Sustainable Stormwater Management: Protecting Peterborough's Harper Creek Through Effective Policy and Priority Placement of Rain Gardens

Includes:

Final Report

By

Emily Amon

Completed for: Peterborough GreenUp

Supervising Professors: Tom Whillans, Stephen Hill

Trent Community Research Centre Project Coordinator: David Tough

Department:	Environmental and Resource Science and Studies
Course Code:	ERSC 4830Y
Course Name:	Subwatershed Permeability
Term:	Fall-Winter
Date of Project Submission:	April 2017
Project ID:	

Trent Community Research Centre

www.trentcentre.ca

Sustainable Stormwater Management:

Protecting Peterborough's Harper Creek Through Effective Policy and Priority Placement of Rain Gardens

Photo taken by Peterborough Field Naturalists

Emily Amon
0553610

ERSC-4830Y

Community Based Research Project

Bachelor of Environmental Sciences and Studies

Submitted April 2017

Supervised By: Dylan Radcliffe & Heather Ray (Peterborough GreenUp)
Tom Whillans & Stephen Hill (Trent University)
David Tough (Trent Community Research Centre)

Acknowledgements

It is with tremendous pride and support that I conclude this yearlong research process, and present my findings in this report. Community based research is necessarily a collaborative endeavour between students, organizations, supporting professors, and community members. Although much of this research process was completed independently, the success, and recognition this project has received would not have been possible without the ongoing contributions, feedback, and guidance of my informal committee of professors, host organization liaisons, and notable community advocates.

This focus of this project was conceived collaboratively between myself, Dylan Radcilffe, Heather Ray, Tom Whillans and Stephen Hill in August 2016, and was meant to support GreenUp's efforts to address downstream water-quality impacts of stormwater runoff, and flood risks in urbanized subwatersheds within Peterborough. I would like to thank Heather Ray and Dylan Radcliffe for their support and guidance from GreenUp in defining the scope of this project, and offering valuable reference guides and feedback wherever possible. I would like to thank Tom Whillans for helping to round out my research goals and methodology, and Stephen Hill for providing invaluable policy support and feedback. I wish to offer gratitude to two other professors: Jim Buttle for contributing hydrology guidance, and Rob Loney for his assistance with GIS integration. Thank you also, to Kim Zippel for the community advocacy she spearheads for Harper Park, and for supporting this research and lending her vast knowledge and resources throughout the entire process. There are a number of other individuals who have helped me along the way with resources, and guidance. Thank you to Tracy Ehl and Bruno Bianco for keeping me in the loop in regards to Peterborough's stormwater funding study and answering many questions in the early stages of this research. I wish to acknowledge the contributions of Charmalee Sandanayake from the City of Peterborough's Geomatics and Mapping department, engineering technologist, Ian Boland from Otonabee Region Conservation Authority, and Tracey Sallaway from Trent University's Maps, Data, and Government Information Centre. All three were instrumental in providing portions of the mapping data used in the compilation of my final results. I

would like to give thanks to all the journalists who have produced articles about this research including Jessica Correa (Random Acts of Green), Berfin Aksoy (The Arthur), and Will Pearson (Trent Community Research Centre). This publicity has led to an increased awareness about the importance of Harper Park, and furthered community knowledge regarding the impacts of stormwater to our local environment. Finally thank you to Peterborough City Council for allowing me to present some of my findings, and the Trent Community Research Centre for continuing to offer these kinds of experiential learning, and place-based research opportunities.

One of the primary goals of community-based research is to find regionally appropriate solutions to research inquiries of local significance. This type of research can have strong implications on local communities, as the results empower hosts with the tools to establish evidence-based policy and management solutions. The choice to focus my case study on the development pressures, and priority stormwater diversion opportunities within the Harper Creek subwatershed caused this research to gain a lot of traction due to local campaigns in opposition to a casino slated for development in the area, and the significant ecological importance of the stream and wetland complex at stake. Furthermore, the City of Peterborough with its history of intense flooding, has recently started to reengage in dialogue regarding stormwater management funding gaps, and new stormwater management policies. Thus it is my hope that the research presented here is both topical, and important to the future of sustainable stormwater management in Peterborough.

The Trent Community Research Centre, Trent University, and Peterborough GreenUp supported this research, and all mapping data has been used under licencing agreements from the City of Peterborough, Trent MaDaGIC, and Otonabee Region Conservation Authority.

Executive Summary

Finding effective ways to manage stormwater in an economically and environmentally sustainable manner is an ongoing concern across municipalities across Ontario. Traditional grey infrastructure alters local hydrology by bypassing natural opportunities for stormwater infiltration in

favour of rapidly discharging stormwater runoff into local water bodies. These traditional systems, in combination with rapid land-use change due to urbanization, create detrimental impacts on urban stream water quality and quantity, and increase flood risks. In response to these environmental concerns, relentless urban expansion, and a change in predictable storm intensities due to climate change, new methods for managing stormwater are necessary moving forward.

Goals

The goals of this research are to:

- Identify current development pressures within the Harper Creek subwatershed
- Justify the use of rain gardens as an effective, low cost stormwater management tool
- Identify and map criteria for prioritizing the placement of rain gardens in the Harper Creek subwatershed to optimize water quality and flood reduction
- Assess the current state level of imperviousness within the Harper Creek subwatershed
- Calculate peak runoff rates within the subwatershed for 10, 25, and 50 year return periods
- Analyze the current Peterborough stormwater policy landscape and identify applicable policies which could support the increased implementation of green infrastructure for stormwater management on a property-by-property and watershed-scale basis

Methods

A variety of methods were utilized in the compilation of this report including:

- Literature Review
- GIS Mapping Integration
- Priority Criteria Selection and Identification
- Calculation of Imperviousness
- Runoff Calculations

Results and Analysis

The results from this study showed that the Harper Creek Subwatershed is reaching critical levels of imperviousness, with no signs of development pressures slowing down. The subwatershed is currently 49% imperviousness, and there are a number of ongoing projects slated within this region that will increase this level of imperviousness and continue to negatively impact the creek. Six priority

stormwater management zones were identified in order to provide a starting point for targeted mitigation efforts through the implementation of rain gardens.

Peterborough Stormwater Policy Landscape

Peterborough is currently examining new methods of funding stormwater infrastructure maintenance. At a committee of whole meeting in February 2017, parts of this research was presented, as a delegation in support of adopting a variable-rate stormwater fee and incentive program within Peterborough. Council accepted the results of the funding study and agreed to assess historic budgetary shortfalls in regards to funding stormwater infrastructure.

Structure

This report will begin with a review of urban hydrology, and stormwater quality characterization, followed by a summary of conventional and innovative stormwater management techniques. These sections will prime the reader with vital background knowledge and rationalize the purpose of this study. Next, the history, and characteristics, of the Harper Creek Subwatershed, and Harper Park will be discussed with particular attention to ongoing developments slated within the region. The subsequent section will focus on methods for calculating runoff, and factors affecting priority locations for permeability projects. The chosen methods for calculating runoff, and mapping priority zones will then be discussed, followed by a detailed analysis of the results, and their implications on future management objectives. Potential sources of error and important factors will be briefly mentioned in this section. Finally, the report will shift from primarily discussing hydrology, to a policy-based discussion regarding sustainable stormwater management options, and the current policy landscape in Peterborough, including recent decisions made by Peterborough's City Council, and personal reflections from presenting as a delegate during this research process. The report will conclude with some final thoughts regarding the protection of the Harper Creek Subwatershed, and future studies in the region.

Table of contents

1.0 Introduction

The purpose of this research is to identify and produce an applicable location prioritization scheme for the optimal implementation of rain gardens within the increasingly urbanizing Harper Creek subwatershed in Peterborough, Ontario. This area has been identified as an ecologically significant region within Peterborough due to the important natural features of Harper Park including a cold-water creek, two wetland complexes, and forested zones. Unfortunately the increased attention directed to this area has not only been for the natural heritage values, and ecological significance the site represents, but rather as a cause of encroaching development pressures from all sides of the subwatershed as the city expands and develops a number of new projects in this area. These new developments and associated hydrological impacts will add to an already arduous pollutant, temperature, and sediment load within Harper Creek, a sensitive stream ecosystem which provides spawning habitat for a native brook-trout population. Therefore it is the goal of this researcher to find appropriate means for mitigating some of impacts of ongoing developments, and present an argument for adopting a more watershed-based approach to city planning and development with a focus on increasing green stormwater infrastructure.

The timing of this research coincides with important policy initiatives within Peterborough City Council to fund and maintain existing stormwater infrastructure with a fee calculated based upon individual lot imperviousness. Thus, another one of the goals of this research is to identify some appropriate legislative options, and commonly employed stormwater policies, which can economically incentivize the implementation of green infrastructure on a watershed scale, and especially within identified priority permeability zones.

1.1 Urban Hydrology

Rapid and increasing urbanization since the early 20th century has led to increased water demands for human populations, and the conversion of large swaths of land from natural landscapes to paved, and impervious surfaces. These two major changes have had cascading effects on local and

watershed scale hydrological processes, which has presented a concern for human and infrastructure protection in the form of flooding, and environmental health due to water quality and quantity inconsistencies (Marsalek, *et al.* 2008). All components of the water cycle are affected by urbanization. In order to appropriately mitigate these impacts, human infrastructure and environmental restoration must reflect the understanding of natural versus altered hydrology. One needs to consider water inputs and various areas where water is lost, as well as the route of hydrological flow within the drainage basin. A brief outline of each water cycle component's response to the effects of urbanization is included below. Of primary importance to the research at hand, and assessing the impacts of land-use change are the differences in depression storage, and infiltration. A simple hydrological cycle schematic diagram, and urban hydrology diagram have been reproduced and are included as Figure A1 and A2 in appendix A.

Precipitation is the primary input in the water cycle. Urbanization affects both the depth and intensity of rainfall events. Studies have shown that total annual precipitation in, or downwind of, large industrialized cities is generally 5-10% higher than in the surrounding areas, and for individual storms, this increase in precipitation can be as high as 30%, particularly on the downwind side of large metropolitan areas (Marsalek, *et al.* 2008). This phenomenon is generally attributed to the 'Urban Heat Island' effect of industrialization, whereby land use change, and atmospheric pollution cause micro-climatic warming around city centres (Marsalek, *et al.* 2008).

A large fraction of precipitation returns to the atmosphere via evaporation or evapotranspiration (evaporation aided by plant processes), depending on the local landscape and water resources. The remaining water may infiltrate into the ground (recharging groundwater), or be converted into runoff and streamflow. Land use changes in urban areas lead to a reduced extent of green areas in cities and thereby contribute to reduced total transpiration from trees and vegetation. While evaporation and evapotranspiration are important in water budget calculations, during urban

stormwater runoff calculations and modelling, both abstractions are generally neglected (Bradford & Gharabaghi, 2004).

Interception is defined as the proportion of water input that never reaches the ground surface. During this process, precipitation wets and adheres to above ground objects, before evaporating and returning to the atmosphere. Interception is a major component within forested drainage basins, where factors such as vegetation, storm length and intensity, and seasonality impact expected interception values. However, within urban areas with low tree cover, interception is generally considered insignificant and is often neglected in calculations of runoff, or water balances (Bradford & Gharabaghi, 2004).

Depression storage accounts for water that is trapped in small depressions on the catchment surface and retained until it either infiltrates or evaporates. Depression storage capacity depends on the catchment surface characteristics, including the type of surface and its slope. Overall changes in landscape depression storage due to impervious land cover have a significant affect on urban runoff rates (Thomas & Benson, 1970).

Infiltration is the process of water movement into the soil under the forces of gravity and capillary pressure. Through this process, shallow underground water stores are recharged and, by slowly percolating towards surface waters, contribute to streamflow during dry periods; this streamflow is termed baseflow, or delayed flow (Thomas & Benson, 1970). Two basic approaches to describing infiltration include: a soil physics approach; relating infiltration rates to detailed soil properties (e.g., hydraulic conductivity, capillary tension and moisture content) and a hydrological approach; which is parametric and utilizes lumped soil characteristics to estimate infiltration rates (Bradford & Gharabaghi, 2004). This latter approach is most commonly used in urban runoff calculations. Compared to natural areas, infiltration rates decrease in urban areas because of increased imperviousness, the compaction of

soils, and human infrastructure designed for expedient removal of runoff towards surface waters (Thomas & Benson, 1970).

As each component of the urban hydrological cycle is explored, it becomes increasingly apparent that the main impact of urbanization on rainwater flow regimes is the change of land from natural soils with plant cover, to highly impervious materials with little vegetation. This contributes to increased runoff and higher risk of flooding and erosion in receiving streams. Reduced hydrologic abstractions, and increased surface runoff, are recognized as the typical impacts of urbanization on the hydrologic cycle (Leopold, 1968). In the first in-depth analysis of the urban hydrological cycle provided by Leopold (1968), it was noted that increased imperviousness of urban catchments contributed to lower infiltration and thereby to reduced groundwater recharge, reduced interflow/baseflow, and contributed to higher rates of surface runoff.

The final components of the urban water cycle are sinks, the storage location of all these contributing water components. Receiving surface waters and groundwater are both considered sinks within natural hydrology, however urban hydrological sinks also must include sewers, water treatment plants, perched aquifers, potable water pipes, and other human storage abstractions.

Groundwater and receiving water bodies are being unintentionally degraded by urban streamflow, and overuse, as they are forced to transport and store high quantities of polluted urban runoff, not adequately filtered or replenished through natural processes (Marsalek, *et al.* 2008). Thus, to protect downstream water uses, it is necessary to manage urban effluents with respect to their quantity and quality, in order to lessen their impact on vital water resources.

1.2 Stormwater Characterization

Stormwater refers to the mixture of rainwater and pollutants resulting from the flow of rain over impermeable surfaces in urban areas, including roofs, sidewalks, streets and parking lots. It is most often drained from urban areas by sewers or open channels to avoid local inundation. Within urban and suburban contexts, stormwater runoff presents a key stressor on receiving creek, stream, river, and lake

surface waters (Lee, *et al.* 2004). XCG Consultants studied Peterborough's stormwater quality, and published a management plan to improve the quality of Peterborough's stormwater in 2014. This study indicated that stormwater discharges were partly or potentially entirely responsible for the pollutant loading in local creeks rising above Provincial Water Quality Objectives.

Stormwater runoff contaminants are caused by urban lifestyles and activities, from driving a car, to using cleaning chemicals, littering, releasing oils, creating food waste, applying fertilizers, road salt, among other sources. Stormwater can be polluted with a wide range of chemicals, nutrients and bacteria. Over 600 different contaminants have been detected in different stormwater characterization studies (Marsalek, *et al.* 2008). Typical contaminant loading in urban stormwater has been well documented, and often Duncan's dataset (1999) is used to characterize typical concentrations of key stormwater pollutants (see Appendix B, table 1). The use of this dataset is consistent with the practice of Green Communities Canada and partner organizations when determining water quality benefits from the implementation of low impact development projects in Ontario, and across Canada (Taylor, & Foung, personal comm., Oct. 2016). Peterborough's Stormwater Quality Master Plan indicates that local stormwater has levels of contamination that can be considered as generally consistent with what has been measured in many other North American urban areas, though some of these values are lower than the average (XCG Consultants, 2014). A copy of the results from XCG's stormwater quality testing, completed in 2011, in comparison to other published values from the North American Stormwater Quality Database (2004) has been reproduced in Appendix B, table 2.

1.3 Conventional Stormwater Management

Stormwater runoff from impervious surfaces has generally been managed with the goal of rapid conveyance and discharge into streams and rivers. Stormwater management has been practiced in Ontario for flood control purposes since the 1970s (Bradford & Gharabaghi, 2004). Stormwater may be transported either by combined sewers, together with domestic and industrial wastewaters, or by separate sewers discharging to the nearest stream or lake. (Marsalek, *et al.*2008).

In many large cities in Ontario, storm sewers have been combined with sanitary sewers and conveyed to wastewater treatment plants, this method was practiced with the goal of providing treatment of runoff during small storm events (Bradford & Gharabaghi, 2004). One unforeseen consequence of these combined systems however, was the impact of large rain events, which overwhelm the system and result in overflow of not only stormwater runoff, but also untreated sewage into the local receiving surface waters (Burns, *et al.* 2012). Smaller cities (including Peterborough) generally have maintained individual sanitary and stormwater systems, where stormwater is discharged directly into nearby streams with no intermediate treatment (Bradford & Gharabaghi, 2004; Cole Engineering, 2012).

Many of the goals of conventional stormwater management have been characterized by interests in reducing peak flow rates, and downstream flooding, with little consideration for stream ecosystem degradation (Roy, *et al.* 2008). This drainage efficiency approach to stormwater management causes changes in the natural hydrological patterns and volume of infiltration, evapotranspiration, surface and subsurface flows. By directing stormwater runoff from impervious surfaces very quickly and efficiently to receiving waters, opportunities for natural losses to groundwater, soil infiltration and evaporation are bypassed, thus increasing overall magnitude, frequency, and volume of stormwater runoff (Burns, *et al.* 2012). Even low intensity storms create high volumes of polluted stormwater discharge due to the complete bypassing of natural opportunities for drainage. Furthermore, there is a significant reduction in summer and winter base-flows as a result of reduced infiltration. Drainage efficiency stormwater management also increases the frequency of low magnitude storm event flows to surface waters, and reduces the recession time for stored water within the basin (Burns *et al.* 2012). Storm intensity, and by proxy, flood risks, are constantly increasing due to ongoing urban expansion and climate change. The environmental impacts of these conventional approaches include changes to temperature, water levels and water quality, in addition to the ironic result of amplified flood

possibilities. The realization of the environmental ineptitudes within conventional approaches to stormwater management has lead to the proliferation and adoption of a variety of strategies for improved stormwater system performance.

