the street centreline significant enough to prohibit runoff from ever crossing from one half of the road to the other; it is important to note that “street centre lines” is yet another publicly available dataset within Hamilton’s Open data initiative. Therefore, as shown in *Figure 13,* the catchments begin at the North end of a street as immediately downstream of the previous catchbasin as possible (bottom left of the figure in this case) and extend downstream to roughly parallel with the ultimate street tree. In cases where the street slope was known to be significant, the catchment was tapered from the centreline towards the curb to account for runoff velocity parallel, rather than perpendicular to the street line. Utilizing QGIS’s analysis tools, the mean area of these catchments was determined to be 421.59 m^2.

Figure 14: Subcatchments (blue) with 3m buffer (yellow) and viable and non-viable trees. Of 1937 trees within the Study Area, 1762 were deemed to be ideal candidates to accept runoff from adjacent roads. This was determined based on the trees were within 3 metres of the established catchments.

Field and desktop surveys of the tree inventory data made it clear that some trees, such as those in the middle of a park would not be suitable to be retrofitted with EDTPs or ETPs. As displayed in *Figure 14,* to isolate the truly “available” trees, QGIS’s “Buffer” tool was employed to determine the number of trees within 0.00004-degree minutes -roughly

3 metres – of the road catchment area boundaries. Trees that were within this buffer were trees either immediately beside the road or directly adjacent the sidewalk and therefore were highlighted as retrofit potentials. This process highlighted 1762 trees with a mean diameter of 23.5 cm that were in ideal locations to accept rainfall runoff from nearby roads (*Figure 14)*. Finally, the statistical summary tool within QGIS was utilized to compute that on average, each catchment was surrounded by 4 potential trees.

Therefore, if an assumption is made that the runoff from the average catchment area of 421.59 m^2 is distributed evenly among the, on average, four trees adjacent to each catchment area, it can be calculated that each tree receives runoff from 105.39 m^2 of road.

Table 6: Summary of the Landsdale-Beasley study area details determined by QGIS-based calculations.

Number of Sub-Catchments	Average Sub-Catchment Size (m^2)	Total Trees	Retrofit Potential Trees	Trees per Sub-catchment	Runoff Area per Tree (m^2)
446	421.59	1987	1762	4	105.39

6.2 Area ratio of 20:1

The first scenario investigated was that which saw the retrofitting of every tree with an EDTP or ETP large enough to account for 5% of the total area runoff-producing catchment the tree was meant to “service”. Therefore, referencing the information found in *Table 6*, 5% of 105.39 m^2 is 5.26 m^2 and coincides with a catchment-to-pit area ratio of 20:1. While the area ratio is the most crucial characteristic of the system, as explored in Chapter 5, both the design storage depth and the final infiltration rate of the system are also significant contributors to SCE. Therefore, if a catchment to pit area ratio of 20:1 is specified, 401 mm of storage depth is implemented by the largest structured soil cell size (*Table 4)*, and the final infiltration rate is set to 6 mm hr^{-1} to represent the most impermeable soils encountered in previously-studied ultra-urban environments, a stormwater capture efficiency of 0.90 can be achieved based on the previous sensitivity analysis. With an efficiency as high as 0.9, the first question that can be raised is whether or not the space exists for each of the 1762 trees to be given an additional 5.26 m^2 of open EDTP or closed and concealed ETP. While 5.26 m^2 of open tree pit sounds extensive, it is important to note that normal tree-planting practice within New York City calls for a pit area of 4.5 m^2 (Grey et al. 2018b). While New York City isn’t Hamilton, its 4.5 m^2 requirement within a much higher density environment suggests that an exposed pit area of 5.26 m^2 within the mostly-residential neighbourhoods of Beasley and Landsdale would present minimal issues. To be certain however, Google Earth Pro was utilized to investigate what exactly an area of 5.26 m^2 would look like in the catchment area. As seen in *Figure 15*, an EDTP area of 5.3 m^2 would account for a very manageable portion of the sidewalk area. With all this said, it is important to note that the implementation of ETPs would be unnoticable to the average citizen. The system would simply be inserted beneath the impervious sidewalk, providing extra rooting volume and water storage without depleting the usable area on the surface.

Figure 15: An overlay of a 5.3 m^2 ETDP footprint within the Landsdale neighbourhood was developed using Google Earth Pro and Paint 3D. As evident, the ETDP requires an insignificant amount of the available sidewalk.

