Calculating Stormwater Price by Volume in Canada: an Analysis of Three Cities

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Abstract

This paper is an examination of some of the many factors that influence the total cost that stormwater runoff inflicts on a city. While many cities are moving forward with implementing stormwater management fees, they are doing so in order to recuperate operating costs incurred by stormwater infrastructure development. These fees, then, are not indicative of the actual deleterious effects stormwater has on Canadian cities.

A second component of this paper is framing the full cost, or at least a fuller cost, of stormwater within the cost and benefits posed by green infrastructure. That is, stormwater management infrastructure that is in some manner incorporated with the living environment. In doing so, this paper will make the argument that devoting more funding to stormwater infrastructure is a viable option for the development of livable and sustainable cities.

Foreword

This paper supports several components of my plan of study. The component perhaps of most direct relevance to this paper is the third component: watershed management. The three learning objectives for that component were green infrastructure, resilience modelling and GIS, and conservation strategies. This paper takes a look at the economics underlying the effectiveness of green infrastructure and compares different forms. It also contained a substantial amount of GIS modelling that looks at the economic effects of water contamination from stormwater, a topic that is certainly relevant to community resiliency as it directly affects the funding available for resiliency-building projects.

This paper also speaks to the learning objectives identified in my second component: resilient communities. The three learning objectives for this component are disaster management, flood mitigation, and climate change. The first two objectives are very much related to this topic as reducing stormwater peak flow rates via green infrastructure is an effective method of mitigating floods and adequately preparing for disasters of that nature.

And finally, this paper speaks in a broad sense the first learning objective of my first component, both titled 'environmental planning.' While this paper may not go into much detail on the subject, the use of green infrastructure provides a great deal of ancillary community benefits beyond stormwater mitigation. In recognizing the value of integrating the natural world as a method for combating the problems caused by urban development, this paper will make the case for a stronger environmental ethic in urban planning.

Acknowledgments

I would like to thank caffeine. Without you, none of this would be possible.

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1. Introduction

Stormwater has long been recognized as an important topic in city planning. While large-scale events such as Toronto's Hurricane Hazel or the occasional deluge that strikes cities like Calgary or Winnipeg might more readily capture the public's attention and prompt political responses, a great deal of resources are spent, lost, or squandered on the day-to-day management of relatively small scale rainfall events.

Nearly every single reasonably-sized municipality in Canada has some sort of plan for dealing with stormwater. However, it would seem that a great many of them do not take into much account the efficacy of their mitigation efforts. While there is growing discussion about the role that green infrastructure can play in reducing stormwater costs, most stormwater infrastructure is of the conventional, grey, type.

This paper will seek to demonstrate how the traditional approaches to stormwater management are economically inefficient because they fail to take into account a more robust cost-benefit analysis when it comes to stormwater. It should be noted that the words 'more robust' were not chosen flippantly in that last sentence. While there are several factors influencing the total costs of stormwater discussed here, there are likely many more factors that will go unanalyzed. Some, such as loss of usable lands, were considered but ultimately discarded due to insufficient data availability. Others are of the 'unknown unknowns' category that will go unanalyzed largely as a result of ignorance in the face of such a hugely complicated and involved topic.

Due to the interconnectedness of the environment, the economy, and human health and wellbeing, research down any one particular branch of this subject inevitably opened doors to other possible factors worth considering. Ultimately, the scope of the project is limited by the available data, time, and one's mental resilience.

This is all to say that this paper should not be considered as a 'full cost accounting' of the total effects that stormwater has on a municipality. However, that being said, those factors that are taken into account here show that the cost of stormwater is much higher than the studied cities calculate. Which leads, in turn, to the need for a recalculation of the alternatives to traditional stormwater management practices.

1.1 Grey infrastructure

The term 'traditional stormwater management practices' used above is synonymous with 'grey infrastructure.' That is, stormwater management infrastructure that is constructed primarily out of abiotic materials and not connected in any meaningful manner to the natural system in which it operates. The most common and likely most easily referenced example would the stormwater management pond.

These are essentially holes dug into the ground, often lined with concrete -- although that is a fading trend -- whose purpose is to temporarily store stormwater (Government of Ontario, 2018). This storage provides two primary purposes. The first role stormwater management ponds (SMP's) perform is one of flood reduction or prevention. By storing large volumes of water in a safe area, these ponds help reduce the total amount of water entering streams, river, and sewers and therefore lower the potential flood risk.

The second role these structures perform is one of water treatment. The majority of problematic compounds present in stormwater (see figure 1) are heavier than water. If held for long periods of time in still water, these compounds begin to settle out of the water column, accumulating as sedimentary sludge at the bottom of the pond. Water skimmed from the upper layers of the pond, then, will be much cleaner than it was when it entered (Toronto and Region Conservation Authority, 2018).

Stormwater management ponds and other forms of grey infrastructure are currently favoured in city design and planning largely due to the fact that they are known quantities: "Compared to green infrastructure, grey infrastructure currently has a clearer asset life, depreciation, and return on investment" (Albertawater, 2018). While research on the efficacy of green infrastructure is increasing (anecdotally, the number of papers of available on the topic skew heavily towards being published in the last decade or so), much of the costs and benefits of green infrastructure remain unknown or at least rather speculative.

1.2 Green Infrastructure

An alternative to grey infrastructure, green infrastructure is types of stormwater management systems that are designed to utilize natural processes to capture, store, and filter stormwater. There are many different types of green infrastructure and only a brief overview will be provided here. More detail on the efficacy and financial considerations of green infrastructure methods will be provided later in the paper. The most common types of green infrastructure are: green roofs, green facades, living walls, rain gardens, swales, pervious paving, planted trees, and

constructed wetlands, (although pervious pavement, admittedly, requires a more liberal interpretation of the term).

Perhaps a description of a green roof would be best if stolen directly from an advocacy group: "a green roof is a rooftop that is partially or completely covered with a growing medium and vegetation planted over a waterproofing membrane. It may also include additional layers such as a root barrier and drainage and irrigation systems. Green roofs are separated into two categories based on the depth of their growing media. Extensive green roofs have a growing media depth of two to six inches. Intensive green roofs feature growing media depth greater than six inches" (Green Roofs for Healthy Cities, n.d.).

Green façades are systems in which vines and climbing plants or cascading groundcovers grow into supporting structures that are purposely designed for their location. Plants growing on green facades are generally rooted in soil beds at the base or in elevated planters at intermediate levels or on rooftops.

Living wall systems are composed of pre-vegetated panels, modules, planted blankets or bags that are affixed to a structural wall or freestanding frame. This form of green infrastructure is considerably more complicated than green façades and more resource intensive. These systems are irrigated and feature either a hydroponic or soil based growing system. Living walls can be located on the interior or exterior of the building. While structurally similar, interior and exterior living walls have notable differences in costs and benefits. For the purposes of this paper, green facades and living walls will be considered together in calculations section as they have similar hydrological profiles when it comes to stormwater management.

A rain garden is a topographical depression in the ground designed to receive surface runoff. This area features vegetation that is compatible with wet soil conditions and often uses native plantings as a primary option. A rain garden can be designed in various ways but the most common form consists of a shallow, excavated depression with layers of stone, prepared soil mix, mulch and specially selected native vegetation that is tolerant to road salt and periodic inundation. The main benefits associated with a rain garden are the collection and storage of rainwater, permitting it to be filtered while slowly being absorbed into the surrounding soil.

Swales are linear features similar in composition to rain gardens. The main difference between the two is that where rain gardens are designed to capture and store water, swales are designed to convey water. Swales will typically transport water to a traditional grey infrastructure collection point, but will attenuate and filter a portion of the water along the way.

Trees are a common form of green infrastructure in for urban areas. They help to retain runoff from impervious surfaces, improve air quality, and reduce the urban heat island effect. There is substantial variation in both price and outcomes between trees of different size as determined by species. This matter will be addressed in the calculations section.

Wetlands are areas where water either covers the soil, or where there is a high saturation of water in the soils at various times of the year. This form of green infrastructure is a key part of the hydrological cycle and helps to moderate ground water levels and urban runoff. Wetlands can be either naturally occurring or human made.

Pervious paving creates a surface layer that allows rainfall to percolate into an underlying reservoir, where it either infiltrates into underlying soils or is removed by subsurface drains. This is achieved by utilizing materials with sufficient void space for water to pass through them.

There are quite a few means by which this is achieved but the results are similar enough for all type to be considered in the same category.

Planting beds encompass a wide variety of planting arrangements including: community gardens, formal gateway plantings, perennial and annual beds, shrub beds, feature gardens, raised planters, mosaiculture, and food production gardens. This category can also include less formal arrangements such as groundcovers and tall shrubs and grasses.

A large part of the appeal of green infrastructure is that provides a large degree of ancillary benefits in addition to stormwater treatment compared to grey infrastructure. Whereas the aforementioned stormwater management pond, for example, largely functions to hold water and provides little to no extra uses, green infrastructure projects can have enormous utility to their surrounding environs.

One of the major inspirations for this paper was a recent publication by the Centre for Neighbourhood Technologies that attempted to quantify the economic benefits of green infrastructure. The factors they took into account were reduced water treatment needs, improved water quality, reduced grey infrastructure needs, reduced flooding, increases to the available water supply, increased groundwater recharge, reduced salt use, reduced energy costs, improved air quality, reduced atmospheric CO2, reduced urban heat island effects, improved community aesthetics, increased recreational opportunities, reduced noise pollution, improvements in community cohesion, urban agriculture, improved habitat, and the cultivation of public education opportunities (Centre for Neighbourhood Technologies, 2010).

It seems evident, then, that there are vast financial and human well-being gains to be made by switching to a green infrastructure oriented system of stormwater management.

However, because so much of these benefits are only beginning to be quantified, there remains substantial uncertainty that must first be tackled before a major shift in political and public views on the topic can be undertaken. That is, of course, taking the optimistic assumption that reasonable arguments based in fact and logic hold sway in the political realm.

1.3 Why Stormwater Pricing?

Stormwater funding is a major concern for those cities that are attempting to tackle issue. In Ontario alone, it is estimated that there is a more than $6.8 billion stormwater infrastructure deficit (Environmental Commissioner of Ontario, 2016). Furthermore, the gap is only projected to widen as climate change is expected to increase the likelihood of storm events in the coming years.

In the CNT paper mentioned above, it was revealed that the price at which many cities value their stormwater retention costs is quite staggeringly low. It is not surprising, then, that such an infrastructure deficit exists. For example, the City of Chicago, with all of the resources that a city of that size and wealth has at their disposal, consider a cubic meter of stormwater to have a value CAD$0.032/$m^3$ (CNT, 2010).

Other cities, like Washington DC, have a much, much higher value for stormwater. They have actually implemented a stormwater credit exchange system and a stormwater fee in-lieu, which is payable to the Department of Energy and the Environment. In 2016, the average price of the exchanged credits was USD$1.85/gallon, which equals CAD$640.22/$m^3$ (Environmental Protection Agency, 2017). The fee to be paid in-lieu of retaining stormwater on site was

USD$3.61/gallon for 2016. This translates to CAD$1249.30/$m^3$ (Department of Energy and the Environment, 2018).

With such a vast discrepancy between the value of stormwater between two major cities, clearly there is room to investigate the economics behind such choices. This paper will attempt to do so in a Canadian context and show how different factors across the country may affect the conditions underlying stormwater valuation.

With the need for a massive investment in stormwater infrastructure already existing, an argument for green infrastructure to take the lead in combating future stormwater management initiatives would be well timed. This paper will hopefully help to inform the discussion on the best way to control and attenuate stormwater.

2. Methodology

2.1 Purpose of this Paper

It is the contention of this paper that Canadian municipalities are undervaluing the full cost of stormwater in their communities. In doing so, they are not devoting an adequate amount of funds to the prevention of stormwater-related issues and are, in fact, missing out on a great deal of potential savings.

In undervaluing the costs of stormwater, Canadian municipalities are therefore undervaluing the benefits realized by green infrastructure interventions. As discussed above, these green infrastructure developments come with a suite of ancillary benefits that can greatly improve the wellbeing in a community.

This paper, then, hopes to highlight the fact that green infrastructure is, in-fact, a highly valuable form of urban development that presents a high return on investment based solely on its stormwater attenuation capabilities. In order to accomplish this, the costs of the green infrastructure forms will be compared with the calculated costs of stormwater on a per volume basis.