1.4 Innovative Permeability Projects

Federal water protection legislation was first introduced during the 1990s, a time that also saw increases research and recommendations for controlling runoff at its source by reducing impervious cover and employing infiltration techniques. Indeed, these simultaneous evolutions sparked the slow emergence of low impact development for stormwater management (Roy *et al*. 2008).

The ethos of the RAIN Community Solutions program from Green Communities Canada is "*Slow it Down, Soak it Up, Keep it Clean"*; a perfect slogan that targets some of the root problems associated with urban stormwater, and the necessary steps to approaching sustainable watershed scale solutions (Green Communities Canada, 2016). In a natural system, the majority of stormwater is infiltrated by soils, slowly filtered through many layers of vegetation, soil, and rock, before reaching the groundwater table, and eventually percolating towards an outlet at a local waterbody. There may be some surface, or subsurface level runoff, but it constitutes a very small proportion of total streamflow, and Horton Overland flow (surface flow caused by storm intensity exceeding the infiltration capacity of soils) is essentially nonexistent. Urban stormwater management does not generally allow for these natural processes of filtration and delayed streamflow to take place. Rather, the rapid conveyance model removes the opportunity for the filtration, or infiltration of stormwater, reducing groundwater recharge, and the natural removal of harmful chemicals, while simultaneously increasing quickflow volumes during a storm event. The increased quantity and rate of stormwater discharge due to conventional stormwater management leads to streambank erosion, flooding, and high contaminant loading (Burns, *et al.* 2012).

Decentralized stormwater management tools such as low impact development (LID) (also referred to in the literature as water sensitive urban design, WSUD) may offer a more sustainable

solution to stormwater management if implemented at a watershed scale (Roy, *et al.* 2008). These tools are designed to pond, infiltrate, and harvest water at the source, encouraging evaporation, evapotranspiration, groundwater recharge, and reuse of stormwater (Mittag, *et al.* 2006). Essentially this is an approach that centres the restoration of natural hydrological flow wherever possible within an urban setting.

In approaching the watershed-scale restoration of altered flow regimes the three main processes to consider are infiltration, detention, and channel forming flow control (Mittag, *et al.* 2006). Infiltration can be implemented by incorporating grass swales, pervious pavements, rain gardens, bioretention, and other best management practises (Mittag, *et al.* 2006). By capturing and infiltrating stormwater at or near the source of runoff, these developments reduce flood frequency, thereby protecting human health and safety while also preventing infrastructure damage (Green Communities Canada, 2016). Furthermore, these techniques can serve to restore critical components of natural flow regimes of stream ecosystems including magnitude, duration, timing, rate of change, and frequency of low and high flow conditions (Burns, *et al.* 2012).

After infiltration opportunities have been maximized, detention may still be required to achieve similar pre-development flow duration curves (Mittag, *et al.* 2006). Detention allows for the slow draining of certain areas, thus reducing flood peaks. Bioretention units, retention ponds, and on-line stormwater wetlands are all potential best management practises (BMPs) for implementing detention storage, however retention ponds and wetlands have been shown to cause some other undesirable environmental impacts (Mittag, *et al*. 2006; Roy, *et al.* 2008). In contrast, within bioretention and rain gardens, the simultaneous use of infiltration and phytoremediation techniques provides the filtration of pollutants, peak flow reduction, and enhanced groundwater recharge. Thus these forms of low impact stormwater development have the best potential to remediate both water quantity and quality issues in streams (Roy, *et al.* 2008).

Finally, once all options have been exhausted for reducing flow peaks, and aiding the return of semi-natural hydrological patterns, stream course-alteration may be required to reduce the impacts of high flow speeds, and bank erosion, in addition to other direct bank stabilization techniques (such as wattles, riprap, etc.) (Mittag, *et al.* 2006).

The term 'Green Infrastructure' can be used to describe many low impact development techniques that use simple engineering to harness the power of plants for flood reduction, pollutant removal, and lessening the demand on traditional city stormwater infrastructure. Not only do these techniques support the health of the watershed, but there are many beautiful, inexpensive, and low maintenance options available that function by diverting stormwater from drains and pipes, and instead allowing it to be infiltrated by soils, and phyto-remediated by select native plants.

A brief description of some common infiltration and retention LID methods including swales, rain gardens/ bioretention units, and stormwater wetlands, is included below to provide the reader with a contextual understanding of the various options for low impact development, and justify the attractiveness of utilizing rain gardens as a versatile and cost effective LID technique wherever possible. The Toronto Region Conservation Authority and Credit Valley Conservation Authority produced a joint document published in 2010 entitled "*Low Impact Development Stormwater Management Planning and Design Guide"* which can offer more detailed descriptions, diagrams, and photos of a variety of low impact development techniques, in addition to appropriate engineering standards, and detailed analysis of the cost-benefits for each method (Dhalla, & Zimmer, 2010).

Stormwater wetlands are constructed shallow marsh systems designed to control stormwater volume and facilitate pollutant reduction. Constructed stormwater wetlands have less biodiversity than natural wetlands but still require baseflow to maintain aquatic vegetation (Houle, *et al.* 2013). Pollutant reduction takes place through settling of coarse material and sediments, and uptake from aquatic vegetation. There are three distinct zones in a stormwater wetland - a forebay immediately after the

inlet to receive stormwater, the wetland area, and a micropool immediately prior to the outfall (Tetra Tech Inc, 2010). The micropool and foray allow for sediment control. Stormwater wetlands generally capture 90% of the runoff from a 5-10 acre drainage area, and hold event water for around 24 hours after a storm. This method increases the delayed flow time, and reduces peak runoffs, while also improving water quality. Around 80% of total suspended solids, 40% of phosphorus, 30% of nitrogen, and 50% of metals can be bio-filtered by stormwater wetlands (Tetra Tech Inc, 2010). One drawback to creating this new habitat, is the alteration of stream 'longitudinal connectivity', which can be considered counter productive to the goals of hydrological restoration (Burns, *et al.* 2012).

Vegetated swales are shallow, sloped, densely vegetated channels built upon the slope pattern of an area. These swales are designed to infiltrate stormwater runoff, with side vegetation at a height greater than the designed stormwater volume (Tetra Tech Inc, 2010). As water flows over this area, vegetation slows the water, and allows for sediments to filter through the subsoil. The design of swales seeks to reduce the stormwater volume through infiltration, improve water quality through infiltration and vegetative filtering, and reduce runoff velocity by increasing flow path lengths and channel roughness (Tetra Tech Inc, 2010). Furthermore, evapotranspiration from the swale vegetation can also reduce stormwater volume. This method is best to accommodate small sized storms, in areas of hilly terrain (Houle, *et al.* 2013).

Two primary design variations exist for swale implementation: dry and wet swales. Dry swales are designed with highly permeable soils and an under-drain to allow the entire stormwater volume to convey or infiltrate away from the surface of the swale shortly after storm events (Houle, *et al.* 2013). Dry swales may be designed with check dams (structures that are placed over top of the swale to reduce flow velocity) that act as flow spreaders and encourage sheet flow along the width of the swale (Houle, *et al*. 2013). Wet swales conversely, are designed to retain some stormwater, and maintain marshy conditions with aquatic vegetation (Houle, *et al.* 2013). Due to their highly permeable soil and

conveyance capability, dry swales are the preferred option in urban settings (Tetra Tech Inc, 2010). The amount of stormwater diverted will depend upon the size of the infiltration unit; however, pollutant removal is estimated at 80% for total suspended solids, 50% for phosphorus and nitrogen, and 40% for metals (Tetra Tech Inc, 2010).

Rain gardens are vegetated depressions that store and infiltrate runoff. Rain gardens, and bioretention units are similar to vegetative swales in regards to their design, function, and the physical processes at work. The main differentiation between rain gardens and vegetated swales is the need to create a 'flat bowl shaped depression' in the design of a rain garden, while swales take advantage of the pre-existing topography. Bioretention units are rain gardens that have been lined at the base to reduce contamination of the surrounding area (this would be used in remediation applications where high chemical or heavy metal loading could be expected) (Tetra Tech Inc, 2010). These gardens are sometimes filled with engineered soils, or located in areas with pre-existing permeable soils to increase infiltration rates. Rain gardens are a soil and plant based filtration technique designed to reduce pollutant loading through the natural bio-physical-chemical processes in the soil and vegetation. Infiltration within the unit benefits water quality, but also has vital implications for enhanced groundwater recharge, and reducing peak-flows (Houle, *et al.* 2012).

Rain gardens are considered one of the best stormwater best management practices as they can infiltrate a substantial volume of flow, and can be implemented relatively simply, regardless of space allowance (Dhalla, & Zimmer, 2010). These gardens are versatile, attractive, and can be implemented just about anywhere, from front lawns, to within road medians, and parking lot islands. Furthermore, rain gardens address all aspects of hydrological condition changes due to urbanization (streamflow pathway, water quality, and water quantity) (Roy, *et al.* 2008). The pollutant removal effectiveness of rain gardens has been studied extensively through field and laboratory experiments and it has been shown that 90% of bacteria, 90% of organics, 90% of total suspended solids, 70-80% of Total Kjeldahl

nitrogen and phosphorus, and 93-98% of metals can be removed through these developments (Tetra Tech Inc, 2010).

It has been argued that the industry favoured approaches meant to address the environmental shortcomings within conventional stormwater management have failed to address the changes to the flow and water quality regime caused by conventional stormwater drainage. The primary industry implemented environmental solution to conventional stormwater management has been a pollutant-load-reduction focused management strategy rather than the infiltration based approaches explored above (Burns, *et al.* 2012). These solutions were borne out of increasing concern regarding contamination of important water bodies due in large part to the deleterious substances being discharged within stormwater runoff, particularly concerns were raised regarding nitrogen, phosphorus and bacteria (Burns, *et al.* 2012). While peak flow reduction was an additional aim, these solutions generally did not adequately address broader hydrological changes due to conventional 'rapid conveyance' stormwater management, and at times created new environmental concerns of their own (Burns, *et al.* 2012).

The most common implemented end of pipe adaptation for stormwater management has been the construction of stormwater retention ponds (Guo & Adams, 1999). Stormwater ponds are designed to contain and store contaminated stormwater runoff and slowly discharge this water back to the initial receiving waterbody, after a lag time to allow for the majority of sediments and contaminants to be settled. Most of these ponds are engineered with a 10-20 year dredge cycle, which eventually becomes the responsibility of the developer or municipality. Although this method of stormwater runoff diversion can aid stormwater system performance for both tasks of reducing peak flow, and pollutant loading, the retention ponds have become an environmental concern of their own (Guo & Adams, 1999; Tixier, *et al.* 2011). Without proper maintenance these ponds essentially become cesspools, dangerous both to human health, and the health of local wildlife species, which often unknowingly use these

contaminated ponds for critical urban habitat (Tixier, *et al.* 2011). Furthermore, natural succession can alter the ponds to act more as wetlands, as emergent vegetation proliferates from the high nutrient loads within the waters (Tixier, *et al.* 2011). This succession can sometimes lead to improved water quality but often, in actuality the unplanned and unmaintained wetland can negatively re-volatilize contaminants, harming local wildlife, and create a strain on groundwater recharge, and water quantity within the receiving stream (Tixier, *et al.* 2011).

It has been found that dredging is a fairly expensive and inefficient process, and it is often difficult to gain approvals for the storage and disposal of contaminated dredgate from stormwater retention ponds. Further complicating the procedure is the tendency for protected species to take refuge in these habitats, thus legally creating a concern for habitat disturbance through dredging, and a long-term concern for biodiversity loss. Often in practice, dredge dates are ignored, and the ill-functioning pond overflows consistently into the receiving stream, without the proper lag time for contaminant settling (Tixier, *et al.* 2011). An additional concern is regarding temperature; the small ponds heat up quickly, impacting streamflow warmth, an especially important concern in cold-water stream watersheds (Burns, *et al.* 2012). Therefore, while stormwater ponds may be a marginally adequate load and peak flow reduction strategy, favoured by developers, they may not actually be an environmentally sound choice for hydrological rehabilitation, the protection of downstream water quality, or the protection of biodiversity and the environment (Guo & Adams, 1999; Tixier, *et al.* 2011).

The city of Peterborough currently has 28 stormwater ponds, five of which are in the Harper Creek subwatershed. The City has not followed the recommended dredge cycles for these stormwater ponds, as maintenance has been historically underfunded. Thus these stormwater ponds are no longer operating at full efficacy. Images of ill-functioning stormwater ponds within the Harper Creek watershed have been included in Appendix D.

Despite the early knowledge that many low impact development techniques (outside of the conventional stormwater pond solution) could be effective in both reducing contaminant loading and hydrologic alteration, the preferred approach to these problems in most communities remained conveyance of runoff to streams or stormwater retention ponds (Bradford & Gharabaghi, 2004). This is partly due to flood reduction concerns taking precedence over ecosystem protection, and partly due to inexperience with implementing these innovative systems as well as perceived additional cost (Bradford & Gharabaghi, 2004). In reality, there are many opportunities for the watershed-scale implementation of LID projects, specifically with rain gardens on a lot-by-lot basis. This could have wide-ranging hydrological restoration implications, and may greatly reduce the stress on municipal sewer systems while also improving stream water quality and condition, and reducing overall capital cost of stormwater infrastructure (Dhalla, & Zimmer, 2010).

1.5 Factors Affecting Rain Garden Location Prioritization

A primary goal of this research is to determine the priority permeability areas for infiltration based LID projects. Most LID techniques applied in urban watersheds have been largely experimental, opportunistic, and often implemented to remedy local stormwater runoff issues, however the location of LID implementation within a watershed can be one of the most important factors in determining effectiveness, both on a local, and watershed-scale (Mitchell, 2005). While there are a number of general principles which can help to determine where developments are best located, or avoided, for the protection of downstream hydrology (eg. Dhalla, & Zimmer, 2010), in general, optimization of rain-garden placement for watershed-wide hydrologic benefit is difficult to determine without using sophisticated models.

Many LID-placement methods target non-point source pollutants from smaller sub catchments based upon variable source area hydrology, whereby areas prone to saturated overland flow are prioritized due to their higher potential for transporting pollutants (Mitchell, 2005). Martin-Mikle, *et al*. 2015 related this concept to the designation of hydrologically sensitive areas (HSAs) based upon the

"probability of pollution transport risk" in the design of their LID location prioritization scheme. Using publicly available data, the GIS-based system the researchers developed considers land uses across the entire watershed, and prioritizes sites where LID would be most effective based on the identification of HSAs using a multi-variable topographic index, and the calculation of suitability for LID application based on land use, spatial scale, position in the stream network, and effective impervious area (Martin-Mikle, *et al*. 2015). The topographic index modeled patterns of surface runoff based on variable surface area hydrology using wetness indexes derived from the drainage area slope and soil water storage based on hydraulic conductivity and soil depth. Higher index values corresponded to pixels determined most likely to become saturated more quickly during a storm event, and thus contribute first to overland runoff. An in depth discussion of the methods and tools used to derive the model is included in Martin-Mikle, *et al*. 2015, and has been identified as a broadly applicable method for determining site locations due to the use of publicly available data, and empirical mathematical relationships, as well as the applicability for use with commonly used GIS applications such as ARC-GIS. One concern with this method however, is the applicability within entirely or predominantly urbanized watersheds. In this case, saturation is not necessarily the problem but rather high runoff rates due to imperviousness, and poor stormwater infrastructure.

Perez-Pedini, Limbrunner, and Vogel explored whether it would be possible to determine the optimal location of stormwater LID projects without using a distributed hydrologic model, and genetic algorithm optimization (as they did) but instead focusing on the coincidence of, for example, the location of impervious areas and LID priority locations, or some other deterministic attribute (2005). Unfortunately, the results of their multivariate statistical analysis found the relationship between watershed peak flow reduction generated by an LID application to a particular hydrological response location, and a variety of delineating characteristics, was too complex to state one dominant feature (Perez-Pedini, Limbrunner, & Vogel, 2005).

Complex modelling was beyond the scope of the researcher's capabilities, thus determining the priority locations within the Harper Creek subwatershed required further research to identify a more simplistic, yet appropriate, set of priority determination factors or methods. Elizabeth Horvath used a combination of zoning by level of imperviousness, and watershed placement (higher in the watershed were higher priority, in addition to higher slope) in order to prioritize stormwater management and restoration zones in her Master's dissertation for the University of Pennsylvania (2011). She further prioritized areas based upon the state of the riparian corridor, and the location of stormwater outfalls. This methodology is attractive, effective, and applicable to the case at hand. Additional important factors influencing prioritization include the property size, presence of known stormwater infrastructure capacity concerns, and more polluting industrial and commercial properties.