Assuming a footprint of 5.26 m^2, a total depth of 1092 mm, and a non-structural ratio of 0.92, the largest structured soil cell option, the large *SilvaCell2*, would theoretically supply each tree with an additional 5.28 m^3 of quality rooting volume. Taking into account that this is additional rooting volume, this implementation strategy would ensure each street tree was provided with much more than the recommended rooting volume of 5 m^3 suggested by Lindsey and Bassuk (1992). The efficiency of this 20:1 system should be a reminder of the significant source of precipitation losses naturally growing trees and forests are and how urban-centric the issue of runoff is. Though this configuration achieves a SCE of 0.90, 5 m^3 of rooting volume is less than half the next recommended rooting volume for trees put forward by Lukes (2010). To reiterate, if a rooting volume of 12 m^3 was achieved using the same structured soil cell, the system's area ratio would be 8.8, and the resultant SCE would be 0.99, suggesting the system would, on average, virtually eliminate runoff; The potential of trees and natural soil volumes to deal with runoff in urban areas needs to be highlighted more strongly.

6.3 Neighbourhood-Scale Results

While exciting, it is important to remember that this SCE figure is speaking only to the rainfall running off from the delineated catchments. For perspective, one should remember that the total sum of these areas, 188 028 m^2 or 0.188 km^2 represents only 8.2% of the total 2.3 km^2 of Beasley and Landsdale, and as such, even an array with an SCE of 0.99 would only capture approximately 8% of the total rainfall runoff from the area. Once concession should be made in this argument, however. It is important to remember that buildings deal with runoff very separately from streets; it is therefore reasonable to excuse EDTPs and ETPs from the responsibility of dealing with roof-sourced runoff that doesn’t have the potential of ever reaching the ETP. This assumption is made based on the reality that the roofs of houses in older residential neighbourhoods as well as developed downtown buildings are almost always directly connected to the sewer system, thereby removing any opportunity for water to be transported from the roof to the ETP/EDTP.

Therefore, using the street centreline data, the total length of road within the neighbourhoods can be determined to be 18 546 metres. Assuming an average width of 12 metres (four, 3-metre-wide lanes), the total road area within the neighbourhoods of Beasley and Landsdale can be estimated at 222 552 m^2. This figure helps depict the impact of retrofitted EDTPs and ETPs. The 188 028 m^2 of potential tree pit catchment area represents 85% of the total road area in the neighbourhoods of Landsdale and Beasley. Therefore, while only capturing 8% of the runoff from the entire area, a regime in which each tree is retrofitted with 5.26 m^2 of ETP area resulting in a stormwater capture efficiency of 0.90 would result in a reduction of road-sourced runoff of 76.5% - a figure that is both not unheard of in case study observations, and not insignificant in terms of runoff reduction potential. Following the same procedure, the SCE of fifteen different scenarios were calculated based on the five structured soil cell depths and three final infiltration rates which can be seen in *Figure 16*. In fact, according to the APM, even if the smallest structured soil cells, which offer only 150 mm of design storage depth were implemented at a 20:1 area ratio, the system would provide a SCE of 0.65, thereby reducing total road runoff by 55%; a figure that is still significant despite not being close to the goal of 75% reduction. Several factors should be noted at this point. Firstly, these shallower structured soil cells aren't designed to be used in tree pit implementations and therefore this figure represents a very conservative estimate of SCE. Even if the investigation was focused on EDTPs, the suggested minimum of storage depth is 300