2.2 Price Factor Analysis

The bulk of the work in this paper will be presented in section 4. These sections will contain individual analyses of the factors selected for stormwater pricing. The factors presented in this section were winnowed from a much larger list of factors that may affect stormwater pricing. This larger list was constructed in the earliest stages of the research and an attempt to be as inclusive as possible. Basically, any factor discovered in the literature on the effects of stormwater that could reasonably be said to affect stormwater prices was considered. The selected factors used in this paper were chosen based primarily on the perceived amount of information available after a review of the existing material. This is not to say that these factors are of any greater importance than those not considered in the paper, but rather that they seemed the best to work with.

Each section will begin first with a literature review. The purpose of this literature review will be to establish the method that will be used for stormwater pricing in the following portions of that section. The contents of the literature review will be drawn from academic sources, government papers, and occasionally grey literature. They are prioritized in that order.

The academic sources were obtained via the York University libraries online database search. Multiple different databases were utilized to this end. The government sources were primarily derived from what official documents were made publicly available by the website of the government body at hand. Finally, the grey literature was obtained from the websites of the organizations that had an interest in the subject. These sources were turned to only as a last resort given their biased nature.

The second portion of each section will be an analysis of the pricing mechanisms determined in the first section as applied to the study sites. Each study site will be considered in its own subsection. This analysis will take into account the different ways the economics, geography, and political landscape (as appropriate) of each study site will affect the price of stormwater for that city. The sources for the information on each study site are quite varied. Most are pulled from the official documents released by that city, but some data are from sources such as environmental assessment reports of companies operating in that area, academic studies conducted in the region, and others along those lines.

Section 4.5, on real estate prices, will have a few additional subsections dealing with the literature on pricing in different bodies of water.

Each section for the price factor analysis will also conclude with a brief discussion that will consider how the different conditions at the study sites may have lead to the difference in prices. Any unusual features or points of note in each section will be taken up here as well.

The final result for section 4 will be a dollar-per-cubic-meter price of the social costs of stormwater for each study site. This information will then be used in the calculations conducted for green infrastructure efficacy in section 5.

2.3 Calculations and Green Infrastructure

As this paper seeks to make a case for green infrastructure as a viable means of combating stormwater in Canada, section 5 will address the efficacy of a range of green infrastructure forms. This will be broken down into several subsections, one for each type of green infrastructure considered. First, a general cost-per-unit will be determined by literature analysis. The sources for these prices will largely consist of financial reports by organizations that have adopted them, academic research, or sometimes the price as presented by the companies that would install such features. From there, the amount of stormwater that will be attenuated by each feature in each city will be calculated. Knowing then the price of the green infrastructure form, the annual amount of stormwater attenuated be each type, and the cost per volume of stormwater, it will be possible to determine the payback period for each type of green infrastructure solely based on stormwater attenuation and initial price. This is, admittedly, a bit of a simple approach that does not adequately address the complexities of building and maintaining public infrastructure. While a more complex analysis of such matters would certainly be valuable, it is a bit beyond the scope of this paper, which is already running up against of the size limit recommended by the University.

2.4 Site Selection

This report will focus on three primary sites across Canada: Vancouver, Toronto, and Calgary. These three sites are all major city centers with reasonably well-developed stormwater infrastructure. This is vital for in terms of data availability. A fourth site, Halifax, was originally considered but the relative lack of usable data meant that it simply was not a viable option.

Indeed, data availability remained one of the most difficult, even frustrating, parts of this entire endeavour.

The three-site selected range across three separate provinces and cover substantially different ecosystems, soil profiles, climatic conditions, and regulations. Furthermore, each city has a unique history and different approaches when it comes to stormwater management. The variations in these factors between the three study sites will hopefully help demonstrate that factors in stormwater pricing conditions are variable. However, all factors are expected to vary between sites by different degrees, which will also help to show the amount of elasticity between sites for each individual factor. That is, some factors will be more affected by changes in local conditions than others.

2.4.1 Toronto

Toronto is the capital of Ontario and the most populous city in Canada. In 2016, the city had a population of 2,731,571 and is widely considered one of the most diverse cities in the world. The City of Toronto has recently expanded its borders through amalgamation; in 1998 the borders between Toronto, East York, Etobicoke, North York, Scarborough, and York were dissolved and formed a new a singular municipality – the City of Toronto (City of Toronto, 2018). Toronto is noted as being a significant Canadian centre of finance, art, entertainment, sports, and tourism.

Located on the Northern shores of Lake Ontario, Toronto is part of the Great Lakes ecoregion and characterized by a humid continental climate. Interestingly, Toronto is split into two separate regions when graded by the Köppen–Geiger System of climate classifications.

Those parts of the city closer to the lakeshore are classified as *Dfa* (Cold continental without dry season and a hot summer) while those regions more distant from the lakeshore are labelled as *Dfb* (cold continental without a dry season and a warm summer) (Climate-data.org, 2018).

Toronto is shot through with many rivers and streams. Some of the more notable of such are the Don River, the Humber River, the Rouge River, Etobicoke Creek, Highland Creek, and Mimico Creek, although there are many more named channels. One interesting note about the various tributaries in Toronto is that they display some substantial variation in degrees of development.

Due the a particularly devastating storm in 1954, Hurricane Hazel, which killed 81 people in Toronto and the surrounding regions, Toronto undertook some rather impressive flooding mitigation measures that were quite impressive for their time. Perhaps most notably of which was the decision to leave a great deal of the ravine surrounding the rivers largely untouched by development. This has left large tracts of the various rivers in a state that closely resembles their natural order. On the other hand, a great number of smaller tributaries and creeks have been completely filled in or covered over in order to make room for development.

The average annual precipitation in Toronto is 831mm, 709mm of which is rainfall with the remaining portion being snowfall. The average temperatures range from a high 26.4^{o}C in July to a low of -7.3^{o}C in January. The record high was 40.5^{o}C recorded on July 8, 1936 and the record low was -32.8^{o}C recorded on January 10th 1859 (Climate-data.org, 2018).

A substantial portion of Toronto's sewer networks, particularly in the oldest sections of town, are combined. This means that stormwater captured in a rainfall event is mixed with raw sewage and carried to the treatment plant combined. While it may seem easier at first blush to

have a combined sewer system, into of two separate ones, this design quickly leads to problems as a rainfall of sufficient intensity will overload the system's capacity to transport water, with a mixture of stormwater and raw sewage being backed up onto the city's streets (City of Toronto, 2018).

2.4.2 Vancouver

Located on the West Coast of Canada, the Greater Vancouver Area is the third most populous metropolitan area in Canada, after Toronto and Montreal. With a population of 2,463,431 in 2016 the Metro Vancouver area hold more than half of the entire population of British Columbia. Vancouver proper is the most densely populated major urban centre in Canada and 4th most in North America, after New York, San Francisco, and Mexico City (City of Vancouver, 2018). It is a notable for its vibrant tourism industry, owing in no small part to the beautiful landscapes surrounding the city, as well a popular location for the filming of movies and television shows.

It is situated on the Burrard Peninsula and straddles the land between the north arm of the Fraser River and the Burrard Inlet, a saltwater channel extending off of Strait of Georgia. Due to its location on a river delta, the majority of the Greater Vancouver Regional District is quite flat, but the regions of North Vancouver and West Vancouver, located across the Burrard on the southern slopes of Mount Fromm, Dam Mountain, and Black Mountain, are notably hillier.

While being substantially more Northerly located than Toronto (49^{o}N to Toronto's 43^{o}N), it is notable for its warm and mild winters and the relative rarity of snowfall. On the Köppen–

Geiger System, Metro Vancouver is classified as *Cfb*, defined as temperate, lacking a dry season (which it certainly does), and with a warm summer. While it has a reputation, and a well-earned one, of being one of the wettest cities in Canada, the actual amount of rainfall experienced in Vancouver varies greatly across the city. Measurements taken at the airport in Richmond indicate an annual rainfall of 1189mm, while measurements taken in Northern Vancouver indicate an annual rainfall of 2044mm in North Vancouver. This may be due to North Vancouver's mountainside location making it more susceptible to the effects of orographic precipitation. A city-wide average of rainfall would be about 1815mm (Climate-data.org, 2018).

The city was originally designed and built with an extensive network of combined sewer system that left it vulnerable to the same combined sewer overflows as Toronto. However, recent legislation has created a requirement to end all CSO events by 2050 and the city has undertaken a program to fully separate storm sewers from sanitary sewers by that point. Although, as will later be shown, this may not be fully realized.

2.4.3 Calgary

The third city, and perhaps the outlier in the calculations to come, is the City of Calgary. This is the capital of Alberta and its most populous city. With a population of 1,239,200 in 2016, Calgary is technically the 3rd most populous municipality in Canada, though this is largely due to the bigger metropolitan areas being split up into smaller distinct municipalities (City of Calgary, 2018). Calgary is notable for having high proportion of corporate offices, especially in the oil sector, having more millionaires per-capita than anywhere else in the country, and a certain

cowboyish culture (however co-opted by millionaire oilmen) as exemplified by the Calgary Stampede – a combination of a rodeo and music festival.

Calgary is located in Southwestern Alberta and is part of the transitional zone between the Rocky Mountains and the Canadian Prairies. Two rivers converge Calgary, the Bow River runs from the Northwest and the Elbow River runs from the southwest. It is both the coldest city considered here and the sunniest. Average daily temperatures range from about 16.5^{o}C in July to about -6.8^{o}C in January. However, the sun shines on an average of 332 days of the year.

On the Köppen–Geiger System, Calgary is classified as Dfb, the same as non-lakeshore regions of Toronto. In an average year, the City of Calgary can expect about 418.8mm of precipitation, 326.4mm of which is rain. Overall, it is a much drier city than either Toronto of Vancouver (Climate-data.org, 2018).

Calgary is a useful counterpoint to the other two study sites here for a number of regions. Its relative dryness and more temperamental climate (owing in no small part to the lack of temperature regulating large bodies of water nearby) ensure that a different form of precipitation regime is presented. However, maybe the more important aspect to consider is that Calgary does not have, and never has had, a combined sewer system. The city has always kept its stormwater and sanitary sewer systems separate. This ensures that some the values calculated for Calgary will be quite different than the other two. Thus, the presence of Calgary provides a great contextual reference for the other two sites.

2.5 A Note on Data Availability

The problem of insufficient availability of data has plagued this report throughout the entire writing process. Where possible, data was first drawn from technical documents and

reports as up-to-date as possible. Failing that, the engineering or planning departments of the cities under study was contacted in the hope that they might have the available data. Often that too was insufficient or plain unavailable. As a result, it has occasionally been necessary to draw some rather spurious extrapolations from the data that *is* available. Is it true that all of the wastewater treatment plants in Vancouver treat the same proportion of stormwater as the Lion's Gate Wastewater Treatment Plant? Not likely, but that is the best guess that can be made with the information at hand. Thus, a word of caution is necessary. This numbers expressed in this paper should be taken as being very rough estimates and not exact figures.

3. Content of Stormwater

Given that the contents of stormwater will vary with both space and time, there is a corresponding variance in the measured values of stormwater pollutant concentrations throughout the literature. In order to develop a generally-applicable value for stormwater pollutant concentration in any given North American city, an average of four sources was taken for each of the pollutants of study. Perhaps somewhat surprisingly, given the variation in individual measurements of stormwater quality, these values are all within not too great a range, which lends weight to the validity of the average extracted from them.

Pollutant	Source (mg/L)				
	Butler and Davis, 2011	Davis and Mccuen, 2005	Martin and Yousef, 1993 (table 5.17)	Hvitved-Jacobson, Vollertson, and Nielson, 2010	AVERAGE
Suspended Solids	90	111	67	79	86.75
BOD	9	16.2	7.8	8.8	10.45
COD	85	52.4	65	59	65.35
Ni	3.2	5.8	1.3	1.45	2.94
P	0.34	0.7	0.263	0.3	0.40
Pb	0.14	0.018	0.114	0.016	0.07
Zn	0.3	0.089	0.154	0.138	0.17

Figure 1: Stormwater Pollutant Contents

It should be noted that the presence of lead (Pb) contaminants will vary greatly depending on time due to lead enriched gasoline being phased out in the later portions out the 20th century across the studied regions. Indeed, the values captured by one of the cited resources (Hvitved-Jacobson, Vollertson, and Nielson, 2010) demonstrates this rather clearly. The authors compared the values in the United States measured by the Nationwide Urban Runoff Program (NURP), conducted between 1979 and 1982, and the National Stormwater Quality Database (NSQD), which is the up-to-date version of such measurements. They found that the values of Pb in stormwater runoff between the two times frames showed a decrease of an entire order of magnitude. Due to this, only the most recent measurement of lead was used in the construction of the above chart. However, the other values from this source were averaged as the authors mention that any "difference between the median NURP and NSQD observations are likely due to the random nature of stormwater data and not significant trends."