1.6 Land Use Based Runoff Modelling

City planning professionals and environmental scientists must find ways of predicting the impacts of land-use change on local hydrology, including changes in total peak runoff rates, runoff contributing areas, groundwater recharge, and other important metrics so that stormwater management systems can be designed to address these alterations from the natural system responses and protect against extreme flooding, groundwater losses, pollutant loading, and erosion of watercourses (Boyd, Bufill, & Knee, 1993). Runoff from pervious surfaces is more difficult to predict than runoff from impervious surfaces because it largely depends on soil and vegetation type, as well as slope and antecedent wetness conditions, while impervious surfaces have been given empirical runoff coefficients based upon the material type (Boyd, Bufill, & Knee, 1993). Furthermore, it is difficult to control and account for source water areas from permeable areas as these locations can contribute a high proportion of total watershed runoff, especially during larger intensity storm events (Boyd, Bufill, & Knee, 1993). Many of the predictive models that are used, are extremely complex and require highly specialized knowledge, data resources, and programming capabilities in order to be implemented.

Throughout the literature countless models have been explored, however, these models are often designed for one specific management goal, within one specific location. This approach to hydrological management and modelling is not necessarily broadly applicable. One reason that long-term runoff and recharge impact analyses are not performed more frequently is that existing models are so complex and data-intensive that either they are beyond what a local planner can manage in terms of time and/or expertise, or the planning agency cannot afford the cost of hiring a professional consultant to perform the analysis (Harbor, 1994).

For the purpose of this study more general analysis was achieved through summary runoff calculations that took into consideration the time of concentration, and maximum runoff for various return periods using rational equations utilizing weighted watershed runoff coefficients and overall level of imperviousness.

2.0 Background on the Harper Creek Subwatershed and Harper Park

The Harper Creek Subwatershed is a relatively uncelebrated location of immense ecological significance within the City of Peterborough. This next section will provide some context of the natural heritage values within the area and ongoing concerns regarding development.

2.1 Physical Characteristics

The Harper Creek subwatershed is approximately 1.92km^2, located in the southwest end of Peterborough. The area stretches from roughly Brealey Rd. and Lansdowne St. to the west, until approximately Lansdowne St and the Parkway to the east. The encompassed area is primarily residential, with a large industrial complex, and some commercial and institutional locations along Lansdowne Street. Most of the subwatershed falls within the boundaries of the Lansdowne West Secondary Planning Area (see appendix C, Figure 1C). The soils are primarily Otonabee sandy loam, characterized as “excessively well draining” within the Peterborough County soils survey of 1981. Much of the area outside of Harper Park is now considered “urban soils” which denote a heavily compacted, or paved surface type.

Harper Park, Harper Creek, and the associated wetland complexes are a significant natural area within the Harper Creek subwatershed, and the City of Peterborough as a whole. The parklands represent roughly one quarter of the total watershed area, and one of the largest undisturbed, naturally treed areas within the city (Otonabee Conservation, 2004). Harper Park stretches from Spillsbury drive to the west, Harper Road to the east, Sir Sandford Fleming Drive to the south, and Lansdowne Street to the north. The land-use directly adjacent to the park is residential to the west, industrial and institutional to the north, and east, and south. The park area encompasses a 2.9 hectare large provincially significant swamp wetland, heavily forested central areas, open meadows, and the creek bed (Otonabee Conservation, 2013; MNRF, 2017). There are roughly 60 identified native plant species, and a wide variety of woodland, bird, and aquatic species that use the Harper Park and wetland complex for vital urban habitat. The endangered five-lined skink has been recorded in Harper Park, as well as the endangered barn swallow. Of notable importance is a locally significant brook trout population, which spawns in the cold waters of Harper Creek (Otonabee Conservation, 2013). Water quality testing from 2001-2003 has shown moderate organic pollutant loading, and increases in sedimentation as well as hydraulic conductivity (Otonabee Conservation, 2013). Changes to the hydraulic regime, water quality, and temperature, due to urbanization will have detrimental impacts on the important ecological features, and biodiversity in this area.

Harper Creek is the city's only cold water creek. The creek stretches approximately 3.2 kilometers, discharging first into Byersville Creek, and then into the Otonabee River (Otonabee Conservation, 2013). The main headwaters are located in Stenson Park, in the west portion of the watershed between Brealey and Spillsbury Drives. The creek flows northeast through the watershed, through the Harper Creek Wetland, under Harper Road, and continues along the west embankment of a railway line, finally discharging into Byersville Creek (Otonabee Conservation, 2013). The park is zoned as a Protected Natural Area as per the City of Peterborough's Official Plan, Schedule A, designated for

nature based recreation, outdoor education, non-destructive research, horticulture, conservation, forestry, and wildlife management (Otonabee Conservation, 2004). The wetland area of the park has recently (March 2017) been re-evaluated and designated provincially (rather than locally) significant under the Ontario Wetland Evaluation System (Otonabee Conservation, 2004; MNRF, 2017). These areas are extremely important to Peterborough's natural heritage, biodiversity, and habitat, however, increasing urbanization is already beginning to drastically impact these crucial natural features.

2.2 Recent Threats to Harper Creek

Despite a city mandate to protect this greenspace, Harper Park, and the Harper Creek Subwatershed are experiencing rapidly encroaching urbanization with numerous city, and private development projects currently proposed within the reaches of Harper Creek. There are currently three different road expansions in various stages of proposal and environmental assessment for the Harper Creek watershed. The proposed road alterations are for Harper Road, Crawford Drive, and Rye Street. Each of these roads is adjacent to Harper Park and would provide greater access to the industrial complex located beside the greenspace. The Rye Street expansion is a particular concern, as it would require the re-coursing of Harper Creek, from its natural meander, and potentially add significant sediment loading to the creek in the process (see appendix D). Another main concern is the proposed development location of the Shoreline Casino - also directly adjacent to Harper Park (see appendix C, Figure 2C and 3C). The casino has been a controversial development for Peterborough for many socio-economic reasons, however the environmental implications of this development have not yet been fully explored. A large development like this will add a heavy runoff load to Harper Creek, which will need to be mitigated, and will reduce the forested land cover of this area.

Among the other plans within the watershed, are a new public works yard on Rye street, a bus shelter and maintenance facility on Harper Rd, a new subdivision in the southwest portion of the watershed, and a new retirement home in the north (Zippel, personal comm., Oct. 2016). Each of these

new developments will almost certainly add to the current overwhelming load on the stormwater sewer system in the area, and increase the impacts Harper Creek is experiencing.

There are also a number of concerns within the watershed which have not been addressed by the city, including a perched aquifer in a subdivision on Pinewood drive which was replaced by a stormwater pond, and has been left unmaintained, and overflowing into one of the natural groundwater springs for Harper Creek, and an additional stormwater pond off of Westview Village which is also consistently overflowing into a forested area of Harper park (Zippel, personal comm., Oct. 2016). These are both extremely troubling findings, which have not been addressed by any authority thus far (see appendix D Figure 1D and 2D). Finally, there is also possible PCB contamination within some reaches of Harper Creek due to a historic waste site that the city operated from the 1940s to the 1960s on Harper Rd (Wedley, 2012). This site was never properly decommissioned, and the city has been cited by the Ministry of Environment as recently as 2014 for continuing to use the site as a dump transfer station, and failing to implement an immediate remediation plan (Wedley, 2012). Each of these developments and threats represent a serious concern for the future health and safety of Harper Creek, the native brook trout population that spawns in this creek, and the watershed health as a whole.

2.3 Recent and Future Plans for Protecting Harper Creek

Recently, the Harper Creek watershed was the site of an extremely successful Depave Paradise project through Peterborough GreenUp at Wireless Solutions at 1774 Lansdowne St W. The Depave Paradise site is located in a highly visible location both in terms of vehicle and pedestrian traffic, and is located in a growing section of the City with little greenspace (Ray, 2015). Of additional notability, is the placement of the rain garden in the higher reaches of the subwatershed, aiding in important groundwater recharge. The project saw approximately 250m^2 of asphalt converted into a massive rain garden, which has been designed to divert 89.0m^3 of stormwater (per 5 cm rain event), and approximately 22.81 kg of sediments, and urban pollutants from reaching Harper Creek (Ray, 2015). This

project was an extremely important measure for both protecting the watershed, and encouraging new projects to be implemented within this watershed.

GreenUp is involved in implementing rain gardens amongst the other Peterborough subwatersheds, including a number of projects in The Avenues and one on Park Street Wine Shoppe, which address the protection of Jackson Creek. GreenUp has also planned two new Harper Creek stewardship projects in the coming year to protect against streambank erosion and enhance fish habitat (see appendix C, Figure 4C) GreenUp is also beginning a new program entitled Sustainable Urban Neighbourhoods (SUN), which will focus on bringing rain-ready best management, practises to targeted residential areas (Ray, personal comm. Feb. 2017). It is the hope that results from this research can help to identify new areas to target within this vital watershed, so that GreenUp can continue to perform this extremely important work, effectively and efficiently.

3.0 Methods

While there are many ways in which this research, mapping, and prioritization scheme could have been accomplished, it was the goal of the researcher to apply realistic, effective, and repeatable methodology so that in the future this experiment may be duplicated for other subwatersheds within the City of Peterborough. This next section will detail the methods utilized for obtaining mapping data, integrating the use of ArcMap, creating the Harper Creek Subwatershed stormwater management maps, analyzing and determining management zones, and summary calculations.

3.1 Obtaining Mapping Data

Mapping data was obtained through four different sources. Trent University's Mapping Data and Government Information Centre (MaDaGIC) graciously assisted with obtaining aerial imagery for the Harper Creek subwatershed through Scholar's Geoportal database. This aerial imagery was taken from the South Central Ontario Orthographic Project (SCOOP) and depicts the area based upon photos taken in 2013. Under the guidance of the Ontario Ministry of Natural Resources, over 40 private and

government entities worked to produce this product. SCOOP digital imagery has a 20 cm resolution and was collected with sensor Leica geosystems ADS80 SH82 for areas of Ontario between April 26th and May 7th 2013. The City of Peterborough Mapping and Geomatics Department assisted with the compilation of property parcel, zoning, road, and stormwater infrastructure data layers for the watershed area. Finally, Otonabee Region Conservation Authority generously sent shape files of the Byersville Flood Plain mapping completed in 2014. Additional contour lines, and water body data layers were individually obtained through Scholar's Geoportal database. All data that has been obtained through and outside agency has been licenced through shared data agreements for the purpose of this research and report. All mapping layers were georeferenced using 1983 NAD UTM.

3.2 GIS Mapping Integration

After all mapping layers had been obtained, they were added to a blank map in Arc. Map 10.4 and clipped to the main subwatershed boundaries delineated by Otonabee Region Conservation Authority's Harper Creek Management Plan published in 2013. The aerial imagery was combined as one group raster layer, and set to 40% transparency so that it could provide additional reference while working with the vector mapping layers. A digital elevation model was then created using the contour layer obtained through Scholar's Geoportal database, and added as it's own individual layer. Then, using the intersection tool the parcel and zoning layers were merged to create one detailed output layer that described all the individual properties in the subwatershed by zone, size, property identification number, and polygon. By creating a new column in the parcel-zoning intersection attribute table I was then able to zoom in and assign runoff coefficients to individual parcels based upon the Peterborough Engineering and Design Standards (2015). These runoff coefficients are specific not only to zoning type, but also to the lot width, and the type of development on the property (see appendix B, table 3). Thus, it was necessary to have the aerial imagery in order to identify the type of residential property (single dwelling, semi-detached, townhouse, apartment, etc), and it was necessary to individually measure the width of each property using measurement tools to determine if it was as 9m, 12m, or 15m+ lot. Figure

3 below depicts this process of assigning coefficient values to various parcels based upon their

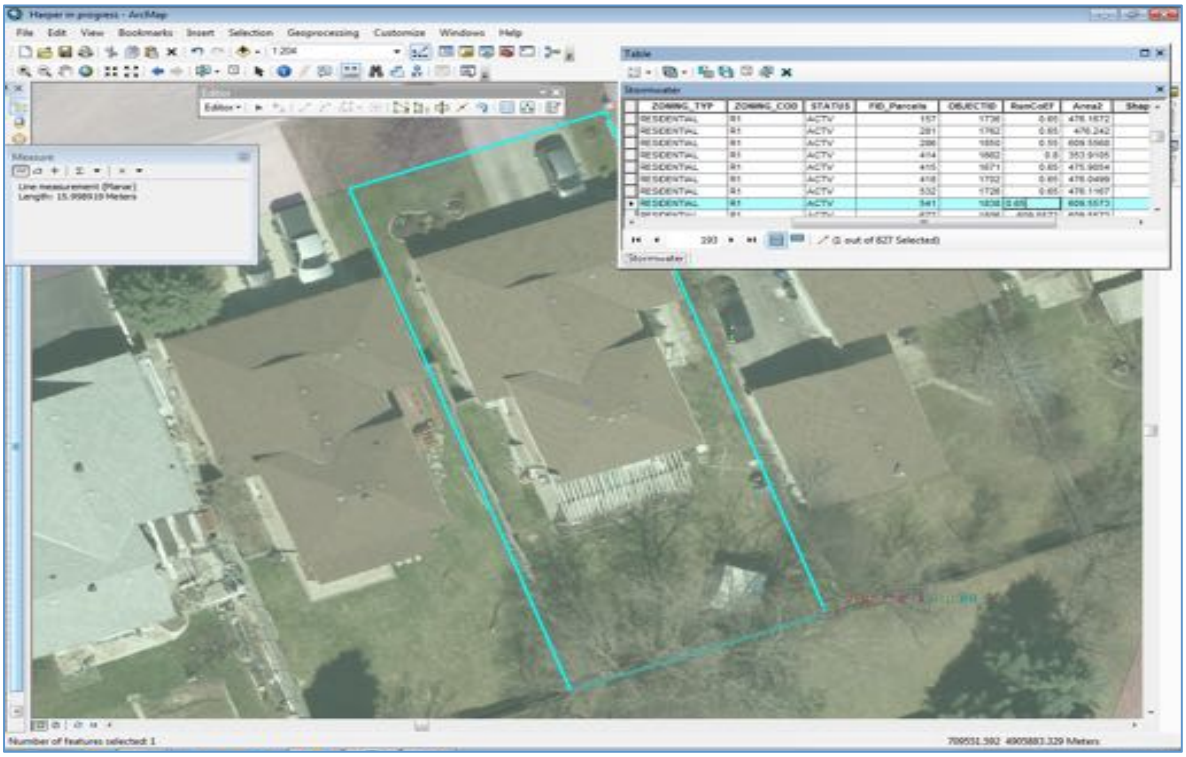


Figure 1. Screenshot of assigning individual properties runoff coefficients in ArcMap 10.4

measurements and zoning characteristics. When the attribute table was complete, simply changing the symbology of the layer resulted in a graphic display of high and low runoff areas within the subwatershed.

3.3 Analysis Plan

The mapping output was analyzed for priority management zones using a variety of criteria. This criteria included priority status for areas of high runoff coefficients (imperviousness), high slope, upper placement within the subwatershed, areas where additional stormwater management techniques have not yet been integrated, locations of stormwater outflows, and particularly polluting industries. This was accomplished by zooming into the map of stormwater hotspots and first highlighting the important stormwater infrastructure already in place through altering the symbology. This helped to make the stormwater outflows, stormwater ponds, and stormwater separators (called "clean outs") more

obvious, in addition to the areas with culverts and open ditch drainage. Then areas of high slope and high imperviousness without any nearby mitigation methods were identified. This was followed by an analysis of each of the other factors, and ultimately six distinct zones were identified. These zones were then annotated on a zoomed-in version of the stormwater hotspot map using Microsoft paint, and aerial photos of the areas with more detail were captured using Google Maps satellite imagery.

3.4 Calculation of Imperviousness

Total subwatershed imperviousness was calculated by weighting the area of each coefficient category (ie. 15m residential, 12 m residential, etc.) by the percentage of the total watershed area it represented. First the sum of the area of each category had to be calculated (by manipulating the data from the attribute table within an excel worksheet), and then the area had to be divided by the total watershed area. This percentage was then multiplied by the runoff coefficient to achieve the weighted runoff coefficient. The sum of the weighted coefficients is equal to the total level of imperviousness within the subwatershed.