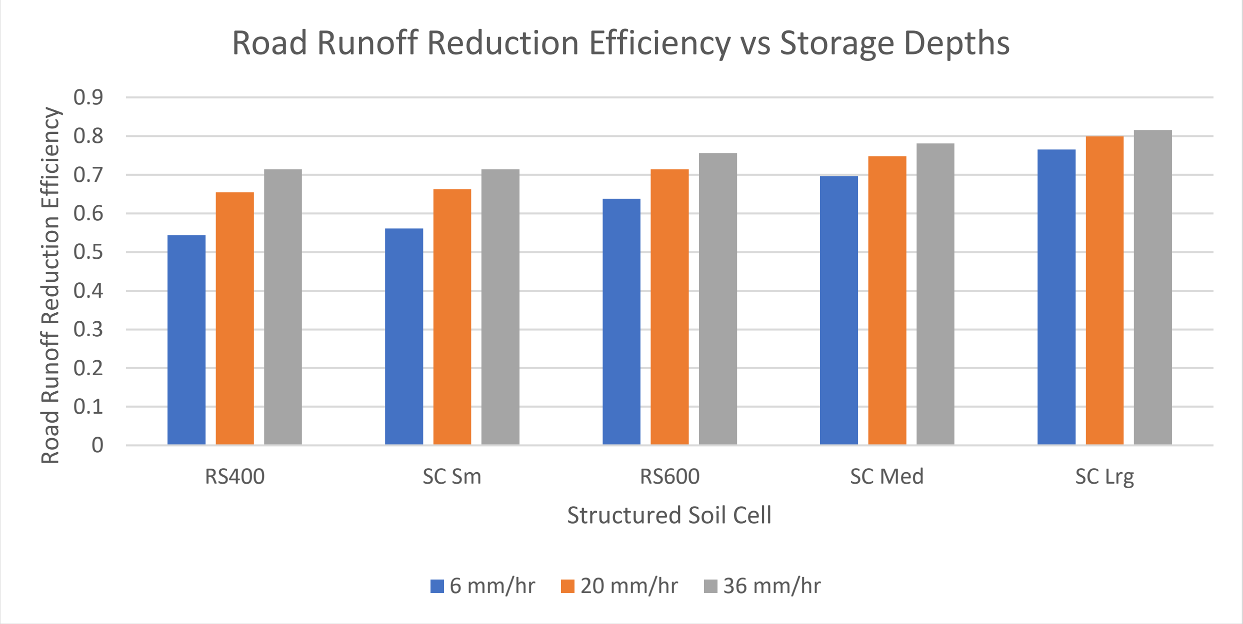

Figure 16: The road runoff reduction efficiency of a 20:1 ratio EDTP/ETP utilizing 5 storage depths and dealing with 3 final infiltration rates. The APM's efficiency allowed for swift calculations of all 15 efficiencies.

mm, in which case the system provides a SCE of 0.83 and a road runoff reduction of 71%. Finally, the final infiltration rate of 6 mm hr^{-1} also represents the lowest infiltration rate observed in hundreds of tree pits. If this figure was raised to the suggested minimum to retrofit without installing an underdrain, the SCE jumps to 0.89, providing a total road runoff reduction of 76%; within the industry accepted range of 75%. What is evident from *Figure 16* is the changing impact of infiltration rate in the context of different storage depths; An increase in the infiltration rate from 6 mm hr^{-1} to 36 mm hr^{-1} for the shallowest cell (*RootSpace 400)* provides a 31% increase in Road Runoff Reduction Efficiency (RRRE) whereas the same infiltration rate increase raises the RRRE by less than a 7%. This suggests that the shallower the system, the more important it is to conduct thorough research on the soils within the proposed system. It should also be noted that smaller structured soil cells offer less than ideal rooting volume improvements for trees. In the case of using a catchment to pit area ratio of 20:1, the retrofits would only provide 2.7 m^3 of additional rooting volume which leaves the tree far below the threshold of 5 m^3 of healthy rooting soil.

6.4 Climate Change and Seasonal Variability

One of the most emphasized points within the ASCE's *Roadmap* is the need to abandon assumptions of stationarity and develop systems and solutions based on more than one stationary criteria. The impacts of Climate Change and the coinciding seasonal variability on the RRRE of the EDTP and ETP implementation scenario was investigated.

As mentioned previously, the strength of the APM begins in its regard of rainfall events statistically rather than historically. This is so important while investigating Climate

Change and seasonal variability because it makes altering the system inputs incredibly easy. Because the APM deals with average system performance statistics, instead of having to conduct model downscaling and detailed application of rainfall distribution changes in continuous modelling inputs, the APM requires only simple adjustments of the three rainfall statistics. For example, in the Hamilton area, Climate Change is expected to increase the frequency of precipitation events within the winter months. Firstly, it should be understood that making this adjustment in a design-storm scenario is impossible as design storms are independent events with an assumed lack of connection to previous or subsequent rainfall events. Furthermore, even in the context of continuous simulation, the modeller would have to tediously manipulate the rainfall data, perhaps by manually shortening the duration between what they deem to be events. On the other hand, using the APM for LIDs, the user simply must adjust the