The concentration of E.Coli was given by only source (Davis and Mccuen, 2005), which provided three sources themselves, the average of which was 4.9x10^4 counts per 100mL.

4. Stormwater Impacts and Costs

4.1 Water Quality, Transport, and Treatment

All three cities in this study have extensive networks of sewers and other engineering features designed to transport stormwater away from the city, essential for the prevention of localized flooding. These sewage systems take two general forms: combined or separate.

In a separate sewer system, stormwater is kept physically separate from other types of sewage, such as domestic sewage. In a combined sewage system, stormwater is mixed with these other sewage types and all taken to the same endpoint, ideally a treatment plant.

One of the primary concerns with a combined sewer system is an event called a combined sewer overflow. This occurs when the amount of precipitation is high enough that the system cannot handle the total amount of both domestic sewage and stormwater and the mixture is then discharged from the system into the surrounding environment (Wanielista and Yousuf, 1993). This is a relatively common occurrence; the Ashbridges Bay Treatment Plant in Toronto, for example, had two combined sewer overflow events in 2017, one on May 1st and another on July 20th.

The cities of Toronto, Vancouver, and Calgary all have substantially different sewage regimes, which makes for a valuable array of conditions within the scope of this study. Toronto's sewage system is largely a combined one (City of Toronto, n.d.) while Calgary's is largely

separate (City of Calgary, n.d.). Vancouver straddles the two sides as it is currently in the process of converting its combined sewer system into a separate one (City of Vancouver, n.d.).

4.1.1 Toronto

Because there is a heavily combined sewer system across all the Toronto, the cost per volume of stormwater will be equal to the cost per volume of treated sewage.

A reasonable criticism of this approach is that it is not accurately representing the fixed costs of the water treatment system in place. That is, regardless of stormwater or not, the plant itself must be built, the pipes laid down, and employees paid because there would still need to be water treatment anyway. However, the extent of all of this is exaggerated over what it otherwise would be because it was specifically designed to take the excess amount of stormwater into account. In the absence of a combined sewer system, the plant would be smaller, there would be fewer employees, and fewer pipes. Essentially, all factors would be smaller. Therefore, it seems appropriate to take all fixed prices into account when determining the cost of stormwater.

Toronto is served by four separate wastewater treatment plants. The Ashbridges Bay Wastewater Treatment Plant, located at 9 Leslie Street, has the highest capacity of the four, able to process 818,000m^3 of wastewater daily. The Humber Wastewater Treatment Plant, located at 130 the Queensway, comes in second with daily capacity of 473,000m^3 of wastewater. The Highland Creek Wastewater Treatment Plant places third, with a capacity of 219,000m^3. Finally,

the North Toronto Wastewater Treatment Plant comes in a distant fourth with a maximum daily treatment capacity of 34,000m^3 (City of Toronto, 2018).

The largest plant, Ashbridges Bay, had total annual operating costs of $57.7M, $59.0M, and $56.4M, for 2017, 2016, and 2015 respectively. For these same years, the total annual influent flow was 240,817ML, 201,229ML, and 212,831ML. This results in cost of $239.60, $293.00, and $265.00 per megaliter of treated sewage, or a total of $0.24, $0.29, and $0.26 per m^3. The 3-year running average per cubic meter of treated water, whether household or stormwater is $0.27. Running similar calculations for the other three plants reveals cost-per-cubic meter values of $0.32/$m^3$ for Highland Creek, 0.17m^3$ for Humber, and $0.29/$m^3$ for North Toronto. This leads to an average treatment cost of $0.26/$m^3$ of wastewater (and therefore, stormwater) in Toronto as a whole.

ASHBRIDGES BAY					
Year	Operating Expense (CAD)	Influent (ML)	$ per ML	Influent (m^3)	$ per m^3
2017	57700000	240817	239.60	240817000	0.24
2016	59000000	201229	293.20	201229000	0.29
2015	56400000	212831	265.00	212831000	0.26
Average	57700000	218292.3	265.93	218292333	0.27

HIGHLAND CREEK					
Year	Operating Expense (CAD)	Influent (ML)	$ per ML	Influent (m^3)	$ per m^3
2017	20100000	62388	322.18	62388000	0.32
2016	19600000	59200	331.08	59200000	0.33
2015	18700000	60208	310.59	60208000	0.31
Average	19466667	60598.67	321.28	60598667	0.32

HUMBER					
Year	Operating Expense (CAD)	Influent (ML)	$ per ML	Influent (m^3)	$ per m^3
2017	18100000	121062	149.51	121062000	0.15
2016	17900000	94168	190.09	94168000	0.19
2015	17100000	98174	174.18	98174000	0.17
Average	17700000	104468	171.26	104468000	0.17

NORTH TORONTO					
Year	Operating Expense (CAD)	Influent (ML)	$ per ML	Influent (m^3)	$ per m^3
2017	1930000	5731	336.76	5731000	0.34
2016	1940000	6422	302.09	6422000	0.30
2015	1700000	7281	233.48	7281000	0.23
Average	1856667	6478	290.78	6478000	0.29

Figure 2: Wastewater Treatment in Toronto

4.1.2 Vancouver

The metro Vancouver area is serviced by five wastewater treatment plants spread out over the Fraser River Delta. The Iona Island treatment plant is located in Richmond and serves approximately one million people with treated water being pumped into the Fraser River. In 2014, the Iona Island plant treated 201,978ML of wastewater. The Lion's Gate wastewater treatment plant is located in West Vancouver. It serves about 180,000 people and treated 30,301ML of wastewater in 2014. The Lulu Island Wastewater Treatment Plant is also located in Richmond, but has a much smaller capacity; it processed 25,795ML of wastewater in 2014 and serves about 172,000 residents. The Northwest Langley Wastewater Treatment Plant is located in Langley (presumably in the Northwestern part of the city). It treated only 4686ML of wastewater

in 2014 and serves a population of about 27,000 people. And finally, the Annacis Island Wastewater Treatment Plant is located in Delta, serves over one million residents, and processed 178,076ML of wastewater in 2014 (Metro Vancouver, 2018).

The province of British Columbia has set an environmental goal to eliminate combined sewer overflows in the province by 2050. This is a particularly difficult task for the city of Vancouver because almost all of the its sewers, at the time of the announcement, were combined (City of Vancouver, Separating Sewage from Rainwater, 2018). Since then, the City has separated the sewage lines in the neighbourhoods of Downtown, West End, Fairview, Hastings, Killarney, Mt. Pleasant, Renfrew, Burrard Inlet, and the Fraser Shorelines. By 2020, the local government plans to have completed sewer separation in Grandview, Kitsilano, Point Grey, Shaughnessy, and Sunrise.

While these are commendable efforts and certainly a good step towards a more effective stormwater management regime, they have not, however, managed to disentangle stormwater from the system at most treatment plants. The following chart, taken from the 2015 Biennial Report Integrated Liquid Waste and Resource Management Report shows the clear link between rainfall level (at the top of the graph) and the response in influent levels at the different wastewater treatment plants.

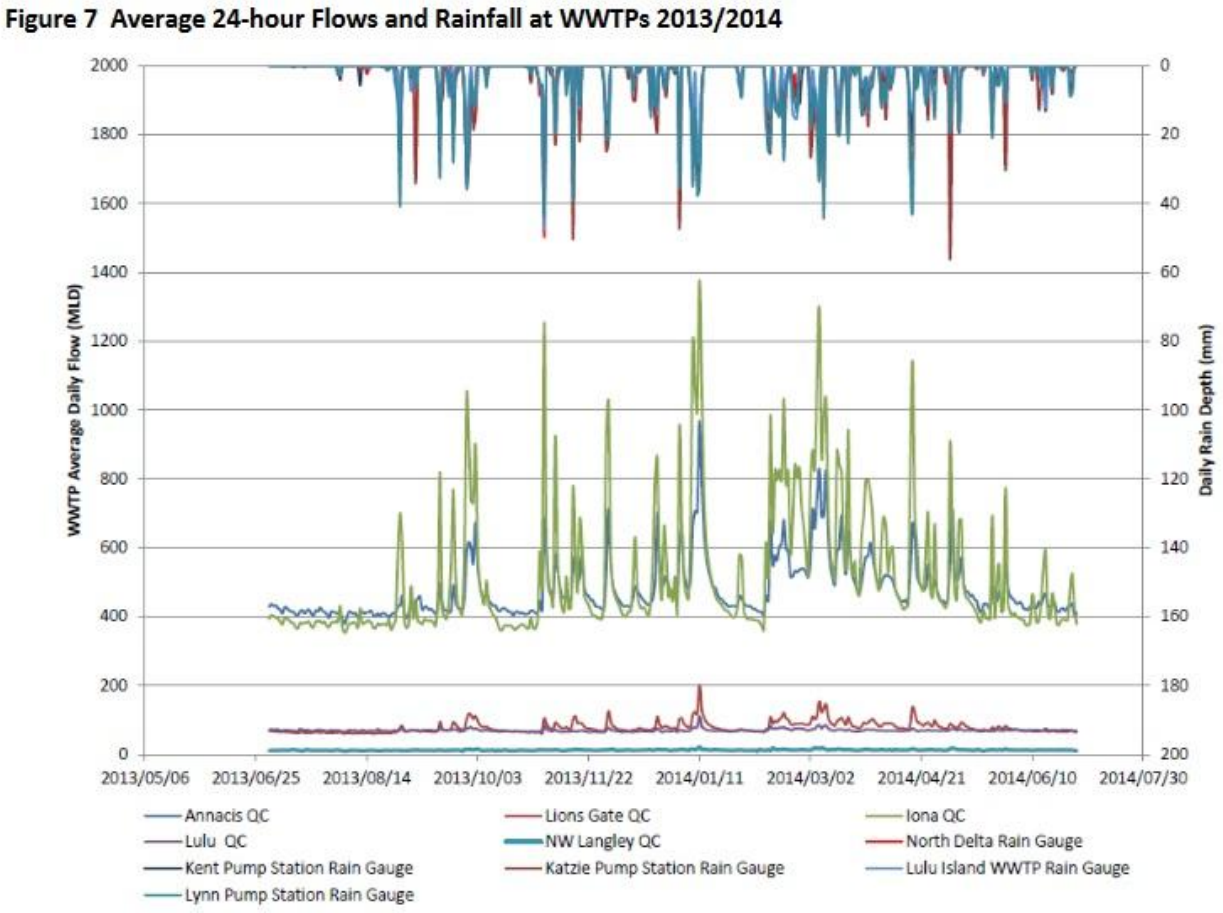


Figure 3: Average 24-hour Flows and Rainfall at Vancouver Wastewater Treatment Plants, source: Biennial Report: 2015-2016, Integrated Liquid Waste and Resource Management, Metro Vancouver

The language used in the report is rather telling about the difficulty in adequately separating a combined sewer system in a modern city. The tone of the writing seems to indicate that the results are falling well short of the expectations.

To quote directly from the report: “While high peak flows at the Iona Island WWTP are a normal response to rainfall for its combined sewer system; the sharp peaks in flows at the Annacis Island WWTP indicate that there are still significant amounts of rainwater entering its sanitary sewer system. This is due in part to combined sewers in New Westminster as well as

high I&I [leaking in of water] occurring in some sewers leading to this plant. Similarly, the peak flows of the Lions Gate WWTP indicate that there are large amounts of I&I entering the North Shore sewers and are a contrast to the limited rainfall responses shown at the Lulu Island and NW Langley WWTPs" (Biennial Report: 2013-2014, Integrated Liquid Waste and Resource Management, Metro Vancouver, p.28, retrieved 2018).