3.5 Calculation of Concentration Time

Time of concentration is a fundamental watershed parameter. It is used to compute the peak discharge for a watershed. The peak discharge is a function of the rainfall intensity, which is based on the time of concentration. Time of concentration is the longest time required for a particle to travel from the watershed divide to the watershed outlet (Wong, 2005). Time of concentration calculation require inputs for the longest watercourse length in the watershed (L), the average slope of the watercourse (S), and a coefficient representing the type of ground cover. Length of the longest watercourse was calculated on Arc Map 10.4 by tracing the length of Harper Creek. Furthermore, average slope was calculated by taking the difference between the headwater elevation, and discharge elevation, and dividing it by the length of the longest stream (rise over run). The concentration time formula was calculated for each coefficient area, and weighted, and then summed to achieve a

distributed result with consideration for the various landuses within the watershed. The time of concentration can be calculated with three standard formulas, however the Federal Aviation Method was selected as it has been recommended for urban impervious watersheds (Wong, 2005). Federal Aviation Administration (1970):

$$tc = 1.8(1.1-C)L\ 0.5S^{1/3}$$

Where: tc= time of concentration (min.)
L = length of longest flow path (m)
S = average watershed slope (decimal)
C = runoff coefficient
1.8, 0.5, and 1/3 are constants

3.6 Calculation of Maximum Runoff

Maximum or peak runoff is an important calculation for understanding the possibility of flooding, given various storm intensities expected within probabilistic return periods. Peak runoff was calculated using well-accepted Rational Equation method. The rational method is primarily used as a design tool for the engineering of minor drainage systems such as storm sewers and ditches (Wong, 2005). It is mostly applied to urban catchments to determine the size of storm sewers and other stormwater infrastructure. Present practise in the Ministry of Transportation limits its use for rural watersheds with drainage areas of less than 100 hectares, or urban watersheds with drainage areas less than 50 hectares (Wong, 2005). This method calculates peak runoff in cubic metres per second, by multiplying runoff coefficients, by storm intensity, and area. Storm intensity for various return periods is taken from established Intensity Duration Frequency (IDF) Curves, by extrapolating the intensity value from the graph at the point in which the storm duration (td) is equal to the previously calculated concentration time (tc). This concept is summarized in the graphic on the following page. Pre-populated IDF curves are available online for all of Ontario through a joint project between the Ontario Ministry of Transportation, and the University of Waterloo. The IDF Curve for the Harper Creek Subwatershed has been reproduced in appendix A, Figure 3A)

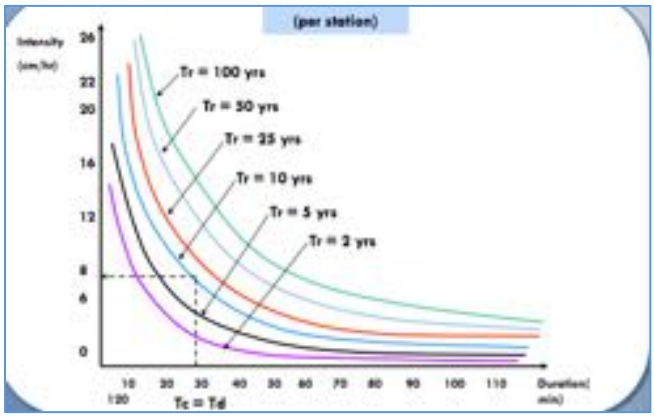


Figure 2. How to calculate storm intensity from IDF curves and concentration time for various return periods when calculating peak storm runoff (Ponce-Hernandez, ERSC 4640, Lecture 4, 2017)

The rational model equation is as follows:

$$Q=CiA$$

Where Q= Peak Runoff (m^3/sec)
C= Runoff Coefficient
i= intensity (mm/hr) from IDF curves for given return periods, (at the point in which concentration time is equal to storm duration)
A= Area

Similar to concentration time, peak runoff was calculated based off the different coefficient categories and weighted by the area each represented within the subwatershed, and then summed to provide the total subwatershed peak runoff for 10, 25, and 50 year return periods.

3.7 Average Annual Runoff

Average annual runoff was calculated from an equation that utilizes annual precipitation (mm), runoff coefficient, and area (m^2) to give an estimated value for the total annual runoff from the watershed. Precipitation values were obtained from the Government of Canada Climate Normals for the Peterborough Airport Station, from 1981-2010. Annual runoff was calculated in thousands of m^3 of using the following equation:

$$Vm = ACPm$$

Where Vm=Annual Runoff (m^3*10^3)
A= Watershed Area
C= Runoff Coefficient
Pm = Average Yearly Precipitation (mm)

4.0 Results

4.1 Digital Elevation Model

The Harper creek subwatershed is highest in elevation in the northwest, and decreases in elevation diagonally as it progresses to the southeast of the watershed boundaries. The map below depicts some areas outside of the scope of the watershed to provide contextual understanding of the topography of the region. The headwaters of the Harper Creek subwatershed are at an elevation of 235m, and the discharge of Harper Creek is at an elevation of 190m.

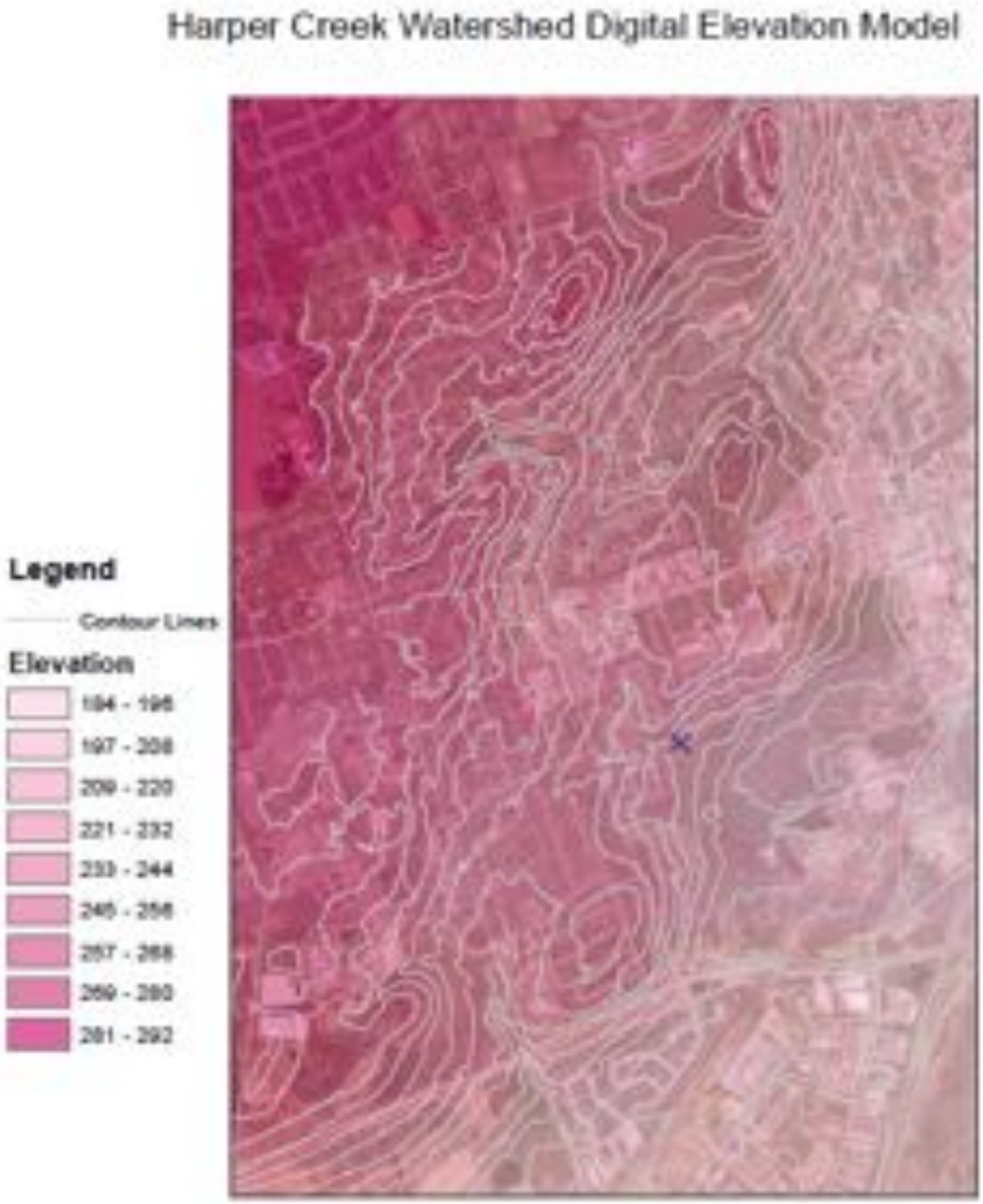
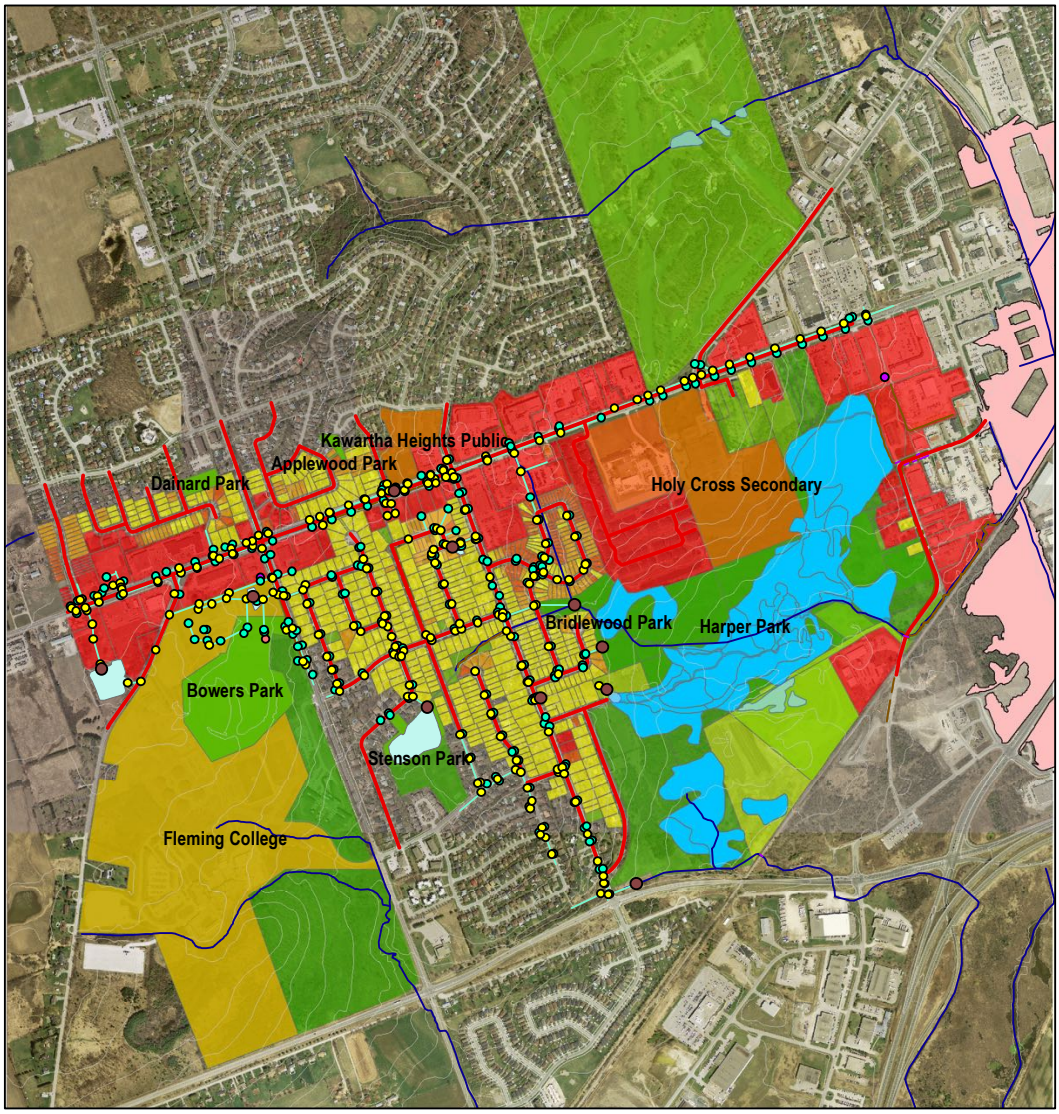


Figure 3. Digital elevation model of Harper Creek Subwatershed, with contour lines, and aerial imagery created in ArcMap 10.4, darker pink colours represent higher elevations.

4.2 Stormwater Hotspots

Highly impervious areas within the Harper Creek Subwatershed are primarily along the commercial zones on Lansdowne St, and Industrial zones bordering the east side of Harper Park. Although it is shown in this map, the Golf Club is technically within the Byersville basin.

Harper Creek Watershed Stormwater Hot Spots



Legend

- Contour Lines
- Storm Manhole
- Storm Plug
- Clean Out
- Catchbasin
- Discharge Point
- Culvert
- Open Storm Drain
- Roads
- Creeks
- Wetlands & Waterbodies
- Stormwater Detention Pond
- Byersville Flooplain

Stormwater Runoff Coefficient

- 0.200000
- 0.200001 - 0.250000
- 0.250001 - 0.350000
- 0.350001 - 0.550000
- 0.550001 - 0.650000
- 0.650001 - 0.750000
- 0.750001 - 0.800000
- 0.800001 - 0.850000
- 0.850001 - 0.900000
- 0.900001 - 0.950000

Figure 4. Stormwater Hotspots within the Harper Creek Subwatershed, with contour lines, aerial imagery, and annotated stormwater infrastructure, created in ArcMap 10.4. Greens represent low runoff coefficients (natural areas), Light yellow to orange represent the residential sector, and dark orange to red represent high runoff coefficients within commercial, industrial, and high density housing areas.

4.3 Stormwater Controls

The purpose of this exercise was to highlight the location of main stormwater control structures already existing within the basin. There are six stormwater storm-clean out structures within the Harper Creek Subwatershed (see Figure 5 below). These structures are stormwater-separators, used for cleaning out and offering some litter removal. Structures have been labelled in order from west to east. Structure 1 is at the Pioneer Gas Station on Lansdowne St. West. Structure 2 is at Kawartha Dodge Chrysler. Structure 3 is at the north side of Forty Drive in a residential and commercial area. Structure 4 is at Cahill Drive just before a stormwater pond outlet. Structure 5 is at Cherry Hill Rd. and Brealey Drive near a stormwater outflow, and Structure 6 is at a Value Village, north of Rye St on Lansdowne St. West. Most of these structures are either near a stormwater outflow or a stormwater pond.

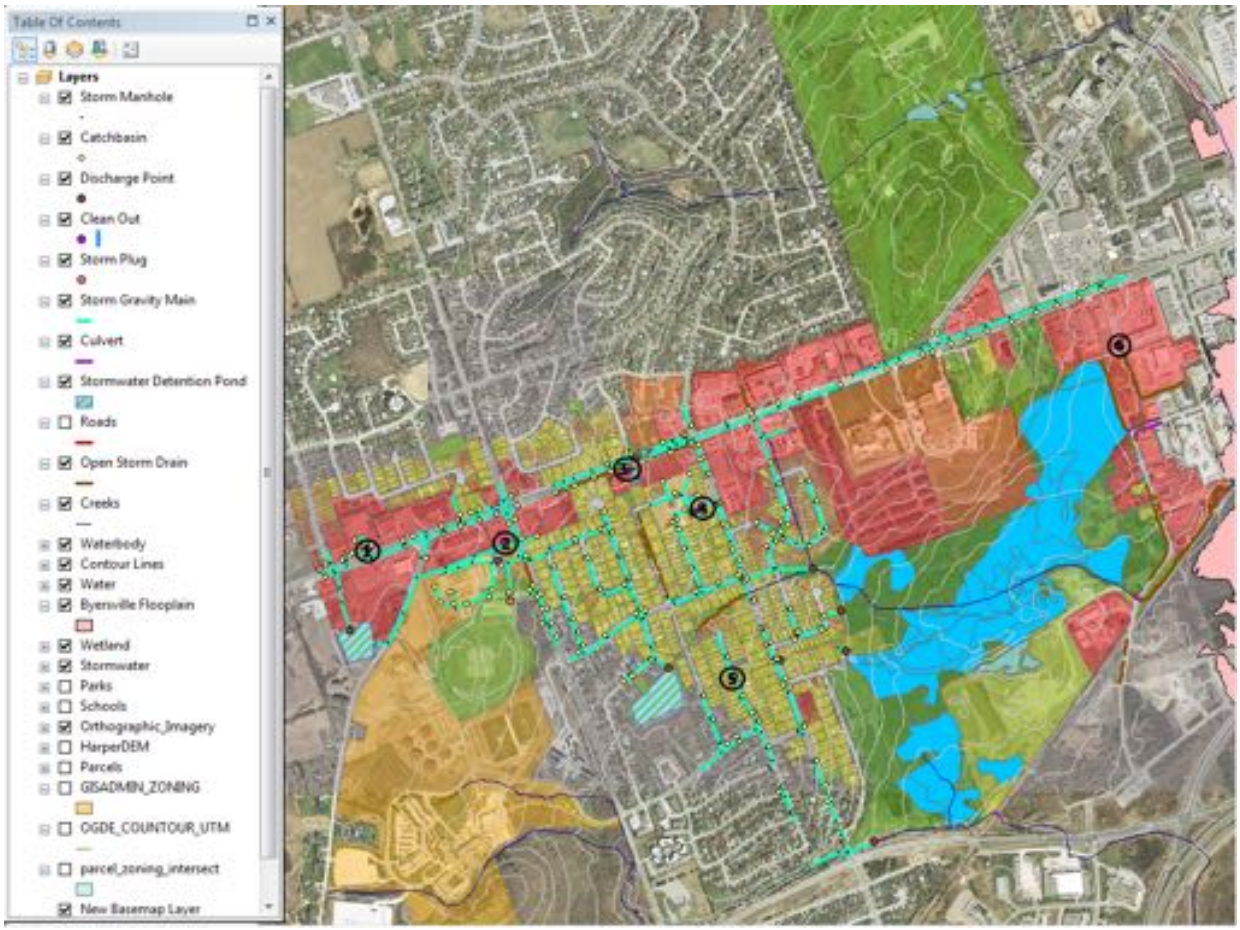


Figure 5. Zoomed in, annotated view of 'Clean-Out' stormwater infrastructure in the Harper Creek Subwatershed, map created in ArcMap 10.4, annotated in Microsoft Paint. There are six stormwater clean-out structures within the Harper Creek Subwatershed.