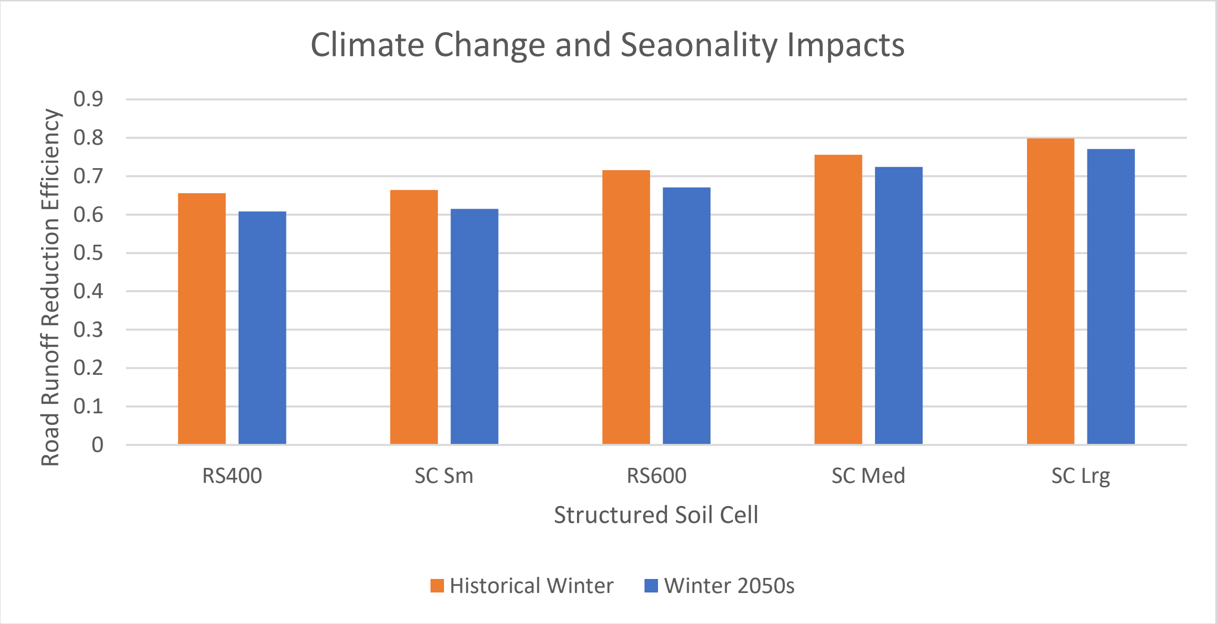

Figure 17: Road Runoff Reduction Efficiency results provided by five pre-fabricated structured soil cells in the context of changing climactic conditions.

interevent duration statistic (relayed in number of hours) to fit climate change predictions.

To demonstrate the ease of this process, the proposed retrofitted ETPs/EDTPs within Beasley and Landsdale were subjected to what are generally accepted climactic changes in the Hamilton area over the coming decades. While the area ratio and final infiltration rates being kept constant at 20:1 and 20 mm hr^{-1} respectively, the average rainfall depth was increased by 12%, from 9.4 mm to 10.96 mm to reflect the 12% increase in total rainfall expected by the 2050s. The interevent duration was also manipulated, being halved from 128 to 64 hours to reflect the expected increase in total and consecutive wet winter days in the 2020s, 2050s, and 2080s in comparison to the historical norms within the 1960-2011 data discussed in Chapter 3. Finally, the focus of this scenario being a winter within the 2050s, the depression storage of the pervious area was reduced from 5 to 2.3 mm in both the "Historical" and "2050s" scenarios to represent the absence of foliage.

Table 7: Summary of Climate Change investigation results utilizing the efficient APM technique. The larger the system, the greater its resilience to changing climactic circumstances.

Soil Cell	Historical rainfall-based RRRE	Winter 2050s RRRE	Efficiency Reduction (absolute)	Efficiency Reduction (%)
RS400	0.66	0.61	0.05	7.3
SC2 Small	0.66	0.62	0.04	7.4
RS600	0.72	0.67	0.05	6.3
SC2 Medium	0.76	0.72	0.04	4.1
SC2 Large	0.80	0.77	0.03	3.5

As expected, and clear in *Figure 17*, the APM for ETPs predicts the RRRE to be reduced within the context of future climactic conditions, independent of the depth of storage implemented. However, the amount the RRRE decreased was definitely impacted by the storage depth. As outlined in *Table 7* below, while the shallowest implementation experienced an efficiency reduction of five points, the deepest only experienced a two-point reduction. Furthermore, within the context of their original efficiencies, the five-point reduction represents a 7% efficiency reduction for the small system in comparison to a 3.5% reduction resulting from the two-point efficiency reduction for the largest system.

7. Conclusions

7.1 Following the ASCE's Roadmap to Sustainable Development

First and foremost, this research set out to apply the mandates set by the American Society of Civil Engineers (ASCE) in their *5-year Roadmap to Sustainable Development* in the context of stormwater management engineering research.

By reviewing the needs of cities around the world for solutions to Climate Change and urbanization, as well as the more Landsdale- and Beasley-specific needs of downtown revitalization, receiving water protection, and a sustainable method of rejuvenating the urban forest, it was ensured that the *Right* project was initiated.

Gleaning information from an in-depth literature review and meetings with climate change and sustainability-focused municipal employees and local organizations such as Environment Hamilton, Trees Please, and the Hamilton Conservation Authority; making use of the invaluable geographic, demographic, social, and physical data now available through The City of Hamilton's Open data initiative; processing and analyzing this data with the free, open-source QGIS; focusing the research on retrofitting ETPs/EDTPs to already-available street trees; exploring the plethora of hydrologic modelling tools now available; and considering the environmental, social, and economic impacts of the project, ensured that all the best resources – computational, physical, natural, intellectual – available were used, and the project was “done *Right*”.

Ignoring the status quo of design storm-based engineering design and utilizing the statistically-based and dynamic APM to explore a number of situations, including the impact of climate change on the implementations, ensured the sustainability of the solutions in the reality of changing conditions.

Adopting a holistic approach to the project, accounting for Climate Change, urban planning, environmental and social consequences, and collaborating in cross-sectoral partnerships during the project worked to “transform” the skill set of the researcher and set an example for engineers to move toward a place of comfort in being, as the ASCE suggests, a combination of, “master builder, steward of the environment, innovator, manager of risk, and leader in public policy.” (ASCE 2018).