Despite these apparently lackluster results, progress on the full separation of stormwater and municipal sewage proceeds apace. The current goal set by the city is a total of 1010km of combined sewer systems, down from 1026km in 2017 (the goal for 2017 was 1020km), and 1035km for 2016 (the goal for that year was 1030km). There is an interactive graph showing the progress of the sewer separation program and, though only tracking a few years, seems to indicate that the discrepancy between the stated goals and the achieved milestones is growing. However, given that the city has given itself until 2050 to complete this task, one could remain hopeful that the trend will reverse itself (Liquid Waste – Total length of combined sewer remaining in the municipal systems, Metro Vancouver, 2018).

The most recent report biennial report released by the city indicated that in 2015 and 2016, 24,385m of combined sewer had been replaced with a separate sewer system at a cost of $72.9 million. That means that on average, every meter of combined sewer system costs $2989.54, or just shy of $3 million per kilometer. Given that there are 1026km of combined sewer remaining, the cost for the complete retrofitting of the remaining combined sewers in Vancouver should be in the ballpark of $3 billion in 2017 dollars.

Unfortunately, the City of Metro Vancouver have elected not to make the individual operating budgets of the area's wastewater publicly available. Thus, a full breakdown of the

efficacy of each plant is not available, as it was for Toronto. However, this does not prevent an analysis of total cost per volume; it just prevents a more granular look.

The total amount of wastewater treated in the Metro Vancouver area was 440,836ML. The total actual costs for operations and maintenance for wastewater treatment in 2014 budget was $127,100,000 (Biennial Report: 2015-2016, Integrated Liquid Waste and Resource Management, Metro Vancouver). This results in a cost per volume of 288.32$/ML, or 0.29$/m^3. This result in remarkably similar to the value given to Toronto.

With this value, it is now possible to estimate the cost-effectiveness of the combined sewer separation program as it pertains the operations and maintenance of wastewater treatment. It should be noted, however, that the stated goal of the program is to reduce or eliminate the occurrence of combined sewer overflows (City of Vancouver, Separating Sewage from Rainwater, 2018). Despite this, the primary thrust of this paper is to take a closer look at how environmentally-responsible decisions are often, in fact, economically-responsible at the same time; thus, such a calculation should be seen as a pertinent and illuminating aside.

The first step then, is to determine how much stormwater must be deferred in order for the $3 billion cost to be justified. At a cost of $0.29/$m^3$, this works out to about 10.58 billion m^3. The next step is to determine just how much stormwater would be prevented from entering the wastewater treatment plants should the full conversion process be completed. Now, the actual amount of stormwater entering the wastewater treatment plant is not given in any technical document (or it is, and it just very hard to find). However, good estimate can be inferred based on the difference in influent flows at waste water treatment between the wet weather days and dry weather days.

Between 2006 and 2011, the average daily dry weather flow of influent into the Lion's Gate Wastewater Treatment Plant was 77.23ML, while the average wet weather flow was 93.35ML a day (Lion's Gate Wastewater Treatment Plant Project Definition Report, 2014). There are, on average, 161 wet weather days in Vancouver (Canadian Climate Normals, Environment Canada, 2018). If it assumed that the primary difference between the wet weather influent and the dry weather influent is due to stormwater, then of the roughly 30,785ML of influent reaching the Lion's Gate plant on an average year, 2595ML, or 8.4%, will be stormwater. If that same proportion is extended to all wastewater treated in the greater Vancouver area, then annually there would be 37,030ML, or about 37 million m^3, of stormwater removed from the system should all sewers be fully separated. This places the payback period for the retrofitting of the sewers to be fully separate in the range of 258 years. Not great. Perhaps, then, the City of Vancouver should look to other methods of reducing stormwater influent.

4.1.3 Calgary

Unlike the other two cities in this study, Calgary has never had a combined sewer system. Since its inception as a city, Calgary has only treated sewage and never stormwater. Instead, an entirely separate set of sewers runs any incoming rainfall untreated directly into the Bow River (City of Calgary Stormwater Drainage System – FAQ, 2018). Due to this, the method of pricing stormwater based on its operational costs in the wastewater treatment plants is not a viable method of pricing. However, other options exist.

The City of Calgary does charge a stormwater service fee, labelled a stormwater monthly drainage charge. The latest available complete budget is for the period of 2012-204. In 2014, the

city charged a monthly rate of $9.20 per user and netted $33.8 million in revenue (City of Calgary, Business Plans and Budgets 2012-2014, 2018). This value is used to maintain the existing infrastructure system and can be considered as costs in-lieu to the treatment of stormwater.

In a personal communication with a member of the City of Calgary staff, it was reported that the average daily amount of stormwater running through Calgary's stormwater sewer system was $3.46 m^3/s$. This means that annually, the total stormwater running through the city was $109{,}114{,}560 m^3$. This gives a total price per volume for stormwater infrastructure treatment of $0.31 \$/m^3$.

4.1.4 Discussion

An interesting, if somewhat ancillary, point to consider is how much each plant costs to service its population. That is, the annual cost-per-person of each plant. The Ashbridges Bay Plant serves approximately 1,500,000 people, the Highland Creek Plant serves about 450,000 people, while the Humber and North Toronto plants serve about 680,000 and 55,000 people respectively. This gives us a cost-per-person of $38.46/person for Ashbridges, $44.67/person for Highland Creek, $26.62/person for Humber, and $35.09/person for North Toronto.

One notable aspect of these calculations is that there seems to be, at first glance, relatively little gains to be realized with economies of scale in Toronto's wastewater treatment regime. The largest plant, Ashbridges, is only nominally more efficient than the smaller plants in processing wastewater. A closer look into the finances reveals that this seems to be primarily due to extremely high electricity costs demanded by this plant as compared to the others; electricity

costs run about one fifth of total operating expenses, compared to between one-tenth and one-twentieth of the other plants. If these electricity costs were comparable to the other plants, then you would see a cost-per-volume more in line with the Humber Plant, and therefore a demonstration of increasing efficiency with scale in water treatment.

A thorough calculation of such costs is outside the scope of this paper, but a general idea of how water treatment costs scale with volume is relatively useful in the broader context of this paper because it helps to inform about what factors may be influencing the costs examined here. After all, if the end goal of this analysis is to better inform decision making about stormwater management, an understanding of the driving mechanisms behind the hitherto-unseen costs of stormwater is necessary.

4.2 Beach Closures

By definition, people enjoy leisure activities. One common leisure activity across all of Canada is swimming or lounging by the beach during the Summer. However, for many days of the year beaches will be closed due to poor water quality, preventing the pursuit of such activities. One of the primary causes of beach closures in the studied regions is due to combined sewer overflows (Greater Infrastructure Investments Needed to Reduce Combined Sewer Overflows, International Joint Commission, 2017). The release of toxic effluent into the waters renders swimming a health risk.

It has been calculated that for the region of St. Catherine's, Ontario, the average household will make 5.24 visits to the beaches per year given pristine conditions, and 0.25 visits per year given non-swimmable conditions (ie, beach closures). Expressed in term of willingness

to pay for improvements to ensure swimmable waters, a study found that the average household placed a value of $4.90 per swimming day in 1995 dollars (Dupont, 2003), which, according to the Bank of Canada inflation calculator, would be $7.46 in 2018 dollars.

A study by the Canadian Water Association utilized this information to provide an estimate for the loss of utility incurred by beach closures in Hamilton. It assumed that the value per-household was applicable across the entire study area of Hamilton (Renzetti and Kushner, 2004). Equipped with this model, it can therefore be determined how much total utility is lost to society due to beach closures every year. With that value known, a cost per volume of stormwater can be obtained.

4.2.1 Toronto

Fortunately, the City of Toronto was kind enough to provide an estimate for the amount of Stormwater released as combined sewer overflows. This was determined not by actual measurements but by a quantitative model (the QQS model), so its accuracy may be a bit circumspect. But, really, the accuracy of this paper is likely a bit circumspect so the QQS model's predictions seems appropriate. The value given by this model is that on an average year there will be 10,187,056m^3 of combined sewer overflow effluent deposited into the Black Creek, Humber River, West Don River, Massey Creek, Lower Don River, Western Beaches, Inner Harbour, Eastern Beaches, and Scarborough Lake (Doshi, et al. 2005).

According to Statistics Canada, there were 1,112,929 independent household in Toronto proper in 2016 (StatsCan, Census Profile, 2016 Census). The City of Toronto monitors the water quality at Marie Curtis Park East Beach, Sunnyside Beach, Hanlan's Point Beach, Gibraltar Point

Beach, Centre Island Beach, Ward's Island Beach, Cherry Beach, Woodbine Beaches, Kew Balmy Beach, Bluffer's Beach Park, and Rouge Beach. Between June 5th and September 5th, 2016, there were a total of 76 beach closures in Toronto due to high levels of *e.coli* bacteria, a direct result of combined sewer overflows events (City of Toronto, Beaches Swimming Conditions History). This represents 7.51% of the total 1012 swimming days available at all beaches combined.

Using the method provided by the Canadian Waters Association, the total days the beaches were closed in 2016 represent a loss of 417,348 visits and a total loss of societal utility equal to $3,113,419.00 in 2018 dollars. The end result being that for Toronto, stormwater costs in terms of beach closures equal $0.31/m^3.

4.2.2 Vancouver

The city of Vancouver is located on the Fraser Delta in the Strait of Georgia and is, therefore, on the shores of the Pacific Ocean. As a result, it has a number of very nice beaches, most of which are on the Western side of the delta as the industrial use of the Vancouver Harbor takes up much of the waterfront on the Burrard Inlet.

As recently as 2016, the Metro Vancouver area has upgraded their water quality testing stations and now has 117 sampling sites at 41 locations. The test sites are located at False Creek, Sturgeon Bank, Wreck Beach, Indian Arm, Port Moody Arm, Inner Harbour, Boundary Bay, Outer Harbour, and Sasamat Lake. They regularly test for fecal coliform bacteria, heavy metals, selected organics, and general toxicity (City of Vancouver, 2017).

The primary recreational beaches in the tested region will be represented by testing sites at Boundary Bay, Wreck Beach, and the Outer Harbour. Much of the inner harbour is heavily industrialized thus not an attractive location for swimming. An important piece of context for this discussion is where the testing sites are located as compared to where the CSO events actually occur. There are many more effective solutions to pollution than dilution, but it nevertheless is important in this particular case. The following images are both pulled from the most recent Biennial Liquid Waste Report and highlight the geographic distribution of the testing sites and combined sewer overflow sites.

In 2015, there were 1106 combined sewer overflow events releasing a total volume of 28,383,000m^3 of effluent. This resulted in a total of 12 days in which a beach was closed. In this case, the only beach to be closed was Whytecliff beach, located on the western end of the West Vancouver peninsula.

In 2016 there were 1426 combined sewer overflow events that released a combined volume of 24,012,000m^3 of effluent in the waters around Vancouver. This resulted in 7 days total of beach closure, all of which were at Wreck Beach, on the Western tip of the main Vancouver spit.

The Vancouver metropolitan region had 1,027,613 households in 2016 (Statistics Canada, Census Profile, 2016 Census). According the Metro Vancouver Health Authority, there are 24 primary swimming beaches in the region, with a 92-day swimming season that means that there is a total of 2208 potential leisure days available in any given year (Vancouver Coastal Health, Beach Water Quality Reports). This results in the closure days representing only a loss of

total recreational value of only 0.54% and 0.32% for 2015 and 2016 respectively. Notably less of an impact than in Toronto.

Using the aforementioned process, these beach closures result in a total reduction of 27,924 and 16,289 trips in 2015 and 2016 respectively. Assigning each trip a value of $7.46, it can be seen that in 2015 and 2016 beach closures cost the Vancouver area $208,315 and $121,517. These values can then be put together with the above-listed volumes of CSO effluent to derive a cost-per-volume (in the event of a CSO) of $0.007/m3 and $0.005/m3. This results in an average of $0.006/$m^3$ of CSO effluent.