There are four stormwater ponds within the Harper Creek Basin mapped within the city's stormwater infrastructure. They are annotated in Figure 6 below. Stormwater pond 1 is at Dobbin Rd, north of Fleming College. Stormwater Pond 2 is south of the Peterborough Sports and Wellness Centre, just north of Bowers Park. Stormwater Pond 3 is at Stenson Park. Stormwater Pond 4 is at Cahill Drive in a residential area, south of a commercial zone on Lansdowne Street. Finally, although it has not been annotated on this map, there is actually a fifth stormwater pond behind the residences adjacent to Holy Cross Secondary School, on Village Crescent, just north of Bridlewood Park (which connects to Harper Park).

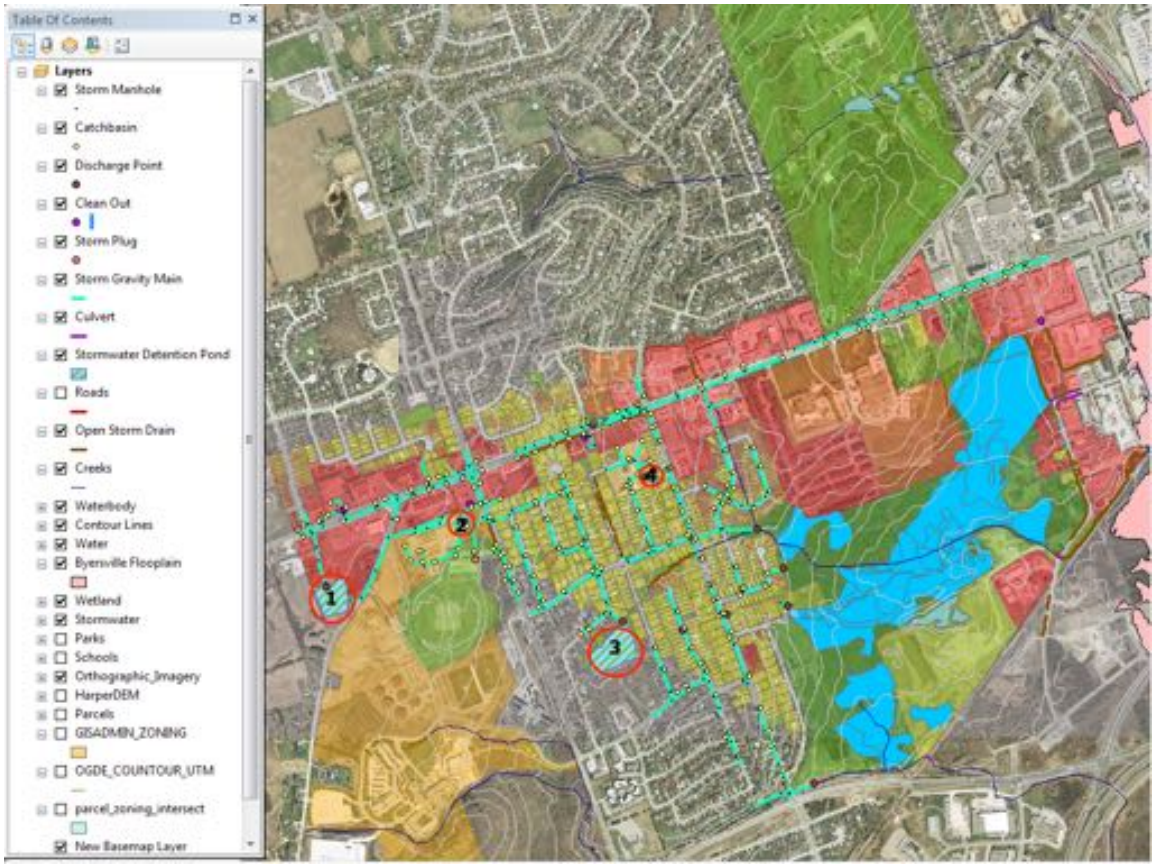


Figure 6. Zoomed in, annotated view of stormwater ponds in the Harper Creek Subwatershed, map created in ArcMap 10.4, annotated in Microsoft Paint. There are 4 stormwater pons structures within the Harper Creek Subwatershed maintained by the city, and one private stormwater pond behind the residences adjacent to Holy Cross Secondary School, which has not been annotated on this map.

4.4 Priority Stormwater Management Zones

Six priority stormwater management zones have been identified based upon criteria such as placement in the stream network, imperviousness, elevation, slope, lack of stormwater controls, presence of polluting industries, and parcel lot size (see Figure 7 below).

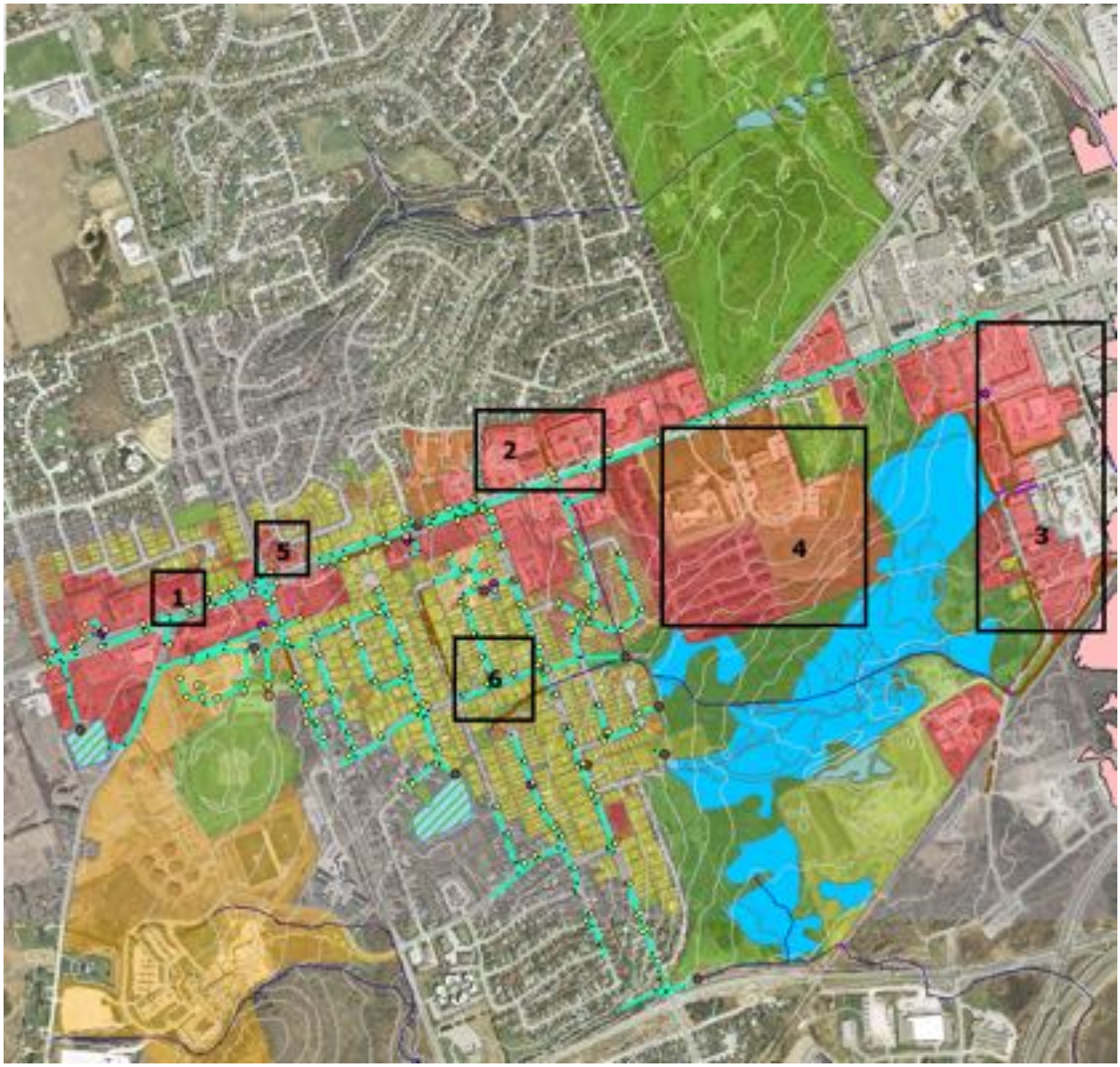


Figure 7. Zoomed in, annotated view of stormwater management priority zones in the Harper Creek Subwatershed, map created in ArcMap 10.4, annotated in Microsoft Paint. There are 6 identified stormwater management priority areas within the Harper Creek Subwatershed. Brown circles represent stormwater outflows. Purple circles represent stormwater clean-out structures. Small yellow circles represent catch basins. Small black dots are storm drains. The teal network represents storm gravity drains mains. Stormwater ponds are green and blue striped features on this map. Purple lines represent culverts, while brown lines represent open storm drainage. Red zones have high runoff coefficients (0.8-.09) while yellow have medium (0.5-0.7) and green zones have low runoff coefficients (0.2-0.4).

Zone 1 is located in an area of high slope, and high stream placement, within a commercial zone (Hockey Sushi/ No Frills Plaza) that has relatively no opportunity for drainage at current levels of imperviousness. Zone 2 is similarly in an area of high slope, close to the northern headwaters of Harper Creek, and surrounded by other highly impervious areas. Zone 3 targets the highly polluting industries adjacent to the Harper Park, particularly the Coach Canada bus yard, which represents a highly paved area, and source of pollutants, which currently drains directly into open sections of the creek. Zone 4 targets the area around Holy Cross Secondary School and Village Crescent, directly north of Bridlewood and Harper Park. Zone 5 is in an area of both commercial and smaller-lot, high-density residential development. Zone 6 targets another highly impervious residential area around Cahill Drive and Forester Avenue where stormwater runoff drains openly into the creek, and it appears no stormwater controls are currently being employed.

4.5 Subwatershed Imperviousness

The Harper Creek Subwatershed is divided between parks, undeveloped land with no plant cover, residential, public (schools and churches), industrial, and commercial land uses. Parks account for the highest land use, at 40% of the total subwatershed area. Residential areas make up the second largest portion of the basin, at 31% of the total area. Undeveloped areas represent 11% of the total land use, while commercial, public, and industrial land uses each represent less than 10% of the total subwatershed area, at 9, 5, and 4 percent respectively. Figure 8 on the following page graphically displays the division of land use within the Harper Creek Subwatershed.

Residential areas within the Harper Creek Subwatershed have the greatest impact on imperviousness within the basin, particularly 12m lots which have a higher runoff coefficient than 15m lots or larger. However, commercial zones while only constituting 9% of the subwatershed area amount to almost 10% of the total subwatershed imperviousness. Figure 9 on the following page graphically displays the relative imperviousness each land-use contributes to with the Harper Creek subwatershed.

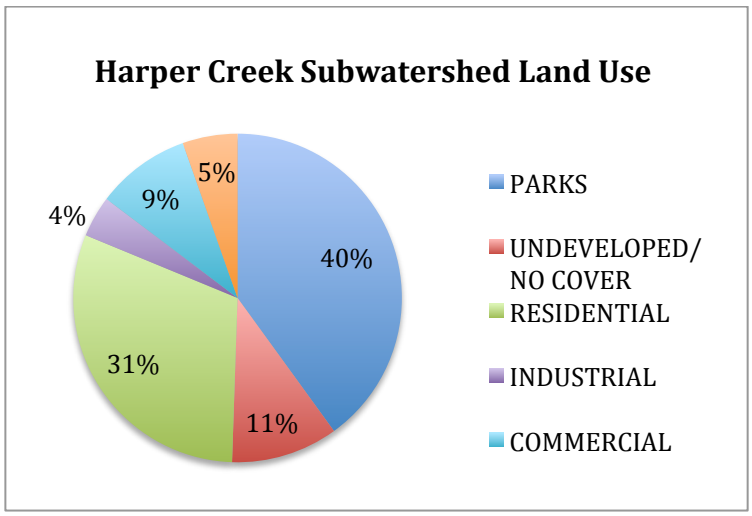


Fig 8. Broad land use types within the Harper Creek Subwatershed broken down by percentage of total subwatershed area.

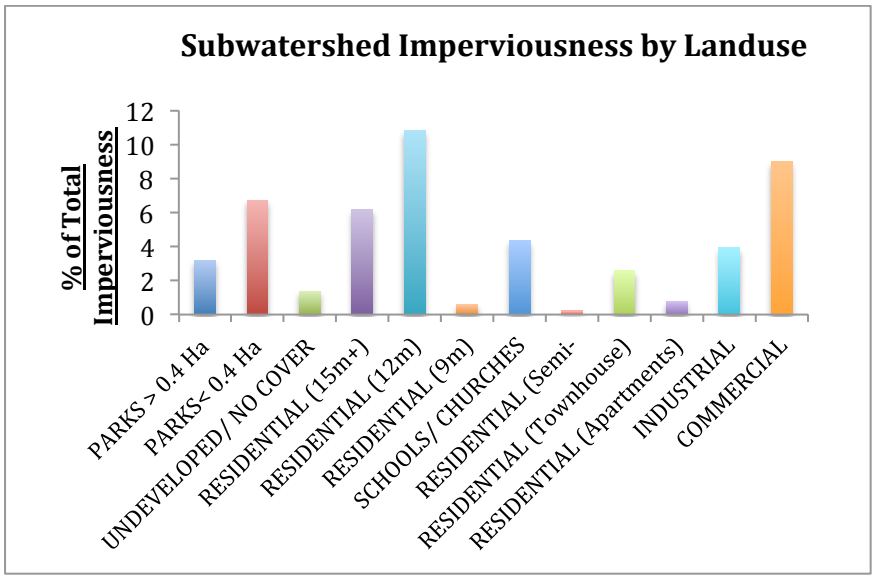


Figure 9. Breakdown of total subwatershed imperviousness by land use, and associated runoff coefficient.

Table 4B in Appendix B summarizes the calculations completed in order to determine total subwatershed imperviousness. It was found that the subwatershed is currently 49% impervious.

4.6 Summary Runoff Calculations

Table 5 in Appendix B summarizes the calculations completed in order to determine peak runoff for 10, 25, and 50 year return periods, as well as average annual runoff. The Harper Creek subwatershed has a concentration time of approximately 130 minutes. Peak runoff for storm intensities with a 10 year return period can reach 34 m^3 / second, while for 25 year storms that value increases to approximately

40 m^3 / sec and for 50 year storm events that figure can be as high as 44.84 m^3 / second. Average annual runoff is around 1219.5 $m^3 \times 10^3$.

5.0 Analysis

5.1 Limitations of Methodology and Potential Sources of Error

There are some notable limitations of the methodology chosen that will be disclosed in order to present a transparent analysis of the results. Firstly, while the use of runoff coefficients is consistent with Peterborough's Engineering and Design standards, these values are based upon average generalizations and do not always hold true to reality. For example, there is a relatively large change in runoff coefficient between very small variations in lot width within residential areas, but upon assigning these values and viewing the aerial imagery in addition to the parcel fabric data, it was apparent that house size did not always correlate to lot size. There were often very large lots with equally large houses on them (and less green space than some other smaller lots). This can lead to some inconsistencies within the true and mapped runoff realities in the area. Furthermore, parkland runoff coefficients are determined by the area in hectares, however the green spaces in the region have been sectioned into small, detached, parcels of larger green spaces. If the aerial imagery had not been present I may have assumed that these were small, disconnected, parcels of green space, rather than one large green space sectioned into multiple parcels. While the aerial imagery was instrumental in overcoming some of these obstacles, some of the images were taken during development stages within the watershed, and show construction of residential lots. For these circumstances it was assumed that the lot sizes stayed the same. Overall this method of assigning and mapping runoff coefficients was labour intensive, and other pixel related programs could potentially be used in the future to reduce this labour.

There were also some notable gaps in the data that must be addressed. Streets were not considered in the calculation of imperviousness within the watershed, as parcel-mapping data was provided in the form of lines, rather than polygons. The roads were graphically displayed as red in keeping with the theme of the stormwater hotspots, however the area was never calculated and

included in the final imperviousness exercises. This is a serious and notable gap. Furthermore, abstractions from stormwater ponds were not included in runoff calculations, potentially leading to an overestimation of concentration time and peak runoff rates. Thus the results presented more accurately depict the peak runoff in the subwatershed if neither roads, nor stormwater ponds exist. Not having the roads accounted for leads to the results being skewed lower, while not having the stormwater ponds would leads to the results being skewed higher. It's not clear if or how these two concerns balance each other out. Although the roads were not included as a source of watershed imperviousness, their area was also excluded from the total area of the subwatershed. Thus the results accurately depict the runoff characteristics from all the properties and potential manageable areas within the subwatershed.