Finally, the ASCE demands engineers use their voices to disseminate knowledge and understanding regarding the importance of sustainable development in the context of global and local issues. To satisfy this requirement, highschool youth enrolled in the Pathways to Education program were engaged in a tree-data collection workshop and encouraged to discuss topics of climate change, sustainable development, stormwater management, and the vital role natural infrastructure plays in the context of each of these. Furthermore, this research was presented formerly at the International Conference of Water Management Modelling (ICWMM), during McMaster’s Three Minute Thesis competition, at a WaterCRESS seminar designed to introduce academic research to the public forum, McMaster University's Civil Engineering Graduate presentation day, and during a thesis defense open to the public. The next step in communicating and promoting the importance of sustainable development is the submission of this report to the City of Hamilton to serve as a recommendation to investigate in detail, the potential of applying this theoretical exploration to the context of reality.

The largest shortcoming of this research regarding the application of *the Roadmap* could be found in the lack of collaboration with municipal divisions and partners to produce tangible, physical results and implementations, as well as the lack of more in-depth community engagement. Once again, the ASCE's mandate for engineers to become "leaders in public policy" requires an investment not only into computational research but also a significant investment into social circles and civil societies. If stormwater management systems are to become truly sustainable, all members of the community must be aware and knowledgeable of, if not involved in, the ongoing processes and this research, while successful in briefly discussing with city departments and local NGOs, failed to address and communicate with the larger community in order to establish the social needs and opinions regarding SWM.

7.2 Meeting the needs of Beasley and Landsdale through Retrofitted ETPs/EDTPs

Two of Hamilton's inner-city neighbourhoods, Beasley and Landsdale are in need of an initiative to spark revitalization and instil a sense of community and hope. As well, additional steps need to be taken to reduce the rainfall runoff entering the sewer system in order to reduce the pollution of Hamilton Harbour in the context of urbanization and climate change. Coincidentally, research suggests a healthier urban forest, which is already a priority of Hamilton, lends itself to meeting both needs. Therefore, the equitable and sustainable establishment of a healthy urban forest within the Beasley and Landsdale neighbourhoods was established as the third major and inter-connected need this project was aiming to address.

Ample tools, data, and research available on nature-based solutions to stormwater management and urban forests pointed to retrofitted extended-depressed and enhanced tree pits as a means to both significantly improving the health of urban street trees, thereby increasing the many social and economic ecoservices provided to the community, and also significantly reducing rates and volumes of runoff. Retrofitted ETPs provide such an ideal solution to each of the three needs of trees in Beasley and Landsdale; increased rooting volume, access to more water, and sufficient infiltration rates produces healthier trees which revitalize individuals and businesses alike (Nowak 2015); increased rooting volume, access to water, and increased infiltration rates for trees in the Beasley and Landsdale neighbourhoods would provide significant additional stormwater storage and pollution reduction capabilities leading to less Hamilton Harbour pollution; and this all works because rooting volume, access to water, and infiltration rates are the most important parameters to tree health in urban environments (Ow and Ghosh 2017).

Making use of the efficient and effective Analytical Probabilistic Model developed by Shouhang Zhang (2014) to evaluate the hydrologic performance of bioretention systems, the computational and analysis capabilities of the open-source QGIS, and information from DeepRoot Inc. and GreenBlue Urban regarding prefabricated structured soil cells, fifteen treatments were efficiently simulated. It was estimated that if each of the specified trees was retrofitted with 5.26 m^2 of either EDTP or structured soil cell ETPs and the final infiltration rate for the ETPs/EDTPs was assumed to be only 6 mm hr^{-1}, runoff entering the sewer system from the roads within Beasley and Landsdale would be reduced by 54% if the smallest depth of 147 mm were to be utilized and almost 77% if the largest depth of 401 mm was utilized. As discussed briefly, it is important to note that these figures refer to the depth of runoff sourced from the road surfaces only. When placed in the context of the entire catchment areas, these figures drop to 5.2% and 7.9% for the small and large installations respectively.

With the aim of this project to not only provide water storage, but additional rooting volume and promote the health of the trees themselves, it should be noted that ETPs, rather than EDTPs be explored as the EDTPs have no impact on the rooting volume or the soil used. However, both do provide water to the often drought-facing street trees. In fact, servicing an average catchment of 105 m^2 with a 0.9 SCE, each tree would receive about 879 Litres of water during an average rainfall event of 9.3 mm, more than satisfying the need to supply street trees with more water. While the implementation of EDTPs would not guarantee Furthermore, it should be noted that in the context of the previously highlighted literature citing a requirement of some trees for over 30 m^3 of rooting volume, none of the implementation scenarios came close. While larger rooting volumes would never be the wrong answer environmentally, both socially and economically, there are limits. Firstly, the largest *SilvaCell* has a total depth of 1.092 metres. Therefore, in order to meet a requirement for 30 m^3 of rooting volume, each retrofit would require a 27.5 m^2 footprint. While these installations do not deplete surface space, electrical, communications, natural gas, and water distribution lines entering and exiting buildings create an extremely dense grid of “unavailable” space; The smaller the footprint, the more feasible the ETP project is. With this in mind, Grey et al. (2018a) and Lindsey and Bassuk (1992) suggest rooting volumes of 5-6 m^3 are more than sufficient in urban environments. Furthermore, it is valuable to remember these are ETP retrofit scenarios; the specified volumes are in fact the volumes being added to the original, already-established rooting volumes. Remembering this, it is clear that all but the smallest structured soil cells would provide significant benefits to the trees and subsequently the communities and natural environments they are located within.