Figure 15 Metro Vancouver Recreational Water Quality Monitoring Locations (2015-2016)

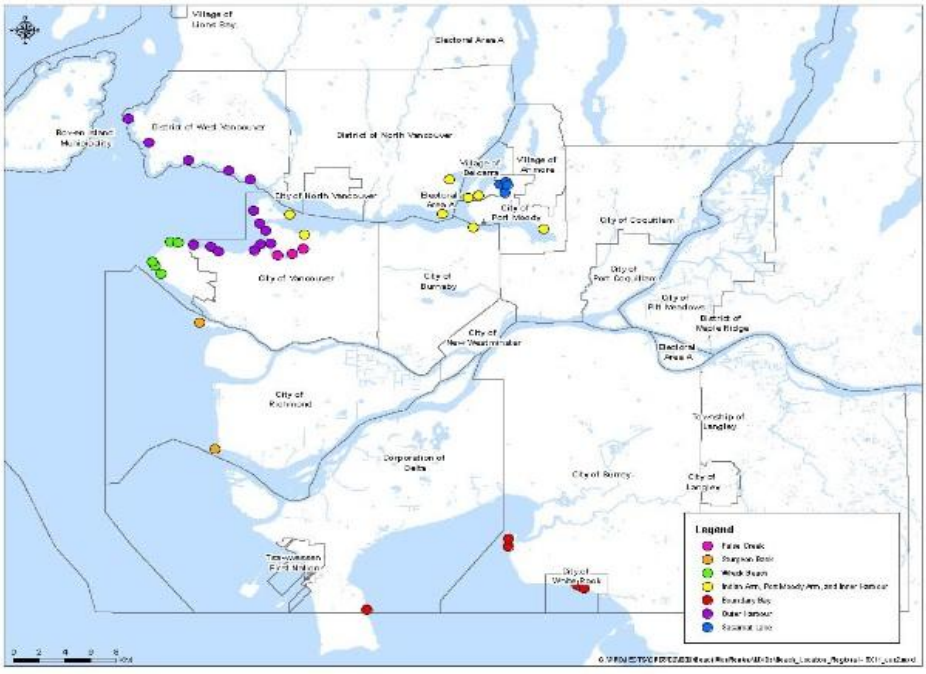


Figure 4: Vancouver Beach Water Quality Monitoring Stations, source: Vancouver Biennial Integrated Liquid Waste and Resource Management Report. Retrieved from: http://www.metrovancouver.org/boards/Utilities/UC-2017_Jun_15-5-10_Ref_1.pdf

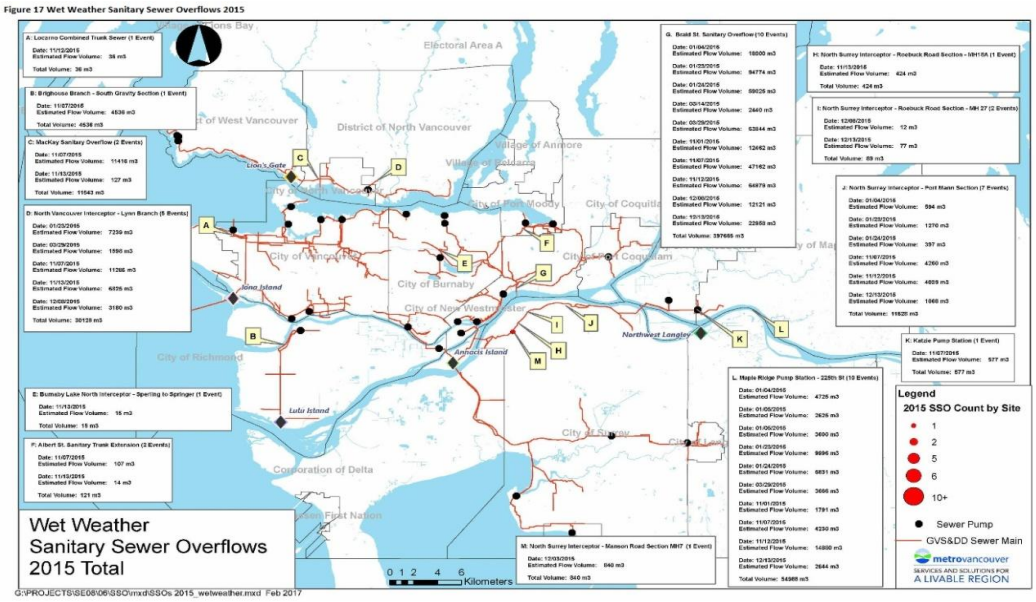


Figure 5: Vancouver CSO outlet sites, source: Vancouver Biennial Integrated Liquid Waste and Resource Management Report. Retrieved from: http://www.metrovancouver.org/boards/Utilities/UC-2017_Jun_15-5-10_Ref_1.pdf

4.2.3 Calgary

Calgary is known for many things. The Calgary Stampede, the beautiful views of the sun setting over the Rocky Mountains, oil. It is not, however, renowned for its beaches. In fact, the casual observer might be forgiven for thinking that Calgary has no beaches to speak of because they would almost be correct. There are beaches in Calgary, so long as the definition is stretched to include any remotely tree-free banks along the Bow River. The existing beaches along the Bow River include the Edworth Park beach, the Bowness Park beach, and Sandy Beach (which is about as Sandy as Greenland is Green).

However, as far as a not-too-meager research time would indicate, it seems that these beaches have never, not once, been closed due to a combined sewer overflow, or due to stormwater for any reason (floods perhaps excepted). This, of course, stands to reason

considering that Calgary's system is completely separate and therefore not susceptible to combined sewer overflows at all.

Thus, it can be concluded that the cost-per-volume of stormwater due to beach closures in Calgary is precisely $\$0.00/m^3$.

4.2.4 Discussion

Perhaps the most important takeaway from this section is that a generalized rubric for beach closure costs is simply not possible. Local geography and demographics hold such a great sway over the extent of these costs that to say that a value in any one region is applicable to any other region is folly.

Even if Calgary was to not have a separated sewer system, it would likely have much fewer beach closures than Toronto or even Vancouver simply due its placement alongside a river. All three of its treatment plants are located on the very southern edge of the city and thus, well downstream of most of the bathing areas. Given that the river whisks water downstream at a rate between $40m^3/s$ and $250m^3/s$ (City of Calgary, Understanding River Flow Rates, 2018), any effluent leakage would likely be removed from the city's limits within a few hours, if that.

While both Toronto and Vancouver are situated on large bodies of water, that does not necessarily imply that effluents dumped into their respective waters will remain in the area for the same amount of time. It is well beyond the scope of this paper to calculate the actual hydrodynamics which govern the removal and dilution of CSO effluents in a water body. However, a comparison of the flushing rates of each region would be useful in demonstrating

that there is disparity present between the two sites. As far as the Great Lakes go, Lake Ontario has relatively quick flushing rate of 7.5 to 8 years (Quinn, 1992). Comparatively, the flushing time of the entire Georgia Basin, alongside which Vancouver is located, is only 1.4 years (England, Thompson, and Foreman, 1996).

Geographic factors at an even smaller scale probably have a greater impact than that. For example, most of the swimming beaches in the Greater Vancouver Area are located on the shores of the Burrard Inlet (see above figures), a coastal glacial fjord that is unconnected from the Fraser River. However, much of the combined sewer outfalls, and indeed the majority of the occurrence sites for combined sewers overflows, are located in the Fraser River watershed. That means that much of the effluent is unlikely to reach the shores of usable beaches. Indeed, the fact that on average Vancouver released two and half times as much CSO effluent as Toronto did yet had remarkably fewer beach closures - a fact with even greater weight considering that Vancouver had more than double the number of potentially affected beaches and a similar number of households in the study area.

Another notable factor is that the Toronto and Vancouver used two different values for e.coli measurements to determine when to close the beach. Toronto posted a beach closure when e.coli levels were greater than 100 counts per 100mL. This value is based on the provincial guideline set out by the Ontario Ministry of the Environment and Climate Change (City of Toronto, About Toronto Beaches Water Quality, 2018). Conversely, the Vancouver Coastal Health Authority only posts a beach closure in the event that e.coli levels exceed 200 counts per 100mL, double the Toronto levels.

4.3 Erosion, Total Suspended Solids, and Water Treatment

The erosion of soil into waters is a major problem nationally. A recent presentation at the Soil Conservation Council of Canada estimated that the total annual economic loss in Canada due to soil erosion was $3 billion (Lobb, Soil Degradation: The Cost to Agriculture and the Economy, 2017). This was, apparently, the first national erosion quantification study done since the 80's. Similar studies in the United States place their national soil erosion costs at somewhere between $460 million and $2.5 billion in 1980 American dollars, equivalent to somewhere between $1.5 billion and $8 billion USD today (Clark et al., 1985). However, both of these studies are focused much more so on the impact to agriculture and therefore, might present different values than what would be expected from an urban environment.

When consider the cost of erosion in an urban environment, there are multiple factors that can be considered. The first is the degradation of water quality due to sedimentation, which can result in complications to water treatment and even to severe health risks. One such potential health risk caused by high levels of sedimentation is cryptosporidiosis, an disease caused by infectious bacteria commonly present in water supplies around the world. The efficacy of treatment methods to remove this and other bacteria types are compromised by high levels of turbidity (the amount of suspended sediment in the water, with high turbidity being a direct result of high erosion rates) (Gomez-Couso, et at., 2009). Indeed, there have been outbreaks of cryptosporidiosis in Canada linked to this phenomenon. The outbreak in North Battleford, Saskatchewan in 2001 has been blamed on a water treatment plant that was not able to effectively sanitize the local river water due to high levels of turbidity caused by higher-than-normal erosion rates (Wallis, et al., 2003).

There has been some work on determining just how much soil erosion raises the cost and difficulty of water treatment. A study in the Ohio corn belt found that 10% reduction in annual gross soil erosion accounts for a 4% reduction in water treatment costs (Forster, Bardos, and Southgate, 1987). Given that the reason that soil erosion raises treatment costs is that the increased amount of suspended solids in the water column complicates the treatment process, then it can be said that TSS is a reasonable proxy for measuring the amount of eroded soils in the water column, consider that the relative proportions are the concern and not the absolute values.

If it the TSS value of stormwater is known, the TSS value of regular river water is known, and the relative volumes of each type of water entering the wastewater treatment plant are known, then the degree to which any individual unit of stormwater complicates the treatment process can also be determined. This is, of course, assuming a linear relationship between treatment costs and TSS.

One thing to note about this factor is how it relates to the other section dealing with cost-per-volume of water treatment. While both may be described as such in simple terms, they are measurements of two different things. The other factor deals with the cost of each individual unit of stormwater or streamwater costs to treat as it enters the plant. This factor represents how much the cost of any individual unit of treated water rises based on how much stormwater is entering the system. It costs more to treat $1m^3$ of combined stormwater and streamwater than it would to treat $1m^3$ of just streamwater alone.