5.2 Priority Stormwater Management Zones

In this section each identified priority stormwater management zone will be explored individually in greater detail to justify why it was chosen, and potential opportunities for stewardship projects in the area. By overlaying all criteria data such as high imperviousness, elevation, pre-existing stormwater management techniques, stormwater outflows, open ditch and culvert drainage and pollution sources (industrial and commercial properties) it became clear that there are a number of prime areas for new mitigation methods, especially in the form of rain gardens. These stewardship goals could be accomplished through programs with Peterborough GreenUp's depave paradise program as well as their new Sustainable Urban Neighbourhoods initiative.

Zone 1

Zone 1 is located in an area of high slope, and high stream placement, within a commercial zone (Hockey Sushi/ No Frills Plaza) that has relatively no opportunity for drainage at current levels of imperviousness. Zone 1 was given primary importance due to the severe lack of infiltration opportunities currently in the area. Furthermore, by placing a rain garden in this high-elevation, upper subwatershed location stormwater infiltration will very slowly aid in groundwater recharge, and filter as it percolates the distance towards Harper Creek. There are currently no control methods being

implemented in this area, and as a busy plaza, there are many pollutants such as oils, gasses, car exhaust, and food waste that are probably currently being directed into Harper Creek. Given the constraints of the parking lot's necessity for the adjacent establishments it may be difficult to gain approvals to depave sections of the asphalt. However, one innovative concept could be implementing curb cuts, and replanting the already existing medians bordering the plaza as a large rain garden which could capture the runoff from this area.

Figure 10. Google Maps satellite aerial imagery of Stormwater Management Priority Zone 1

Zone 2

Zone 2 is similarly in an area of high slope, close to the northern headwaters of Harper Creek, and surrounded by other highly impervious areas. Zone 2 was selected not only for its placement within the stream network, and impervious catchment, but also because there are some large pollutant sources identified in the region, such as a gas station, hardware centre, and car dealership. There is relatively no opportunities for natural drainage in this zone, however the Applewood Retirement Residence has a small patch of greenery in front and on the east borders of their building. This area could potentially be converted into two rain gardens to mitigate the runoff coming off these heavily paved properties. The retirement home is suggested for this project as as rain gardens are generally

quite aesthetic, and there is an opportunity to work with volunteers and members of the community to create this beautiful and functional feature for the guests at Applewood Retirement Residence, furthermore, it is directly adjacent to the Ultramar, so this project could help to reduce gasoline residues from being transferred downstream.

Figure 11. Google Maps satellite aerial imagery of Stormwater Management Priority Zone 2

Zone 3

Zone 3 targets the highly polluting industries adjacent to the Harper Park, particularly the Coach Canada bus yard, which represents a highly paved area, and source of pollutants, which currently drains directly into open sections of the creek on Webber Avenue. Putting a rain garden, or, preferably bio-retention unit, in this location would capture and contain the polluted runoff from this area and allow for phytoremediation processes to remove the pollutants from these discharges.

Zone 4

Zone 4 targets the area around Holy Cross Secondary School and Village Crescent, directly north of Bridlewood and Harper Park. There is currently a stormwater pond behind the residences on Village Crescent which has been left unmaintained and overflowing into Bridlewood Park. Although maintaining this infrastructure is primary priority in this zone, there is opportunity for Holly Cross Secondary School to implement a rain garden above their track, where there is already a circular paved area that does not

Figure 12: Google Maps satellite aerial imagery of Stormwater Management Priority Zone 3

appear to be useful for any particular purpose. In communication with Kim Zippel in early stages of this research, this area was identified as a potential priority area due to its location in the upper watershed, and the designation of Holly Cross as an "Eco School" with a focus on incorporating environmental programming and sustainability initiatives. This is another project in which volunteer participation and community cooperation could be achieved.

Figure 13: Google Maps satellite aerial imagery of Stormwater Management Priority Zone 4

Zone 5

Zone 5 is in an area of both commercial and smaller-lot, high-density residential development at Brealey Drive and Lansdowne St west, and was actually the area in which the highly successful Wireless Solutions Rain Garden was implemented. The rain garden was not marked on the stormwater hotspots map, thus this area was selected through the prioritization scheme without realizing that stormwater management in this zone has actually already been addressed! Unfortunately through personal communication with GreenUp it has been mentioned that this rain garden may not be exist in the future due to owner concerns regarding maintenance. Thus this area is still a relevant location for further rain garden projects. Some projects could be implemented in the neighbourhood around Stewartcroft Crescent, where there is currently high-density housing.

Figure 14: Google Maps satellite aerial imagery of Stormwater Management Priority Zone 5.

Zone 6

Zone 6 targets another highly impervious residential area around Cahill Drive and Forester Avenue where stormwater runoff drains openly into the creek, and it appears no stormwater controls are currently being employed. While there is a stormwater pond north, and west of this development,

there does not seem to be any kind of controls within this zone, and the stormwater currently drains directly into reaches of Harper Creek. Although there would not be a significant change in stormflow by implementing infiltration techniques here, there is still an opportunity for pollutant reduction through the use of rain gardens, lined bio-retention units or potentially another small stormwater pond.

Figure 15: Google Maps satellite aerial imagery of Stormwater Management Priority Zone 6.

5.3 Impacts of Imperviousness and Land Use Change on Harper Creek

The harper creek subwatershed is immensely urbanized. Total imperviousness was calculated at 49% exclusive of roads. It can be stated that the subwatershed is most likely over 51% impervious if roads were factored into the equation. While parks greater than 4 hectares (ie. Harper Park) were the largest single land use for the Harper Creek watershed at 26%, parks have the lowest runoff coefficient at 0.2, thus these areas only contribute to a meagre 7% of total runoff contributing area from imperviousness. This finding makes logical sense as heavily vegetated areas with healthy, undisturbed soils are highly permeable, and vital to the infiltration of stormwater runoff. Conversely, roughly 36% of the watershed is made up of dense residential housing, with runoff coefficients between 0.55 to 0.75 depending on the lot size. The residential sector contributes greatly to the overall problem of

imperviousness. Furthermore, commercial and industrial buildings are highly impermeable urban features, often with large parking lots, and hard metal roofs, which do not allow for much, if any, natural drainage at all. These features have a runoff coefficient of 0.9, and represent around 20% of the entire watershed. These areas disproportionately impact overall imperviousness and pollutant loading into Harper Creek. The Harper Creek subwatershed is currently extremely urbanized particularly vulnerable to new development, and in critical need of mitigation for the already intense hydrological shifts that are occurring.

As impervious cover increases, stream health decreases. The Impervious Cover Model (ICM) provides a generalization of this relationship. Figure 16 below shows that as little as 10% impervious cover negatively impacts stream health. Beyond 25%, stream health is degraded and beyond 60%, it is considered to be drainage (Schueler, *et al.,* 2009). Thus with a roughly 50% impervious watershed, it is truly impressive that Harper Creek still maintains it's characteristic cold-waters and supports aquatic species. Much of this resilience may be due to the filtration properties of the large wetland complexes. If headwater areas have minimal impervious cover, and urban areas with high imperviousness are located only in the higher-order sections of the watershed, streams may have a better chance of maintaining integrity, however neither of these factors are currently true for the Harper Creek subwatershed (Environment Canada, 2013).

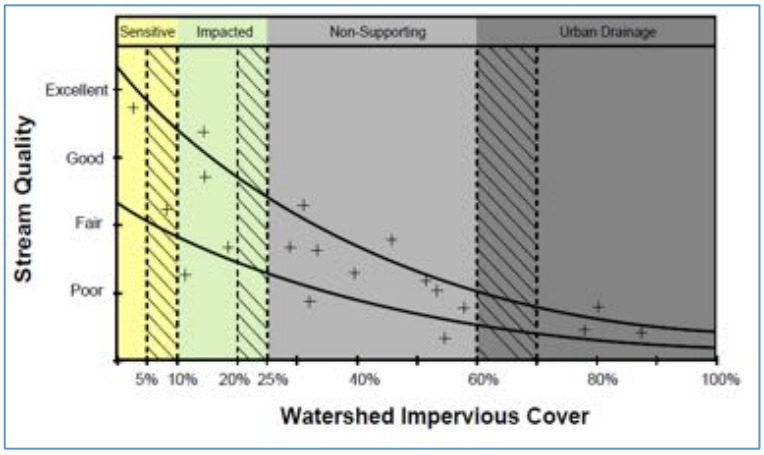


Figure 16. Impervious Cover Model reproduced from (Schueler, et al., 2009).

Environment Canada's document "*How much habitat is enough?"* published in 2013 provides guidelines for preserving ecosystems from degradation. The guideline for urbanizing watersheds is less than 10% impervious land cover in order to preserve the abundance and biodiversity of aquatic species. Significant impairment in stream water quality and quantity is highly likely above 10% impervious land cover and can often begin before this threshold is reached. In urban systems that are already degraded, a second threshold is likely reached at the 25 to 30% level (Environment Canada, 2013).

Highly impervious watersheds experience severe impacts including loss of fish and wildlife habitat, along with channel erosion and downstream flooding. Urban development both magnifies peak discharges and creates new peak runoff events. Studies cited by Environment Canada detail relationships between imperviousness and runoff characteristics, stream morphology, water quality, pollutant loading, stream warming, as well as aquatic biodiversity (2013). In justifying the 10% imperviousness threshold Environment Canada cites a number of studies on cold-water creeks and brook trout populations. Wang and Kanehl (2003) found that high-quality macroinvertebrate communities were possible in cold water streams if impervious land cover constituted less than 7% of the watershed area, but that low quality index scores were inevitable above 10% imperviousness (Environment Canada, 2013). Imperviousness levels between 7 and 10% represented a threshold for urban developments where minor changes in urbanization could result in major changes in cold-water stream macroinvertebrate communities (Environment Canada, 2013). Stranko et al. (2008) observed Brook Trout presence in small suburban and urban streams to be strongly positively correlated with watershed forest cover and their absence from cold water streams with as little as 4% watershed impervious cover. Furthermore, negative linear responses for Brook Trout still occur below the 10% threshold (Environment Canada, 2013). Guideline values of 5 to 7% impervious cover provide a more conservative limit for urbanizing watersheds, though they may be difficult to obtain and maintain. For urban watersheds that have, to date, exceeded the 10% impervious surface guideline, a second

threshold of 25 to 30% or less impervious surfaces is suggested (Environment Canada, 2013). These findings make the continued presence of a healthy native Brook Trout population in the Harper Creek subwatershed particularly remarkable, and of true ecological and scientific significance.

6.0 Peterborough Stormwater Policy Landscape

6.1 Towards Solving the Problem of Imperviousness

Various factors have impeded the transition from conventional stormwater management to widespread implementation of integrated sustainable watershed based stormwater management. The focus here is on watershed scale solutions as there is a need for consistent institutional, legislative, economic, and social shifts across the watershed if implementation of low impact development is to be effective at achieving hydrological restoration goals. Seven barriers towards LID implementation have been identified by Roy *et al.* 2008, including: uncertainties in the performance and costs, insufficient engineering standards and guidelines, fragmented environmental jurisdictions and responsibilities, inadequate institutional capacity, lack of legislative mandate, lack of sufficient funding and market incentives, and finally resistance to change.

However, many of these concerns have already been resolved. For example, the Toronto and Region Conservation Authority's *Low Impact Development Stormwater Management Planning and Design Guide* (2010) devotes entire sections on engineering standards, cost performance, and current Ontario legislation, in addition to identifying opportunities for LID implementation at the local, neighbourhood, and watershed scale. This is a comprehensive guide, which is available to the public, and very clearly explores the motivation and methods for implementing LID practises within municipalities across Ontario. XCG Consultant's Stormwater Quality Management Master Plan (2014) identifies the following barriers for LID implementation in Peterborough: "The desire or requirement for urban intensification; what private developers consider to be market preferences; accepted approaches to site and roadway design that have evolved over decades and have proven efficacy, but which may inadvertently hinder true innovation; the need to meet regulatory requirements for stormwater

treatment and flow control, and adhere to specific guidelines from regulatory agencies, that may also dictate or promote certain design approaches, at the expense of true innovation; and, the potential for higher cost to implement innovative design because of what may be requirements for new construction approaches, new materials or structures, or because of added complexity in obtaining necessary approvals." It is the view of this researcher that these excuses are insufficient deterrents for LID implementation in Peterborough. Many LID techniques (such as rain gardens, and vegetated swales) can be seamlessly integrated into the landscaping of a home or building, thus the argument regarding market preferences and space requirements are weak at best. Further, there is a wide range of literature criticizing the standard site and roadway design for stormwater in regards to how these methods fail to meet flow control and water quality measures, indeed it is these shortfalls which have provided motivation for this research project. Finally, it has been proven throughout the literature that LID is cost effective, and saves between 20 and 80% of the cost of standard stormwater conveyance models, even when maintenance is factored in (Roy *et al.* 2008). The United States Environmental Protection Agency determined an average 35% total capital cost savings for municipalities through the integration of green infrastructure to reduce the load and maintenance requirements on historic grey infrastructure. The decentralized nature of these techniques does make it difficult to assure that they are functioning appropriately over time. (Keely, 2007). Thus, appropriate maintenance of LID projects must be adhered to and monitored to ensure their efficacy. However, this represents just a small barrier in comparison to the wide range of benefits that can be obtained from implementing these projects at a local, neighbourhood, or watershed-scale. Instead of rejecting this innovation, Peterborough has a great opportunity to encourage these new projects, to address current stormwater infrastructure deficits and enhance local water quality.

6.2 Watershed Based Stormwater Policies

The expanding understanding of urbanization effects on hydrology, in addition to broad stormwater funding and infrastructure shortfalls amongst many municipalities has led to a political

environment which is open to considering stormwater burden at the scale of individual parcel lots. This circumstance is a response to the notion that infiltrating rainfall in locations close to where it first falls is an effective approach to restoring regional hydrology and improving surface water quality (Keely, 2007). In addition, stormwater user fees are becoming more and more common, and accepted as a necessary means of addressing flood risks, and increasing infrastructure demands due to expansion (Bradford, & Gharabaghi, 2004). Finally, recent advances in remote sensing have made parcel-level data suitable for this purpose readily available and fairly inexpensive (Keely, 2007).

One of the main benefits of individual parcel assessments for stormwater user fee planning is the transformation of nonpoint source pollution from stormwater runoff into a point-source problem. It is very difficult to directly trace the cumulative downstream impacts of urban imperviousness to individual contributors, however, it is fairly easy to determine how much runoff is coming off of an individual property. Therefore, by distributing the responsibility for mitigating these cumulative impacts amongst all contributing properties, the impacts can be more appropriately addressed, and the burden is equally distributed amongst all contributors (Parikh, *et al.* 2011). Another beneficial consequence of these individual parcel-based fees is the increased public awareness of the environmental impacts of imperviousness within their watershed (Keely, 2007). This understanding could potentially increase the public acceptance of stormwater fees, and motivate individual actions to reduce property related impacts on the local environment (Keely, 2007).

In addition to addressing parcel-level impacts and stormwater infrastructure needs, there is a great opportunity within these types of fees to provide economic incentives towards reducing the level of imperviousness on a lot by lot basis through the implementation of rain gardens and other LID projects (Parikh, *et al.* 2011). These projects can be partially or fully subsidized by the municipality or be used as a means of lowering the property-based stormwater fee, depending on the need. Some areas in Minnesota have found success funding rain garden projects based upon the quantifiable water quality

improvement from the LID project. This approach looks at the cost of removing the phosphorus or nitrogen that would have entered a local stream from the runoff produced by the property, and offers this amount for the implementation of the rain garden (Schmidt, personal comm., Oct. 2016). This is a novel concept in that it quantifies, and rewards the project based upon the 'good' that it creates, in contrast to the stormwater fee, which quantifies the 'bads' that the impermeable area on each property contributes to.

Another innovative alternative approach to direct subsidies is a tradeable allowance/ emissions trading system (similar to cap and trade) whereby land developers who find it relatively expensive to implement the required level of stormwater quality management within their own development can purchase a stormwater quality offset which will fund management in other locations (Parikh, *et al.* 2011). During one of the public consultations for the Peterborough Water Resource Funding Study, it was noted by a man in attendance that the downtown core has much less opportunity to reduce their impervious land cover, as there is a legal mandate for dense development (Guiel, personal comm., Sept. 2016). Thus, such a system could be used to make the stormwater fee more equitable to all property owners, and encourage low impact development within prioritized areas with the greatest environmental values to be protected. Often these techniques have not been utilized as setting a cap on watershed level runoff or impervious surfaces can be seen as legally challenging however, in my early stages of research this seems like a very promising alternative to a simple rebate for LID (Parikh, *et al.* 2011). This program could ensure stormwater infrastructure funds are still met, create a balance between property opportunities and constraints, and encourage the use of low impact developments where they're needed most (Parikh, *et al.* 2011).