8. Possible Future Research

8.1 Shortcomings and Lessons for Future Research

8.1.1 Model Assumptions

Making use of what was available, the Analytical Probabilistic Model for Bioretention areas was proven to be an efficient tool to establish system performance of a single bioretention area. Founded on probability and useful due to its efficiency, it was decided that the area statistics would be summarized into averages in order to preserve the computational efficiency of the APM. With that said, there are several assumptions required to make this possible that must be acknowledged. Firstly, the lack of rainfall statistics of Hamilton meant that the statistics for mean event volume, event duration, and interevent time for Toronto, Ontario were utilized. For perspective on the potential impacts on the performance metrics produced by the model, Toronto experiences 785 mm of annual rainfall whereas Hamilton experiences 6.4% more at 835 mm annually. One way to deal with this difference would be to simply raise the mean event volume by 6.4% from 9.3 to 9.89 mm. For perspective, if this were done utilizing the medium SilvaCell, the road runoff reduction efficiency would be reduced from 74.8% to 74.0%. However, while it could happen that Hamilton experiences 6.4% more voluminous rainfall events but experiences the same number and length of rainfall events interspersed by equally long interevent periods as Toronto, this is highly unlikely. What is more reasonable to assume is that it is a combination of event intensity and length that leads to this increase, which would impact each of the three rainfall characteristics utilized. It was determined most wise, therefore to simply use the unadulterated characteristics for Toronto. What is important to note is the incredible ease at which new results could be obtained given the production of Hamilton rainfall characteristics. Having only to change Excel cell values to produce the new SCE, it would be incredibly easy to run the Hamilton calculations once they are produced.

In the context of adapting to different statistics, the APM is not only incredibly deft at efficiently calculating system performance of different cities, it would also be incredibly well-suited to investigate the impacts of Climate Change on the system performance. Utilizing available data on the way in which climate change will impact rainfall event characteristics, the APM can quickly summarize the system performance. This makes the APM and incredibly useful and resilient tool in the context of the ever-changing climate the world finds itself in now.

Another note should be made regarding the assumed final infiltration rates. As discussed in Chapter 4 and 5, the variability in infiltration rate measurements in urban areas due to various levels of soil compaction can be significant. With no ability to take measurements in the study area, the final infiltration rate was set to three different values – 6 mm hr^{-1}, 20 mm hr^{-1}, and 36 mm hr^{-1} – representing the lowest observed infiltration rate in a field study exploring tree pit infiltration in New York City, the minimum suggested final infiltration rate required to forgo underdrain installation while maintaining its ability to promote tree growth, and a the mean infiltration rate found in the study mentioned above (Elliott et al. 2018; Grey 2018).

On the topic of precipitation losses, the evapotranspiration rate was assumed to remain at 0.1 mm hr^{-1} during the inter-event time. Rates of evapotranspiration are dependent on rates of radiation from the sun, temperature, humidity, and windspeed among other factors, this modest rate was chosen to ensure a conservative estimation and more importantly, because the evapotranspiration rate was found to have a negligible impact on the SCE independent of how large or small it was. This occurrence highlights an important consideration when understanding literature that suggests evapotranspiration can be responsible for up to 80% of precipitation losses in urban areas (Rahman, Armson, and Ennos 2015). This statistic can be understood as pointing out the general lack of sources of precipitation losses in urban environments. Finally, it should be acknowledged that while interception is considered in a very general way by the APM, being depicted simply as a source of depression storage, this depiction is in fact quite an accurate representation of the interception process and therefore the model is sufficient in this regard. With this said, the assumed values of both evapotranspiration and interception could be interpreted as conservative. The benefit of a model underestimating rather than overestimating the impacts of evapotranspiration and interception on the SCE is that one can easily conclude the figures produced are conservative estimates of the true potential of ETPs to effectively contribute to SWM systems.