4.3.1 Toronto

A number of sources have reported on the total suspended solids loading in stormwater from multiple areas. Obviously, there will be a lot of regional and temporal variations, but in general the value for TSS in stormwater is about 86.76mg/L. Comparatively, recent tests from environmental monitoring stations at the Humber and Don Rivers indicated that the median total suspended solids level was 11mg/L. It should be noted that is a substantial improvement over historical levels, which measured in the range 30-40mg/L in the late 1960's and early 1970's (Toronto and Region Conservation Authority, Regional Watershed Monitoring Program: Surface Water Quality Temporal Trends Update, 2011-2015, 2018)

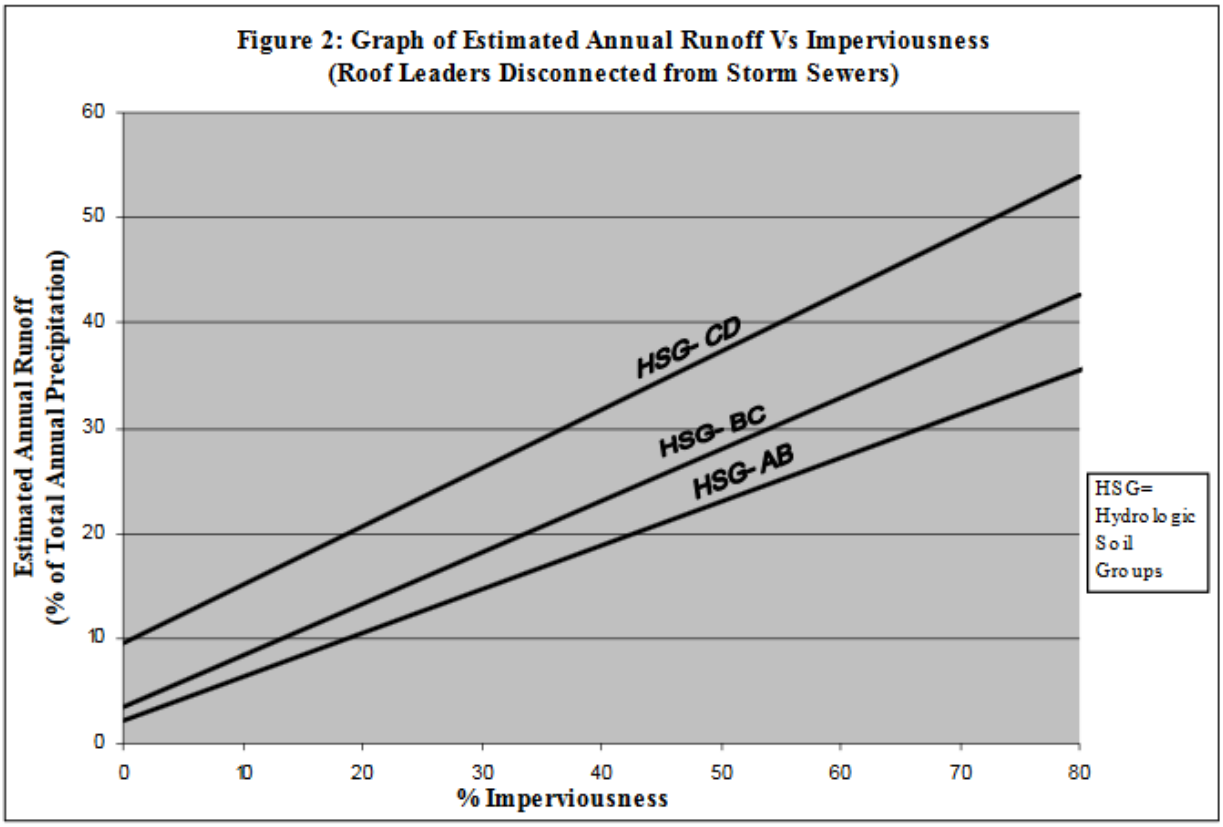
The total amount of water treated in each plant is also known. The Ashbridges WWTP processed an average of 218,292ML over the last four years while Highland Creek, Humber, and North Toronto all processed averages of 60,599ML, 104468ML, and 6478ML of water over that same time period. In total, that is an average annual volume of 389,837ML of water treated every year.

While one might think that the total volume of stormwater in the City of Toronto would be a known quantity and easily furnished to the curious researcher by the government. It turns out that that is not the case at all. It is, in fact, a complete mystery to the entire governing structure of Southern Ontario just how much stormwater is in the city. Which means that that value must be extrapolated from existing literature.

One study that looked at the degree of imperviousness in the Greater Toronto Area will provide the first step in this process. This study created a series of four 2km-wide transects beginning at the downtown core and stretching outwards towards the very edges of the GTA.

Overall, they found that the percent of imperviousness within these transects ranged from 35% to 95% imperviousness, averaging at 65% (Conway and Hackworth, 2007).

The City of Toronto published a technical document on guidelines for wet weather flow which will help to inform the second part of this extrapolation. They published a chart showing how much of the average annual rainfall will be received as runoff depending on the soil type and the percent of impervious landforms.



LEGEND

HSG=Hydrologic Soil Groups
AB- Sandy loams and gravels (very pervious)
BC- Medium textured loams (pervious)
CD- Clay loams & silty clay loams (impervious)

Figure 6: Runoff vs. Impervious by soil type, source: https://www.toronto.ca/wp-content/uploads/2017/11/9191-wwfm-guidelines-2006-AODA.pdf

A map of the geology of the Greater Toronto Area indicates that the soils underlying Toronto are a relatively even split of silty sand deposited by the glacial lakes that previously dominated the region and clayey sand deposited as glacial till during the last ice age (Geology Ontario, 2015). This means that the most appropriate soil type would the uppermost line of the graph - GSG-CD.

If one were to take 65% as an average degree of imperviousness (which intuitively seems a bit light given the area of consideration is Toronto proper and not the Greater Toronto Area), it can be estimated that roughly 45% of the total annual rainfall in the Toronto area becomes runoff. Given an area of 630.2km^2, and annual rainfall of 709mm, we arrive at a total rainfall volume of roughly 446,812,000m^3. Thus, using the above chart, it can be determined that there would be roughly 201,065,000m^3 of overland flow annually in all of Toronto.

But of course, only a portion of that total volume makes it into the city's sewer systems. To determine that proportion, perhaps Calgary might be the best example here. It is known exactly how much water travels through the Calgary's stormwater systems, which would be a direct representation of how much overland flow is captured by the system, which gives a rough estimate for how much a city of similar design may capture. Using the same process as above it can be determined that roughly 121,220,064m^3 of water occurs as overland flow in Calgary's boundaries every year. Given that 109,114,560m^3 of water flows through the storm sewer pipes, roughly 90% of the overland flow in Calgary is captured by the stormwater system. If we assume Calgary to be a good analogue then, given that Toronto relies on a combined sewer system, roughly that same proportion then should enter the treatment plants instead of being piped

directly into the river. 90% of 201,065,000m^3 is 180,985,872m^3 – a little less than half of all of the water treated in Toronto.

With the TSS levels given in chart 1 at roughly 86.75mg/L, or 0.08675mg/m^3, the total amount of sediment arriving in the 180,986,872m^3 of stormwater at the various wastewater plants would be 15,700,611kg. Conversely, the much cleaner river waters at 11mg/L, at 208,851,128m^3, deliver only 2,297,362kg of sediment annually. The combined water turbidity, then, becomes 46.17mg/m^3. That represents a 420% increase in turbidity and, according to the relationship laid out in this section's introduction of a 4% price change for a 10% change in turbidity, indicates a roughly 168% increase in water treatment costs over what would otherwise exist without the stormwater input.

Recalling back to section 4.1, Toronto's average treatment cost is \$0.26/m^3. If stormwater increases costs by 168%, then the cost of treatment in stormwater's absence would be \$0.097/m^3. The cost for treating stormwater itself has already been accounted for in section 4.1, this section deals with how much more expensive treating non-stormwater is. The price difference between treating 208,851,128m^3 of non-stormwater at \$0.26/m^3 and \$0.097/m^3 is \$34,042,733. Given that this extra cost is incurred by an estimated 180,986,872m3 of stormwater, it can be determined that the cost-per-volume of stormwater due to complicated treatment procedures in Toronto is \$0.19/m^3.

Another method, although maybe just as circuitous, is to calculate the benefit derived from reductions in stormwater related erosion savings as reported by the City of Waterloo based on their findings for the economics of green roofs. This comes as a bit of roundabout fashion as the technical paper itself does not appear to be publicly available. However, a 2005 report to the

City of Toronto used the findings from the Waterloo paper to state that the values for savings on erosion due to green roofs would amount to roughly $5,055 per hectare of green roof installed (Doshi, et al. 2005). This value is, unfortunately, given without much further context. However, it is also backed up by other research that places similar cost savings in the same ballpark. A report based on a broader Canadian context, found that on average 2000m^2 of highly permeable landscape greenspace would provide a net stormwater benefit of $1,238.76. This amounts to a price of $6193.80 per hectare, slightly pricier but still similar. The first value, being based in city within a similar climatic zone to Toronto, seems the more appropriate price.

First, it is not stated exactly what type of green roof is being studied here. Green roofs come in two broad categories: intensive of extensive. The most significant technical difference between the two is the depth of the soil medium with extensive green roofs being shallower than intensive. The line between the two is regarded to be 6 inches (15.24cm). The deeper the substrate, the more well developed the supported plant community can be and therefore, the greater the ability to store and process rainfall (in general – plant composition is highly important to the final attenuation rate).

From there, the composition of the soil and the plant community, as well as its liveliness, can make a very large different in outcomes. A study conducted in the City of Portland found that green roofs can reduce between 10% and 100% of rainfall in a given year – a bit of a range (City of Portland, Bureau of Environmental Services, 2004). Given that there is a wide range of possible outcomes here, the most logical approach would be to use the values from a wide-ranging survey. One such survey found that "a typical green roof will absorb, filter, retain, and store up to 75% of the annual precipitation that falls on it" (Johnson, 2008). That same study

considered the average green roof to be between 3 and 4 inches in depth, not a particularly deep medium.

The average rainfall in the City of Waterloo for the last 26 years is 774mm per year (Farmzone – Statistics: Waterloo Ontario). Using the 75% retention estimate provided above, it can be reasonable inferred that the average amount of stormwater captured per square meter of green roof in Waterloo (and therefore, Toronto) will be roughly $0.580m^3/m^2$. If every hectare of green roof saves $5,055 of erosion costs, then every square meter will save roughly $5.06. If every square meter of green roof prevents roughly $0.580m^3$ of stormwater, then it stands to reason that the value Waterloo places on erosion per cubic meter for stormwater is $\$8.72/m^3$. Not a small amount at all.

Given the relatively opacity of the numbers underlying this assumption. A quote from the Waterloo Green Roofs Feasibility Study (not the technical report which these values are derived from) might help illuminate the underlying mechanisms for this value. The report states that "Green Roof systems would decrease the amount of runoff flowing directly into creek systems and lakes, which would in turn, decrease the velocity and duration of the flow. The reduced velocity and duration of the runoff will decrease the potential erosion to creek banks and creek beds. The reduction in erosion will decrease sedimentation due to a decreased amount of suspended solids in the flow. The overall result is improved creek stability and a reduction in the frequency of creek maintenance and rehabilitation." (City of Waterloo, n.d.).

4.3.2 Vancouver

Fortunately, Vancouver has actually published a report that allowed one a way to infer the amount of stormwater being treated in the city (see section 5.2). From the above calculations, it can be reasonably inferred that the city of Vancouver processes about 37,030ML of stormwater across all of its treatment plants in any given year. In that same year, the total amount of water entering the system is 440,836ML.

There are a large number of water quality monitoring stations scattered along the lower reaches of the Fraser river and there has been a substantial amount of research published in the last several decades tracking the most minute changes in the most obscure types of contaminants. But for some reason, none of these stations and none of this research include total suspended solids. All stations seem to measure turbidity as expressed in NTU, the nephelometric turbidity unit. Basically, this is a representation of how much light can pass through a given unit of water, and it is measured by the attenuation of a white light shined in at a 90^{o} angle to water column. Despite the many at-face-value similarities of NTU and TSS, and many attempts at drawing a correlation between the two, ultimately it is just not possible to use one as an indication of the other *in a general sense* (Hannouch, et al., 2011,. Packman, Cummings, and Booth, 1999). While these studies and others have drawn correlations between the two values, the differences between the individual sites prevents a universal correlation. Thus, a wider net must be cast in order to find TSS values for Vancouver.

The Roberts Banks Terminal is a port located on the cost of the Lower Mainland, immediately adjacent to Vancouver. The Vancouver Port Authority has published a number of studies on the potential for expanding the capacities of the port in the Roberts Bank. Thankfully,

the environmental consultants behind this report did an admirable job at conducting water quality assessments as part of the environmental impact study of such an expansion. The inshore monitoring sites, while not located in the river itself, are placed immediately outside the mouth of the main arm of the Fraser River. Obviously, there is going to be some dilution (indeed, likely substantial levels of it) of the total suspended solids count due to the fact that the tested waters include a mix of the river waters from the Fraser and ocean waters from the Strait of Georgia. The estimates presented here, then, likely undervalue the amount of suspended sediment per volume of water entering the water treatments plants in Vancouver. However, they are, apparently, the best values available and are therefore the ones that will be used.