6.3 Peterborough Stormwater Funding Study

In response to many of the concerns identified throughout this report, and the City of Peterborough's *Stormwater Quality Management Plan* (2014), Flood Reduction Master Plan (2010) and a number of other studies, the City of Peterborough recently commissioned a Water Resource

Stormwater Funding Feasibility study to determine an appropriate stormwater funding model to address infrastructure budgetary shortfalls. Like other Ontario municipalities, the City of Peterborough has encountered increasing requirements for stormwater management because of regulations, aging infrastructure, changing weather patterns, and community growth (Bradford & Gharabaghi, 2004). The goal of this study is to find sustainable funding options that will create an equitable, self-supporting, and dedicated budget source for stormwater management in Peterborough (Ehl, 2016).

The preliminary results from this study have found that the City of Peterborough would prefer a varied-rate stormwater fee based upon individual parcel lots. The 'polluter pays' approach, whereby people pay for stormwater based on the amount of runoff generated by an individual property is preferential because it recognizes how much stormwater each property creates, and therefore must be managed by the City to reduce flooding and protect water resources (Ehl, 2016). The funding committee has found that the variable-rate approach would be less expensive in terms of administration than a tiered flat fee, and easier to explain to the public. The plan for this policy is already considering subsidies and credits for stormwater management measures on individual properties, and the potential need for rate relief for low-income households (Ehl, 2016).

The basic concept for this policy was approved by City Council on November 7th, and the committee presented a formal report and recommendations to Peterborough City Council on Feb 6th 2017. Within this report, a mix of affordable and sustainable green, gray, and natural infrastructure was recommended for used to manage storm related infrastructure, as well as pollutant lot level control measures as a complement to traditional stormwater controls. This report detailed funding strategies to address current budget constraints equally roughly 6million dollars per annum and recommended that a stormwater fee be established within the all-inclusive tax budget. City council chose to accept some of the recommendations, particularly to find a dedicated source of stormwater funding through a

dedicated fee within the all-inclusive tax budget, but did not commit to meeting the roughly 6 million dollar targets in allocating these funds.

The following week (February 13, 2017) I was able to present some of my findings from this research to stress the need for incorporating more green infrastructure both from an economic and environmental standpoint. I also discussed the effective way in which determining priority locations and incentivising projects in this area can be accomplished through user fees and trade and offset programs. The presentation was well received, and it is my hope that explicit incentives for reducing impermeable land-cover, especially in prime locations, can be incorporated to guide some rehabilitation of Peterborough's natural hydrological regime.

7.0 Future Studies

7.1 Ongoing Research in the Harper Creek Watershed

The Peterborough field naturalists and other advocates for Harper Creek and Harper Park are ensuring that no new developments are approved without the city discussing the impacts these developments are having on Harper Creek. Although the Casino plan adjacent to Harper Creek has been approved, the new status of Harper Park's wetland complex as Provincially Significant may impact the type of stormwater control methods and buffers necessary surrounding this development, and lead to better protections for the creek. In the spring of 2017 a new study of the Brook Trout within Harper Creek will begin in partnership between Peterborough Field Naturalists and Trent University. This study will help to understand the resilient Brook Trout population in Harper Creek and define the population's movement patterns (Trent School of the Environment, 2017).

7.2 Recommendations for Future Research

Future research in this subwatershed could also focus on the establishment of stormwater diversion goals, and designing a comprehensive plan to reduce the level of imperviousness within the Harper Creek Subwatershed to roughly the 30% threshold if possible. Another important future focus of research could be mapping groundwater recharge within the Harper Creek Subwatershed, to better

understand where to target hydrological restoration. Finally, other studies in Peterborough could include a similar permeability priority assessment for other urban creeks in the region, such as Jackson Creek, Baxter Creek, or Byersville Creek. It is my sincere hope that this research can have important implications for the protection of the Harper Creek subwatershed, and the adoption a more holistic approach to city planning which considers the watershed as a whole, and the impact that urbanization can have on these vital water resources.

Works Cited

Bradford, A., & Gharabaghi, B. (2004). Evolution of Ontario's stormwater management planning and design guidance. *Water Quality Research Journal of Canada*, *39*(4), 343-355.

Boyd, M., Bufill, R., & Knee, R. (1993) Pervious and impervious runoff in urban catchments, *Hydrological Sciences Journal*, 38: (6), 463-478, DOI:10.1080/02626669309492699

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., & Hatt, B. E. (2012). Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape and Urban Planning*, *105*(3), 230-240.

City of Peterborough, (2015). *Engineering Design Standards.* Utility Services Department. Peterborough, Ontario.

Cole Engineering (2012). *Detailed sanitary sewer EA for the mitigation and management of extraneous flows into the sanitary system master plan. (*WIO-194). Peterborough, Ontario. City of Peterborough.

Dhalla, S., & Zimmer, C. (2010). Low Impact Development Stormwater Management Planning and Design Guide. *Toronto and Toronto and Region Conservation Authority: Toronto, ON, Canada*, 300.

Ehl, T. (2016). Peterborough Water Resource Funding Study Consultation Notes. Peterborough City Council, October, 2016.

Environment Canada. (2013). *How Much Habitat is Enough? (3rd)*. Environment Canada, Toronto, Ontario.

Guo, Y., & Adams, B. J. (1999). Analysis of detention ponds for stormwater quality control. *Water resources research*, *35*(8), 2447-2456.

Green Communities Canada. (2016). The stormwater story RAIN community solutions. Retrieved from http://www.raincommunitysolutions.ca/en/for-property-owners/rain-story/

Harbor, J. M. (1994). A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology. *Journal of the American Planning Association*, *60*(1), 95-108

Horvath, E. (2011). Using GIS for Prioritization in Subwatershed Restoration *Submitted to The Pennsylvania State University for Master in Geographic Information System*.

Houle, J. J., Roseen, R. M., Ballestero, T. P., Puls, T. A., & Sherrard Jr, J. (2013). Comparison of maintenance cost, labor demands, and system performance for LID and conventional stormwater management. *Journal of environmental engineering*, *139*(7), 932-938.

Keeley, M. (2007). Using individual parcel assessments to improve stormwater management. *Journal of the American Planning Association*, *73*(2), 149-160.

Lee, G. F., Jones-Lee, A., Drive, E. E. M., & Macero, E. (2004). Urban Creek and Lake Water Quality Issues as Impacted by Urban Stormwater Runoff. *Report by G. Fred Lee & Associates, El Macero*, 11-53.

Leopold, L. B. (1968). Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use. *Geological Survey 554.* Dept. of the Interior. Washington, USA.

Marsalek, J., Cisneros, B. J., Karamouz, M., Malmquist, P. A., Goldenfum, J. A., & Chocat, B. (2008). *Urban Water Cycle Processes and Interactions: Urban Water Series-UNESCO-IHP* (Vol. 2). CRC Press.

Martin-Mikle, C. J., de Beurs, K. M., Julian, J. P., & Mayer, P. M. (2015). Identifying priority sites for low impact development (LID) in a mixed-use watershed. *Landscape and Urban Planning*, *140*, 29-41.

Mitchell, G. (2005) Mapping hazard from urban non-point pollution: A screening model to support sustainable urban drainage planning. *Journal of Environmental Management*: 74(1) 1-9

Mittag, M., Medina, D. E., Kealy, M. J., Brown, B., & Byrd, J. (2006). Stormwater Management

Techniques for Ecosystem Restoration using Flow Regime Improvements. *Proceedings of the Water Environment Federation*, *2006*(13), 677-702.

Otonabee Conservation. (2013). *Harper Creek Management Plan, Final Report.* City of Peterborough:Otonabee Conservation.

Otonabee Conservation. (2004). *Harper Creek Opportunities and Constraints Study.* City of Peterborough: Otonabee Conservation.

Parikh, P., Taylor, M. A., Hoagland, T., Thurston, H. W., & Shuster, W. (2011). At the intersection of hydrology, economics, and law: application of market mechanisms and incentives to reduce stormwater runoff. *Economic Incentives for Stormwater Control*, 167.

Perez-Pedini, C., Limbrunner, J. F., & Vogel, R. M. (2005). Optimal location of infiltration-based best management practices for stormwater management. *Journal of water resources planning and management*, *131*(6), 441-448.

Ray, H. (2015). *Depave Paradise Final Report*. Peterborough GreenUp. Internal Report For submission to Green Communities Canada.

Roy, A. H., Wenger, S. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., Shuster, W. D., Hale, W. T., & Brown, R. (2008). Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environmental management*, *42*(2), 344-359.

Schueler, T. R., Fraley-McNeal, L., & Cappiella, K. (2009). Is impervious cover still important? Review of recent research. *Journal of Hydrologic Engineering*, *14*(4), 309-315.

Tetra Tech Inc. (2010). *Stormwater Best Management Practises (BMP) Performance Analysis.* United States Environmental Protection Agency - Region 1. Boston, MA.

Thomas, D. M., & Benson, M. A. (1970). *Generalization of streamflow characteristics from drainage-basin characteristics*. US Government Printing Office.

Tixier, G., Lafont, M., Grapentine, L., Rochfort, Q., & Marsalek, J. (2011). Ecological risk assessment of urban stormwater ponds: literature review and proposal of a new conceptual approach providing ecological quality goals and the associated bioassessment tools. *Ecological Indicators*, *11*(6), 1497-1506.

Trent School of the Environment, (2017). Harper Creek brook trout study. https://www.trentu.ca/environment/faculty-research/harper-creek-brook-trout-study

Wedley, B. (2012). *City has been illegally dumping waste at former Harper Rd. landfill site.* Retrieved October 03, 2016, from: http://www.thepeterboroughexaminer.com/news/archives/2012/05/11

Wong, T. S. (2005). Assessment of time of concentration formulas for overland flow. *Journal of Irrigation and Drainage Engineering*, *131*(4), 383-387.

XCG Consultants Ltd. (2014). *Stormwater quality management master plan final project report*. (XCG File No.: 3-2087-12-01) Oakville, Ontario. City of Peterborough.

Appendix A: Diagrams and Reference Figures

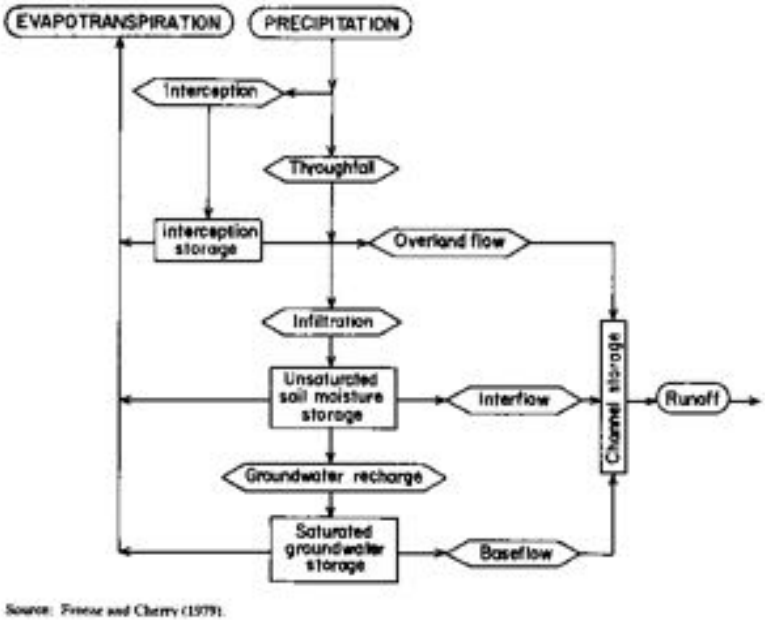


Figure 1A. The hydrological cycle schematic diagram with different hydrological processes (reproduced from Freeze and Cherry, 1979).

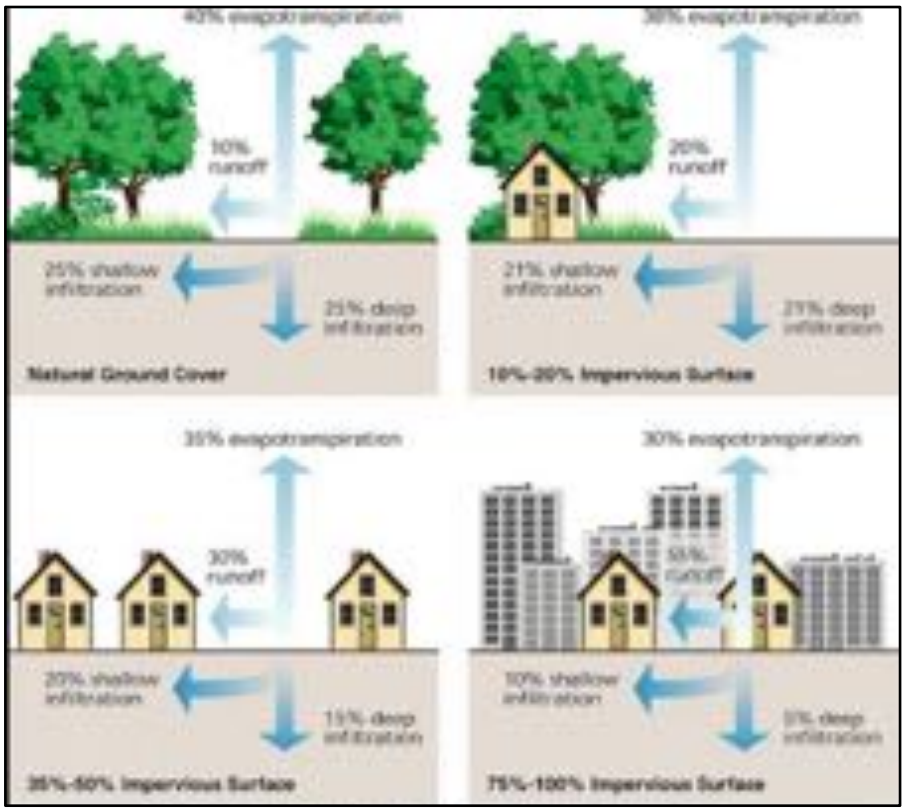


Figure 2A. The basic hydrological effect of landuse change within the urban water cycle (USDA, 1998).

Location summary

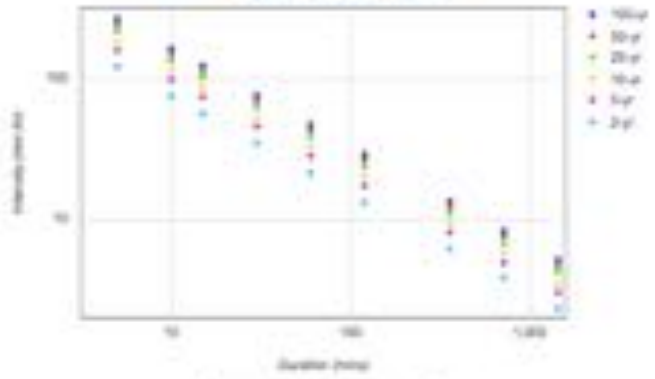
These are the locations in the selection.

IDF Curve: 44° 13' 45" N, 78° 22' 14" W (44.229167,-78.370833)

Results

An IDF curve was found.

Coordinate: 44.229167, -78.370833
IDF curve year: 2010



* Switch variable: Intensity or Depth

Coefficient summary

Data year: 2010
IDF curve year: 2010

Click a return period in the table header for more detail.

Return period	2-yr *	5-yr *	10-yr *	25-yr *	50-yr *	100-yr *
A	21.3	28.1	32.6	38.3	42.0	46.7
B	-0.699	-0.699	-0.699	-0.699	-0.699	-0.699

Statistics

Rainfall intensity (mm hr^{-1})

Duration	5-min	10-min	15-min	30-min	1-hr	2-hr	6-hr	12-hr	24-hr
2-yr *	121.0	74.5	56.1	34.6	21.3	13.1	6.1	3.8	2.3
5-yr *	159.6	98.3	74.1	45.6	28.1	17.3	8.0	4.9	3.0
10-yr *	185.2	114.1	85.9	52.9	32.6	20.1	9.3	5.7	3.5
25-yr *	217.5	134.0	100.9	62.2	38.3	23.6	10.9	6.7	4.2
50-yr *	241.4	148.7	112.0	69.0	42.5	26.2	12.1	7.5	4.6
100-yr *	265.3	163.4	123.1	75.8	46.7	28.8	13.3	8.2	5.1

Rainfall depth (mm)

Duration	5-min	10-min	15-min	30-min	1-hr	2-hr	6-hr	12-hr	24-hr
2-yr *	10.1	12.4	14.0	17.3	21.3	26.2	36.5	45.0	55.4
5-yr *	13.3	16.4	18.5	22.8	28.1	34.6	48.2	59.4	73.1
10-yr *	15.4	19.0	21.5	26.5	32.6	40.2	55.9	68.9	84.9
25-yr *	18.1	22.3	25.2	31.1	38.3	47.2	65.7	80.9	99.7
50-yr *	20.1	24.8	28.0	34.5	42.5	52.4	72.9	89.8	110.6
100-yr *	22.1	27.2	30.8	37.9	46.7	57.5	80.1	98.7	121.6

Figure 3A: IDF Curve for Peterborough Airport, nearest gauging station to Harper Creek, obtained from Ontario Ministry of Transportation IDF Curve Look Up Tool.

Appendix B: Tables

Table 1B. Commonly cited studies of stormwater constituents, and contaminant values. Reproduced from Marsalek*, et al*. 2008.