The assumption was also made that there was no ETDP/ETP entrance inefficiency. The APM equation does not consider individual cases where, for example, the velocity of runoff is too great to make the 90-degree turn through the curb cut and into the EDTP/ETP. Along similar lines, no details regarding the sidewalks and how they differ from road surfaces in each of the catchments were acknowledged in this study. With this said, it should be clear that this was in no way a design experiment that took into consideration specific site conditions, but an evaluation of the potential held in retrofitted ETPs in the study area. Naturally, in the next phase of the study, more specific considerations of street slope and tree location would be required to speak to the specific design of the 446 catchment areas highlighted in this study.

It should be noted that assumptions are inevitable and necessary within modelling research – especially when pertaining to a topic as variable as rainfall runoff. Though irresponsible to utilize these findings for design purposes, the goal of this case study being to evaluate the potential stormwater capture efficiency of retrofitting ETPs across the Beasley and Landsdale neighbourhoods, the responsible acceptance of the limitations of the assumptions outlined above allowed for the production of informative estimates meant for preliminary investigations.

8.1.2 Traditional Standards

When given time to process it, the requirement of the ASCE to, “abandon traditional standards” is quite a serious charge indeed. While effort was made to “abandon” traditional methods of research and engineering, it is often a difficult and uncomforting process to do so. For example, one of the largest shortcomings was the lack of collaboration involved to produce this research in the context of the ASCE’s guideline to integrate and collaborate with as many stakeholders as possible. While meetings were held with city departments and locally-based organizations, and a group of high school students was engaged in the data collection process, no effort was made to involve those currently living within the study area as originally planned or to collaborate with industry partners working on similar projects, as was hoped. If a lesson can be learned from this experience, it is the effort required to establish a truly collaborative relationship. For example, while meetings were held and ideas were discussed with the city of Hamilton, the sectored nature of municipal departments and other organizations was evident. One meeting I had the privilege of participating in involving multiple departments discussing the implementation of additional street trees highlighted how differently each stakeholder understood the other's responsibilities and key concerns. While this negatively impacted the ability to collaborate with multiple departments within the City, it should be taken as a reminder that perhaps the most necessary work to be done regarding Sustainable Development as an engineer is that which consistently brings different organization departments, professional disciplines, and societal sectors together in order to increase cross-sectoral understanding and promote collaboration.

Furthermore, when applied to engineering research, the ASCE asks the researcher to tread a very fine line between being too focused on a topic to have an audience and being too general to have the audience care about what is being said. This was a difficult balance to find and it often seemed that the research was alternating between these two extremes.

8.2 The Value and Dangers of Online Resources

The large and integrated scope of this research exposed the shear amount of information and tools openly and instantly available to researchers and engineers alike. With a click of a mouse, and about a minute of loading time, hundreds of thousands of data points attributed across hundreds of thousands of trees in Hamilton can not only be accessed and secured, but visualized and analyzed to determine the heights, diameters, species, locations, densities, health, etc. of trees without the researcher using a single instrument other than a computer, and perhaps without stepping outside. The same goes for hydrologic calculations that can be processed iteratively for millions of time steps – a process that would take many human lifetimes to compute by hand – within a matter of hours, if not minutes. General demographics and characteristics of neighbourhoods can also be easily acquired and overlaid on high-resolution satellite imagery and investigated using the powerful QGIS application to produce accurate representations of said neighbourhoods without ever visiting them. With the power of analytical probabilistic models, remotely collected rainfall data can be quickly transformed into performance statistics of LID implementation. Finally, online publishing of journals and reports from an increasing number of researchers and organizations from around the world that can be accessed through the Online McMaster Library make it difficult to not find a necessary statistic, detail, or observation, all without having to turn a single page or visit a library.

While this overflow of data, available resources, and computational tools has prompted incredible growth in every sector, including that of SWM research over the last two decades or so, this data-centred approach has also created an immense requirement and need for high-quality data and the responsible use of it. This is perhaps the largest shortcoming of this research. With initial plans to contribute valuable real data on natural infrastructure with potential to contribute positively to the hydrological regime in the Beasley and Landsdale neighbourhoods, this research is yet another example of innovative creation of information and data rather than inventive.

8.3 Exploring ETPs to promote Stormwater and Urban Resilience

The focus of several SDGs and the ASCE's *Roadmap to Sustainable Development*, *Resilience* is a concept describing the ability of a system to adapt to, recover from and mitigate the negative impacts of changing and unknown stresses. SWM engineers now realize that traditional assumptions of a static environment and constant rainfall patterns leave little room to consider the impacts of inevitable upstream urbanization, ever-increasing usage rates, pollution sources, and imperviousness, or the reality of these changes being backdropped by a significantly altered and continuously varying meteorology (Semadeni-Davies et al. 2008; Razavi et al. 2016; Dong, Guo, and Zeng 2017). This oversight can be seen in countless examples from around the world, including a number within Canada (Grahn and Nyberg 2017; Powers 2013; H. E. Lee and Kim 2017; Dhakal and Chevalier 2016; Roodsari and Chandler 2017; Nie 2015; Czajkowski et al. 2018). In contrast, a resilient perspective assumes the environment *will* change and system failures are *inevitable* (Dong, Guo, and Zeng 2017). Instead of focusing only on resisting SWM failures and resulting floods, resilient SWM aims to effectively manage failures and floods when they inevitably occur, while acknowledging the impacts of SWM on the societal, environmental, and economic systems it is inextricably linked to (Razavi et al. 2016; Willuweit and O'Sullivan 2013; Zhou 2014).