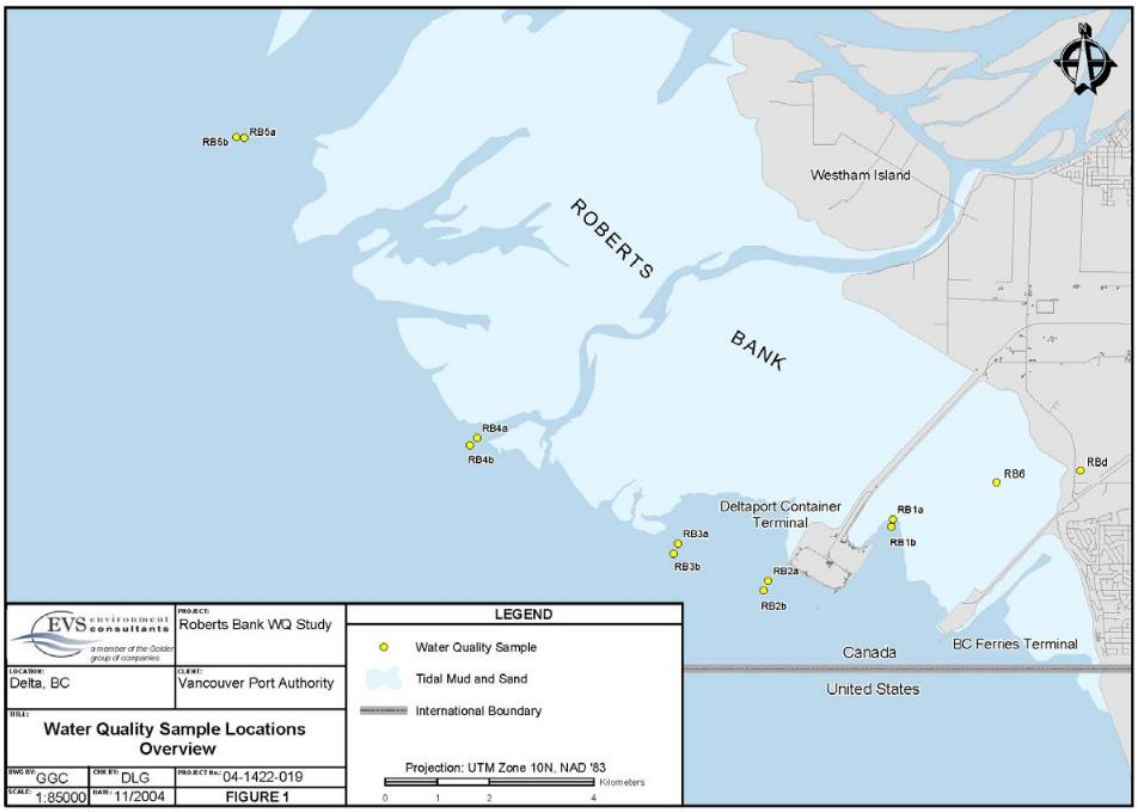


Figure 7: Water Quality Sampling Locations, Vancouver Port Authority, Source: http://www.robertsbankterminal2.com/wp-content/uploads/DP3-EA-Application-Water-Quality.pdf

The average annual levels of total suspended solids for the near shore monitoring sites (labelled 'a' in the above diagram) were approximately 32mg/L. Substantial seasonal variation was noted, with the wet seasons highs reaching nearly 80mg/L and the dry season lows less than a tenth of that (this information was presented only in bar chart form, so the numbers are bit inexact) (Vancouver Port Authority, 2014).

A 10% decrease in soil erosion rates, measured by total suspended solids in this case, will lead to a 4% reduction in the cost to treat any given volume of river water. In Vancouver, with the cost to treat a $\$0.29/m^3$, a 4% change would equal about \$0.01 per m^3.

If there are 86.6mg/L of total suspended solids in stormwater, and there are 37,030ML of stormwater, then there is 86.6kg/ML and therefore 3,206,798kg of sediment in that total volume of stormwater. The same process yields a value 12,921,792kg of sediment in the 403,806ML of non-stormwater entering the treatment plants. The combined total of suspended solids for the mixture of stormwater and non-stormwater entering the system then is 16,128,590kg for 440,836ML; this results in an average TSS value for water treated at the plant of 36.58mg/L. This represents a 14.3% increase in TSS levels over the non-stormwater value, which should translate to about a 4.57% increase in the cost to treat any individual unit of water. So, every m^3 of water treated in Vancouver is roughly $\$0.013/m^3$ more expensive than it otherwise would be in the absence of stormwater influence.

At a cost $\$0.013/m^3$, the total increased annual price of water treatment due to the confounding effects of stormwater-increased TSS can be determined by multiplying it by the 403,806ML of non-stormwater treated. That is to say, an extra \$5,379,478 a year. This increase is caused by the 37,070ML of stormwater, and so the total cost per volume of stormwater here is

$0.145/m^3$. This value represents the money lost on the difficulties imposed on the treatment of otherwise cleaner water.

4.3.3Calgary

Once again, it would seem that Calgary simply does not have this problem. Or at least does not do so in a manner that can be quantified with the same methods as the other cities are. Owing to its separated storm sewer system, there is no functional mixing of the two water types and therefore stormwater does not increase the amount of total suspended solids in treated and does not increase the complicate the treatment process. The value for soil erosion, TSS, and waste treatment for Calgary then is $\$0.00/m^3$.

4.3.4 Discussion

Obviously, there were some pretty... extravagant assumptions being made here. It would have been infinitely easier if the values for total stormwater processed in Toronto and the actual turbidity of the waters in Vancouver were available. But despite searching online records and contacting the city administrations themselves, there was simply not any data to be had. This section, then, may be better looked at in terms of a proof-of-concept rather than an accurate description of costs.

4.4 Stormwater Infrastructure

One of the most commonly used methods of controlling stormwater in Canada is the stormwater management pond (Drake and Guo, 2008). The basic premise of such an installation is to hold stormwater temporarily. This achieves two primary goals. The first is that in storing excess water in a predetermined location, the extent of flooding is reduced. Once the amount of water entering the sewers exceeds their capacity to transport it, backups and flooding occur. Therefore, any water prevented from entering the sewers then is equally prevented from flooding streets, houses, and businesses. A report on the efficacy of stormwater management ponds in Markham, Ontario found that following the construction of a pond, flood peaks were reduced by more than 80% for all storms in the study area (TRCA, 2002)

While it varies by design and local legislation, a common goal for stormwater retention ponds in both Ontario and British Columbia is to treat 90% of the annual runoff in its catchment basin (Ontario Ministry of the Environment and Climate Change, 2016). A sample retention pond built in Hamilton has a maximum extended detention capacity of 17,800m^3 (Gregory, 2014). The catchment basin for this site is 36 hectares, or 360,000m^2. The average rainfall for Hamilton is 835mm (Climate-data.org, 2018), resulting in a rainfall volume of 0.835m3/m^2. With a 90% treatment rate, the total amount of stormwater that this sample pond is designed to treat is 270,540m^3. So, for every m^3 of the maximum volume, it can be said that there will be 15.2m^3 of stormwater treated. Therefore, the cost per volume of treated stormwater annually will equal 6.58% of the cost-per-volume of construction of the pond.

The second primary goal of stormwater management ponds is detention and water quality control. Stormwater is high in suspended sediment, much of which can be quite toxic to human,

animal, and plant life (see chart 1 on stormwater content). Because much this sediment is quite heavy relative to water, if left for an extended period of time it will settle down the bottom of the water column, eventually forming a layer of deposited detritus on the bottom of stormwater management ponds. This sediment is to be later dredged out of the pond. Failure to do so will sharply decrease the efficacy of the pond (Schwartz, Sample, and Grizzard, 2017).

While many municipalities are not particularly shy about building stormwater management ponds, they are less willing to cough up the dough (so to speak) after the fact to pay for continued operations and maintenance. Indeed, one relatively recent study found that the majority of municipalities were unprepared for the not-particularly-inexpensive costs of dredging the ponds they have built in the near future (Drake and Guo, 2008). This complicates matters.

The price per volume of stormwater for stormwater management ponds can be roughly calculated as the total cost of the construction, operations and maintenance, and dredging of the pond over its lifetime divided by the total amount of stormwater the pond is estimated to retain over the same time frame. However, because many cities are skimping on the operations, maintenance, and, in particular, the dredging of the ponds, this prices listed here may be under representing the true costs of the ponds by significant margin.

Not only does this present a problem of undervaluing the full costs, but the consequences can be quite dire depending on the conditions. As noted above, a great deal of the sediment located on the bottom of the stormwater ponds is highly toxic. If the local conditions are correct, this accumulated sludge can be so toxic that it may only be disposed safely in specially located toxic waste sites, although that is unlikely (Government of Ontario, 2018),

All sediment dredged from stormwater management ponds must first be tested by the municipalities per Environment Canada's *Regulation 347*. Depending on the toxicity it will then be disposed of in a fitting site (on-site, off-site, on land, toxic waste site). Where the sediment must be dumped can have drastic outcomes on the price of dredging, with some estimates claiming the range to be between $\$14/m^3$ and $\$669/m^3$ (Graham and Lei, 2000).

4.4.1 Toronto

For Toronto, a stormwater management pond situated in the University of Toronto – Mississauga will form the basis of the analysis. This pond was commissioned for roughly $2.7 million by the University (University of Toronto, 2007). The project design specifies that the pond is designed to hold a maximum volume of 8303m3 of stormwater (MGM Consulting, 2018). This results in a construction cost of $325/m3. Using the 6.58% value derived in the introduction to this section, the deferred infrastructure costs for the City of Toronto can be estimated at $\$21.39/m^3$.

4.4.2 Vancouver

The Metro Vancouver region published their own study on the Best Management Practices for stormwater retention. Most of the values they used for cost estimates come from work done in Oregon. Which makes sense because both cities have a pretty similar topography and meteorological regime. In this report, the city posted an equation for a rough estimate of the expected costs of a wet stormwater retention pond. The equation given is: $\$28.90 \times (35.31V)^{0.70}$

where V is the total volume of stored water. The same report mentions that the typical construction costs for a wet stormwater retention pond usually range between $26 and $53 per m^3 of storage volume (Greater Vancouver Sewerage and Drainage District, 1999). Updated to 2018 dollars that means the per-volume price ends up being between $37.42 and $76.27.

However, these prices seem actually quite low compared to other estimates. One study published for the Town of Gibsons, BC found that the estimated price-per-volume of a projected stormwater management pond was $175/$m^3$ (Town of Gibsons, 2016). This is a particularly valuable point of reference because Gibsons is both very similar and very dissimilar to Vancouver.

They are quite similar in terms of local climatic and geophysical conditions. Gibsons is located just a short jaunt from Vancouver across the Strait of Georgia. However, in terms of the logistics for construction, Gibsons is quite different. Vancouver is connected to the rest of the North American economy via highways, rail lines, and a major airport. Gibsons is entirely disconnected logistically from the rest of the continent except by a ferry that takes a circuitous route around Bowen Island. While this makes Gibsons a truly lovely little town to vacation in, it likely exacerbates the prices of construction due to the being such a distance from sources of material and skills.

Using the 6.58% of the installation costs as a guide, we can see that in Vancouver there is a range of $2.46/$m^3$ to $5.01/$m^3$, with an average of $3.74/$m^3$. Just to show how rates can differ in the same climate but with different conditions of construction, the cost of stormwater in Gibsons would be roughly $11.15/$m^3$.

4.4.3 Calgary

The City of Calgary itself is frustratingly stingy with its publishing of any hard numbers relating to the construction of stormwater management ponds. However, the nearby Town of Okotoks, located just 18km South of Calgary, should be able to provide a reasonable facsimile for Calgary.

The town of Okotoks has proposed a development of new stormwater management pond that is required to hold up the 62,000m^3. This is actually insufficient for the prevention of the 100-year flood and further methods of stormwater reduction are necessary, but it nevertheless provides a standard to which the model can be applied. The pond is proposed to cost roughly $2,000,000 which equates to total price of $32.26/$m^3$ (Town of Okotoks, 2014). Using the 6.58% value derived above, the cost-per-volume for total annual stormwater treatment then ends up at roughly $2.12/$m^3$. This value is relatively low compared to Toronto, but that may be a reflection of local conditions like cheaper land and construction material values. Or it could be just an example of wishful thinking on behalf of the city governance.

4.4.4 Discussion

There is quite the discrepancy between the values arrived at for Toronto and the values found in the other cities. However, this may be due to the fact that a university site was chosen as the example for the city and is actually a good way to highlight the range of applicable values for this section. There are a wide number of different forms of stormwater management pond available with quite a range of price between the different forms (Government of Ontario, 2018). While the documents available do not go into substantial depth, it might be assumed that the

University of Toronto places a higher value on naturalizing the landscape than the municipalities do. As a result, they may be willing to pay a higher price for the 'frills' available with stormwater management ponds, resulting in a higher price. In fact, this higher price does keep in line with other estimates from not-too-distant areas.