Chemical constituent	Units	Urban stormwater		European CSO data
		Mean of Duncan's dataset (1999)	U.S. NURP Median site (U.S. EPA, 1983)	(Marsalek et al., 1993)
Total suspended solids (TSS)	mg/L	150	100	50-430
Total phosphorus	mg/L	0.35	0.33	2.2-10
Total nitrogen	mg/L	2.6	-	8-12
Chemical Oxygen Demand, COD	mg/L	80	65	150-400
Biochemical Oxygen Demand, BOD	mg/L	14	9	45-90
Oil and grease	mg/L	8.7	-	-
Total lead (Pb)	mg/L	0.140	0.144	0.01-0.10
Total zinc (Zn)	mg/L	0.240	0.160	0.06-0.40
Total copper (Cu)	mg/L	0.050	0.034	-
Faecal coliforms	FCU/100 mL	8,000	-	10^4-10^7

Table 2B. Values for Peterborough Stormwater Quality compared to US National Stormwater Quality Database, Reproduced from Peterborough Stormwater Quality Master Plan (XCG, 2014)

Parameter	Units	US NSQD Medians (Jan. 2004)	Peterborough 2011 medians	
			Outfalls (25 Outfalls, 2 Events = 50 Samples)	Stormwater pond influent (33 Inlets, 2 Events = 66 Samples)
Total phosphorus	mg/L	0.27	0.13	0.15
Nitrite + Nitrate	mg/L	0.6	0.49	0.84
Total Suspended Solids	mg/L	58	37	56
Fecal coliform	CFU/100mL	5,081	n.r	n.r
E. coli	CFU/100mL	n.r.	635	530
Cadmium	mg/L	0.001	0.0003	0.0004
Copper	mg/L	0.016	0.0076	0.0059
Lead	mg/L	0.016	0.010	0.006
Zinc	mg/L	0.116	0.031	0.027

Notes:
"n.r." = not reported.
E. coli densities typically 0.7 to 0.9 that of fecal coliform.

Table 3B. Runoff Coefficients from Peterborough Engineering Design Standards, 2015

Zoning	Coefficient
PARKS > 0.4 Ha	0.20
PARKS< 0.4 Ha	0.25
UNDEVELOPED/ NO COVER	0.35
RESIDENTIAL (15m+)	0.55
RESIDENTIAL (12m)	0.65
RESIDENTIAL (9m)	0.75
SCHOOLS/ CHURCHES	0.75
RESIDENTIAL (Semi-Detached)	0.80
RESIDENTIAL (Townhouse)	0.85
RESIDENTIAL (Apartments)	0.90
INDUSTRIAL	0.90
COMMERCIAL	0.90

Table 4B. Harper Creek Subwatershed Imperviousness Calculation

SUMMARY IMPERVIOUSNESS				
Zoning	Coefficient*	Area (m2)	% of subwatershed	Subwatershed Imperviousness
PARKS > 0.4 Ha	0.20	551185.83	16.04	3.208366331
PARKS< 0.4 Ha	0.25	924669.54	26.91	6.727945619
UNDEVELOPED/ NO COVER	0.35	135842.72	3.95	1.383758604
RESIDENTIAL (15m+)	0.55	387824.67	11.29	6.208033181
RESIDENTIAL (12m)	0.65	572813.93	16.67	10.83634536
RESIDENTIAL (9m)	0.75	27742.94	0.81	0.605577369
SCHOOLS/ CHURCHES	0.75	199517.74	5.81	4.355105542
RESIDENTIAL (Semi-Detached)	0.80	9462.46	0.28	0.220318016
RESIDENTIAL (Townhouse)	0.85	104017.36	3.03	2.573242225
RESIDENTIAL (Apartments)	0.90	30454.22	0.89	0.797711597
INDUSTRIAL	0.90	149515.45	4.35	3.916377007
COMMERCIAL	0.90	342881.41	9.98	8.981365219
Total		3435928.27	100.00	49.81414607

**Coefficients derived from Peterborough Engineering Design Standards 2015*

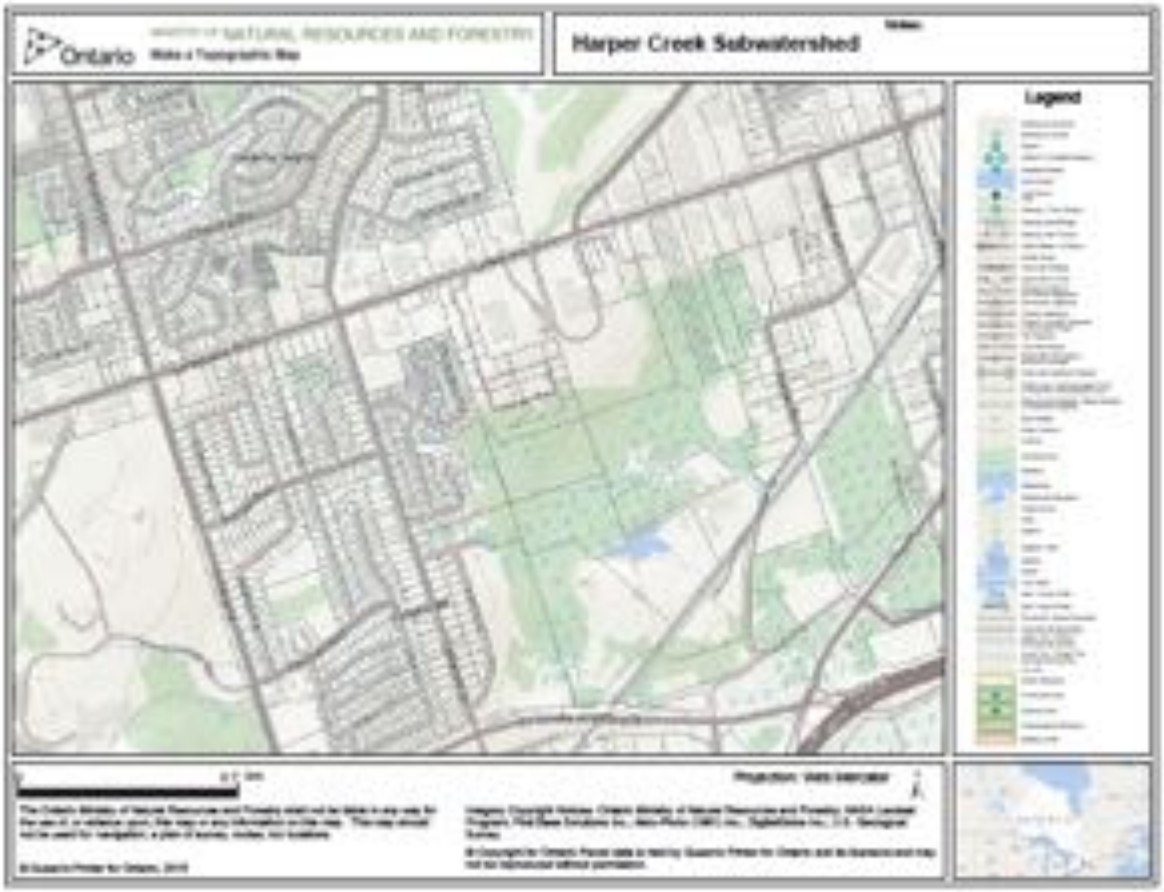
Table 5B. Summary Harper Creek Subwatershed runoff calculations, concentration time calculated using the FAA equation (1970), the rational method (Q=Cia) was used to calculate max runoff, and average annual runoff was calculated using the equation Vm=A*C*Pm where Vm is average annual runoff, A is area, C is runoff coefficient, and Pm is annual precipitation, annual precipitation value obtained from 1981-2010 Government of Canada Climate Normals Data for Peterborough Airport.

SUMMARY RUNOFF CALCULATIONS					Max Runoff (m3/s)			Average Annual Runoff (m3* $10^{\wedge 3}$)
Land Cover	Runoff Coefficient	Area (m2)	Weighting	Concentration Time (mins)	10 Yr	25Yr	50 Yr	
PARKS > 0.4 Ha	0.20	551185.83	16.04	31.22	2.22	2.60	2.88	78.54
PARKS< 0.4 Ha	0.25	924669.54	26.91	49.46	4.65	5.46	6.05	164.70
Undeveloped/ No cover	0.35	135842.72	3.95	6.41	0.96	1.12	1.25	33.87
RESIDENTIAL (15m+)	0.55	387824.66	11.29	13.42	4.29	5.03	5.58	151.97
RESIDENTIAL (12m)	0.65	572813.93	16.67	16.22	7.48	8.79	9.75	265.28
RESIDENTIAL (9m)	0.75	27742.93	0.81	0.61	0.42	0.49	0.54	14.825
SCHOOLS/ CHURCHES	0.75	199517.73	5.81	4.39	3.01	3.53	3.92	106.61
RESIDENTIAL (Semi-Detached)	0.80	9462.46	0.28	0.18	0.15	0.18	0.19	5.39
RESIDENTIAL (Townhouse)	0.85	104017.36	3.02	1.64	1.78	2.09	2.31	62.99
RESIDENTIAL (Apartments)	0.90	30454.22	0.89	0.38	0.55	0.65	0.72	19.52
INDUSTRIAL	0.90	149515.45	4.35	1.88	2.70	3.18	3.53	95.87
COMMERCIAL	0.90	342881.40	9.98	4.32	6.20	7.28	8.08	219.87
TOTAL		3435928.27	100.00	130.13	34.40	40.39	44.84	1219.49

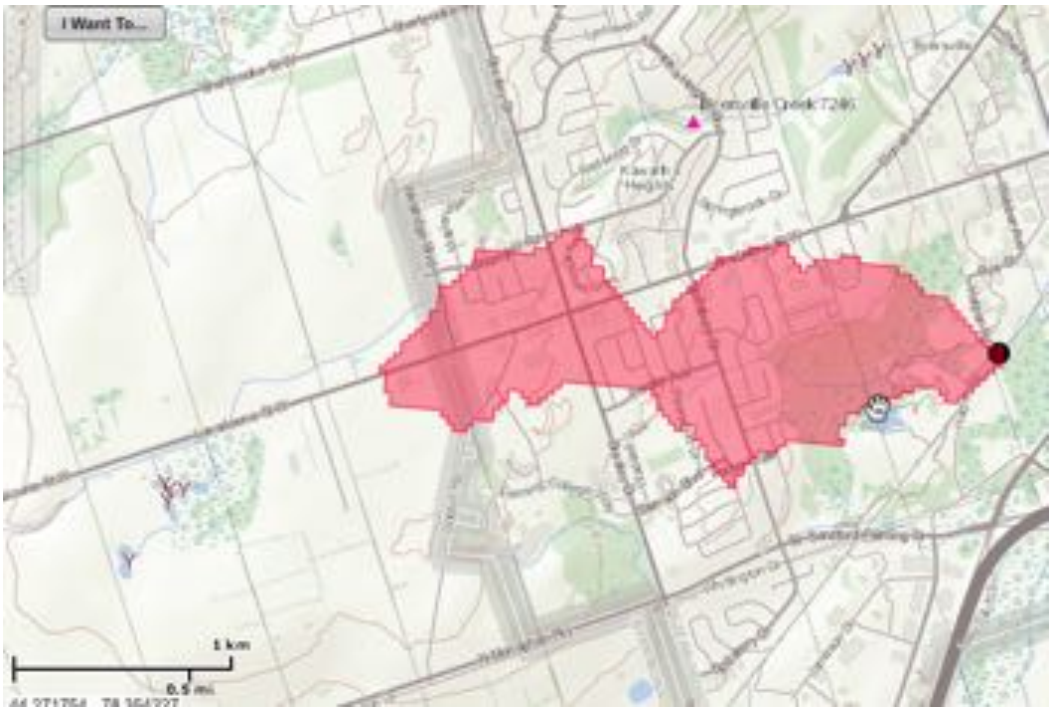
Appendix C: Maps

a)

b)


Ontario
Harper Creek Subwatershed
Legend

c)


I Want To...
1 km
0.5 mi

d)

e) 

***Fig**ure 1C. Maps of Harper Creek Subwatershed: a) - reproduced from ORCA 2012, Harper Creek Management Plan, b) Aerial Photo from South Central Ontario Orthophotography Project annotated on Microsoft Paint, c) Topographic Map of the watershed produced using Ontario MRNF Make a Topographic Map tool, d) Ontario Flow Assessment Watershed Map of Harper Creek Watershed, e) Soil Survey of general Harper Creek area, majority Otonabee sandy loams and urban.*

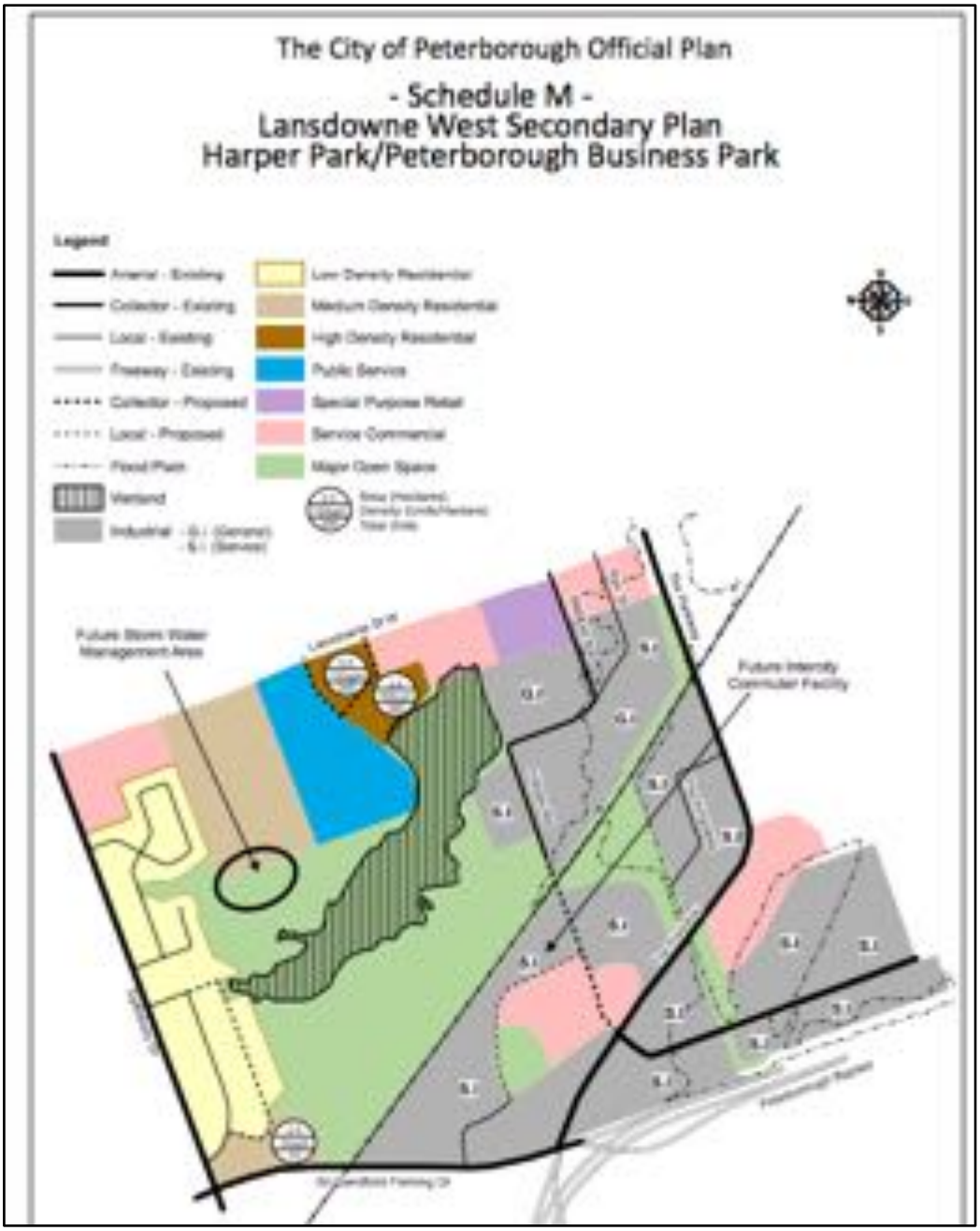


Figure 2C. Planning zones around Harper Park (City of Peterborough, 2016)

Figure 3C. Harper Park in relation to proposed Shorelines Casino Site, and other city-owned lands slated for potential development produced by NO-CASINO-PTBO, 2016.

Figure 4 C.Two proposed stewardship sites for creek-bed stabilization and restoration work by GreenUp , 2016.

Appendix D: Photos

All Photos Taken Personally By the Researcher

Figure 1D. Stormwater pond at Westview Village Retirement Home (left) and frothy, unsettled outflow (right) continuously releasing, slowly beginning to alter the natural forest vegetation towards a wetland complex.

Figure 2D. Pinewood drive stormwater pond, with emergent vegetation, 5 years past it's dredge date (left) , and constant outflow (right).

Figure 3D. Creek reach on Rye Street, through the industrial complex (left) Creek reach within Harper Park (right) the evidence of sedimentation erosion is clear in the right image.

Figure 4D. Two stretches of the wetland complex, close to Harper Park on the left, and closer to Stenson Park on the right.