While the quantification of stormwater resilience has been highlighted as an important step to ensuring cost-effective design, its cross-sectoral nature and assumptions of non-stationarity make it quite difficult to objectively measure (Martínez-Cano et al. 2014; C.K. et al. 2015; Hussam and Akshat 2017). One of the more basic methods of adding and quanitfying stormwater resilience found in the literature is to highlight the addition of “redundant” storage or runoff retention provided by the LID implementation. For example, if the traditional SWS was successfully designed to meet standards of dealing with 25 mm storm events and the ETP implementation provided an additional 5 mm of storage, then the ETP could be seen to provide 20% redundancy to the stormwater system and therefore it could be argued 20% resilience was added to the system (Mohammad and Zahra 2017; Nie 2015). However, the issue with this common approach is that it has the potential to erroneously rely on the assumption of stationarity that the concept of resilience and the ASCE so strongly opposes; naturally, if current meteorological conditions are maintained and 25 mm still accurately describes the 90th-percentile storm the SWS was designed for then yes, redundancy and therefore resilience of the system is still 20%. However, from the perspective of non-stationarity – on which resilience is founded and climate research points to – the extra 5 mm of storage may very well become necessary storage rather than extra or redundant storage, thereby changing the apparent resilience of a system, while the very definition of resilience is the way in which a system can respond to unexpected stimuli and inevitable failure, not necessarily predicted increases in rainfall. Therefore, one should be careful in using the concept of stationarity to define a characteristic based on non-stationarity.

This dynamic nature of resilience which makes it so difficult to quantify is one of the reasons countless peer-reviewed articles outline the potential of GI and NBLID such as ETPs to better deal with uncertain future operating conditions sustainably than traditional SWM (Nie 2015; Wongsa et al. 2018; Eckart, McPhee, and Bolisetti 2017; W. Liu, Chen, and Peng 2014; Wild, Henneberry, and Gill 2017; Mal et al. 2018; Joksimovic and Alam 2014). As discussed in a variety of ways above, trees- their roots, branches, leaves, etc

– and the soil they grow in are incredibly dynamic systems and can change drastically over time. Because of this, ETPs have a much greater potential to adapt to changing weather than traditionally concrete, figuratively and literally, SWM features. To reiterate, depending on the amount of water received, a tree can grow up to twice as quickly. As this occurs, a tree can provide orders of magnitude increases of interception (Xiao and McPherson 2016; Huang 2016) and ET losses (Black, Nnyamah, and Tan 1980; Pataki et al. 2011); as roots expand further into the ETPs, infiltration rates can be similarly bolstered (Elliott et al. 2018; Kuehler, Hathaway, and Tirpak 2017; Bartens et al. 2008); Finally, inline with the ASCE's acknowledgement of resilience being a cross-sectoral concept, the healthier, faster-growing tree canopies lead to increases in other ecoservices such as air quality, urban heat island mitigation, street beautification, energy cost reduction, and habitat creation (Kuehler, Hathaway, and Tirpak 2017; Burden 2006; Mullaney, Lucke, and Trueman 2015).

While virtually impossible to objectively quantify a concept based on non-stationary principles, this seems to provide reason to use a solution that is, in the same way, non-stationary, always adapting to the inputs of its environment and surroundings. Therefore, while installation of ETPs would provide redundant storage volumes and quantification of this stationarity-based conception of resilience would result in figures in support of their installation, with the characteristic of true malleability, ETPs can also satisfy the unknown, yet incredibly important requirements of non-stationarity-based resilience.

8.4 Next Steps

As previously outlined and in accordance with the ASCE's mandate to promote sustainable development, the next steps of this research will be to present the findings to the City of Hamilton and advocate for the consideration and investigation into the implementation of enhanced tree pits as a step Hamilton can take toward sustainable development.

As for future research within this field, the APM is an extremely capable tool and an obvious next step would be to establish an equation that involved evapotranspiration and interception more than it currently does. Furthermore, an obvious need is rainfall characteristics for the Hamilton region.

What is absolutely necessary, however is research that steps outside the boundaries of traditional academia and is involved with the wider world around it. This research exposed the sectoral nature of the research and engineering world and therefore the most beneficial research would be paired with industry partners working to collaborate with various city departments and NGOs to approach projects with a needs-centred perspective, making sure to utilize every connection, every tool, and every piece of natural infrastructure available in order to create a more collaborative and sustainable future.

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