Going somewhat farther afield but not so far as to be unusable, the City of Grand Rapids, Michigan conducted a study looking at the reduction in stormwater volumes with an increased tree canopy. They found that a 6% increase in the tree canopy of the City of Grand Rapids would result in an estimated $80 million dollars of reduced stormwater infrastructure costs. In this particular study, they calculated that the cost of deferred infrastructure came out to $1USD/gallon, or for those of us who use rational measurement units, a little over CAD$350/$m^3$ (City of Grand Rapids, 2015). So, the value for Toronto is not at all too far outside the expected ranges.

One might criticize the choice of sample ponds here as being not particularly representative, especially in the case of Toronto. Unfortunately, that one example is being used a last-minute replacement. A much larger-scale examination of prices for the City of Hamilton was originally going to be the method used. However, the failure to obtain some key values from the city's water department in time nixed that process. And so, this pond was used instead as it was the only readily available source of information on a compressed timetable. Despite this, the range in values possible for different designs of stormwater management ponds is an important consideration and bears mentioning. So, a nice segue into that point is appreciated.

4.5 Real Estate Prices

4.5.1 Lakes, Waterfront

There are a number of studies that correlate water quality with the price of residential buildings on the waterfront or near to it. Because there are many ways to measure water quality, and each study was conducted in a different region at a different time, there is a substantial amount of unpacking that needs to be done before one can draw a direct link between stormwater and real estate prices.

A recent study conducted in Florida, and funded by the Florida Association of Realtors, looked at how water clarity affected the price of homes in two separate counties (Florida Realtors, 2015). This was a robust study that sampled water quality based on chlorophyll *a*, dissolved oxygen, turbidity, and the secchi disk method. The researchers attempted to control for as many potentially confounding variables as possible, and also looked at how the changes in water clarity affected price over both a monthly and yearly time frame.

Their results showed that on a yearly basis, a 1-foot increase in the secchi disk depth produced a value loss of 14.66% in one county and a 10.32% in the other. The other values measured showed a less strong correlation, but the researchers pointed out that the secchi disk was likely the most accurate tool for this particular study due to the fact that it most accurately represented the human experience of water clarity; which is what it is assumed that the real estate price changes are based on. Interestingly, these changes were not limited solely to waterfront properties, with properties $1/8^{th}$ of a mile (about 200m), showing price changes of 11.42% and 8.02% respectively. Price changes were measured out to distance of 4 miles (6.4km) from the water's edge and found to continue to be affected, although minimally, out to that point.

Most valuably, the study further demonstrated how a 20% change in water clarity from the average yearly value would affect housing prices for the study area. They found that a 20% improvement in water clarity from the average would result in a 12.55% and 7.02% gain in housing value respectively.

A similar studied conducted by the American National Center [sic] for Environmental Economics, and published by the Environmental Protection Agency, looked at how real estate prices change with water clarity in the Chesapeake Bay. They found that 10 of the 14 studied counties demonstrated a positive correlation with housing prices and clarity (that is, less clear waters reduced housing prices), seven of which were statistically significant. This paper also studied how prices are affected with deviations from the mean water clarity measures. They found that, on average, a 10% change in Kd (light attenuation in water) would produce a 3.32% change in waterfront housing prices (Walsh, et al., 2015). This is quite comparable the above study in Florida's values as well, with 3 of the 7 counties reporting a price change that would put them between the two points on the Floridian range of values.

Moving further North, another study was conducted in lakes around New Hampshire and Maine, again looking at how water clarity affected lakefront housing prices. This study further confirmed the link between real estate values and water clarity, albeit to less of a degree than the previous studies. The researchers found that a 1m change in Secchi disk depth across four regions (with multiple lakes in each region) in both states resulted in a home sale price difference ranging from between 0.91% and 6.64% (Gibbs, et al., 2002). When one converts this to a 10% change in clarity, in order to better streamline it with other studies, these values become a range of 0.44% to 2.89% per 10% change in water clarity.

This contrasts with another study conducted in South Florida, this time in Marin Country, that showed drastically higher values when accounting for water clarity's effect on home prices. This study compared water clarity, ph, salinity, and dissolved oxygen. They found that a for a 1% increase in water clarity, there was a mean housing price increase of $36.069.73 (Bin and Czajkowski, 2013). The mean home value for this study area was notably higher than in many other studies, at $937,294. So, for a 1% increase in water clarity, there was a 3.85% increase in housing value. Even with that in mind, this result is an entire order of magnitude larger than many of the other studies reported.

This discrepancy between marginal prices may be linked to a cultural value that is not taken into account during the hedonic analysis conducted for these reports. While no paper thus far has confirmed this quantitatively, it seems reasonable to assume that the cultural value placed on clear water in rural New Hampshire may be different than that of South Florida. It could be theorized that those people willing to pay for million-dollar homes on Florida's beaches may have a higher budget for spending on luxuries like pristine water.

Another possible source of confusion between the different studies is that the connection between home price and water clarity is likely non-linear. Working on the assumption that a homebuyer will value improvement in water clarity more in lakes that are relatively clouded as compared to the more transparent water bodies, a study was conducted in Maine that used a non-linear equation to attempt to account for this issue. They ran separate hedonic models for housing qualities and lake qualities, creating two constants that were then used in an equation that took the natural logarithm of the mean minimum secchi disk depth (Michael, et al. 1996).

Using this equation, and the information for the lakes provided, it could be determined that for this study area, a 10% increase in secchi disk depth would lead to a mean increase in housing prices of 2.86% and a 10% decrease in depth would show a corresponding 3.16% decrease in housing prices. It should be noted that 2 of the 22 lakes in the original paper were discounted here because they returned negative values for the constants from the hedonic analysis which in turn created abnormally large changes that were likely due to some specific quirk of the lake in question and are not reasonably generalizable.

4.5.2 Lakes, Non-Waterfront

It has also been observed that water quality changes can affect housing prices a substantial distance away from the waterfront. A 2005 study was conducted in the St. Mary's watershed, a small region in the Chesapeake Bay, that linked housing prices to water quality as measured in term of total suspended solids (TSS) and dissolved inorganic nitrogen (DIN) (Poor, et al. 2006). Total suspended solids, as the name implies, is a measure of the sum amount of sedimentary material suspended in the water column. Dissolved inorganic nitrogen is a nutrient that, when found in abundance, can lead to runaway algal growth. While the sum impact of either of these measures is highly complicated, in this section they can be assumed to be components of turbidity, or cloudiness, in water and therefore perform roughly the same measure as a secchi disk does; being a proxy for water clarity as observed by home buyers.

This study found that a 1mg/L increase in TSS would reduce housing sale prices by $1086 and a 1mg/L increase in DIN would reduce housing sale prices by $17,642. Based on mean concentrations of 13.1310mg/L for TSS and 0.625mg/L for DIN, and mean house prices of

$204,823 and $200,936 respectively, it can be determined that a 10% change in water quality would result in a price change of 0.71% for TSS and 0.55% for DIN.

While these numbers by themselves are far below the value given in the previously mentioned studies, it comes with two very important caveats. The first being that both TSS and DIN are only partial components of water clarity and therefore the values under represent water clarity effects as observed in a secchi disk. The second is that these values are for the entire watershed, rather than just the immediate waterfront areas. In fact, only about 2% of the of the sample homes sales were from waterfront sites.

The area-scale approach to linking water quality and real estate prices was further expanded on in another study in Florida. A large-scale study that analyzed housing prices around more than a hundred lakes in Orange County, Florida calculated the price changes with water quality in 100-meter increments out to a distance of a kilometer (Walsh, et al., 2011). The researchers found that a 1-foot change in Secchi disk depth (an average change of about 17%) would result in corresponding change of about 0.72% for all homes 100m from the water's edge, dropping to 0.18% at 1km from the lakefront. The researchers also calculated the change in waterfront property value per Secchi-disk-foot to be about 1.24% (or 0.73% for a 10% change in water quality), notably smaller than the calculations for waterfront properties from other studies.

In this same paper, the researchers also looked at how the relation between clarity and housing prices may be further influenced by the size of the lake itself. While it is something that may be taken into consideration in further studies, their conclusion that a tenfold increase in lake size (from 100 acres to 1000 acres) resulted in roughly a doubling of the change in prices experience with a one foot change in Secchi depth may not be relevant to this paper. The sheer

size of the water bodies in consideration here (the Great Lakes and, effectively, the Atlantic and Pacific Oceans), push well beyond the reasonable generalizability of that conclusion.

Water clarity, of course, is not the only way to measure water quality. One metric used by researchers looking at property values in the Adirondacks of Northern New York was the presence of absence of loons (birds of genus *gavia*). These birds are a common indicator species - one whose presence, absence, or abundance is a reliable proxy for water quality and ecosystem health. This research found that the simple presence of loons on a lake would substantially raise the mean sale price of a home on the waterfront. In an area where the mean sale price of a waterfront home was $362,557, the presence of loons would raise the price by $46,158, or about 12.7%. Each individual loon was calculated to have a marginal price of $3308 (Tuttle and Heintzelman, 2014). While this paper will not go into detail attempting to link the number of loons in a system to stormwater, the finding just covered nevertheless play an important role in helping to justify the conceptual underpinnings of this work; that ecosystem services are highly undervalued in modern municipal accounting.

4.5.3 Rivers

There have been a number of studies linking housing prices to the water quality of lakes, but few linking prices to the water quality of rivers. One study did address this matter, but did so only for a specific measure of water quality, and one that may not be linked to housing prices in an incremental way, the way water clarity would be. This study, again conducted in the Chesapeake Bay region, looked at how fecal coliform counts may affect prices alongside a small tributary of the Severn River (Leggett and Bockstael, 2000). They found that reducing the fecal

coliform levels from 130 counts per 100ml for the mid reaches and 240 counts per 100ml in the upper reaches to 100 counts per 100ml at all points resulted in about a 2% increase in housing value. This equates to roughly 1.5% per 100 count per 100mL change.

Further research into the topic of river water quality and housing prices again looked at fecal coliform levels and also added in dissolved oxygen content. This study was conducted in Oregon and Washington and was consistent with Legget and Bocksteal's findings concerning fecal coliforms, showing that this study area displayed a 2.81% decrease in prices with a 100-count increase in fecal coliforms 100mL and sites within ¼ mile of the study site dropping down to a 0.71% loss at distances beyond 1 mile (Netusil, et al., 2014).

The values for dissolved oxygen content were quite dramatic. A 1mg/L change of DOC in the dry seasons resulted in a 13.71% decrease in property prices within ¼ of a mile and still retaining a 3.12% loss at distances greater than a mile. The signal from the second site studied was not as high in magnitude, likely due to some differences in local geography as noted in the study. Within ¼ of a mile at the second site, the drop was only 1.23% (not significant) but rose to 4.49% at ½ mile, 2.95% at ¾ mile, and 3.17% at a mile or beyond. The first study site (Johnson Bridge) had a mean DOC of 9.30mg/L and the second site (Burnt Creek Bridge) had a mean DOC of 6.94mg/L. The fecal coliform levels were only collected at the second site (Burnt Creek Bridge) and had a mean count of 306.31 per 100ml.

The problem with this data is that it may be difficult to integrate into the $\$/m^3$ model because differences in fecal coliform levels are not readily assessable by the naked eye the way water clarity is. Rather, the salient information available to purchasers of property may be more

based on a threshold model based on whether or not there are official warnings issued for the water bodies.

On the other hand, dissolved oxygen content is a proxy value for the amount of biomass in the stream, with low levels of DOC representing sites with significant eutrophication. Thus, it may be a more accurate metric because the levels of algal biomass in the stream may be more visible to the naked eye, and therefore, the casual glances of perspective homebuyers.

4.5.4 Toronto

A GIS model was used to calculate the value of real estate losses due to poor water visibility in this section. First, a map of the city was created that showed all 2011 census dissemination areas (the smallest unit in the census) (Statistics Canada, 2018). Each dissemination area has an exact value for the number of individual households in it (University of Toronto, n.d.).

With the location of each dissemination area, and their respective households, established, the central-points were calculated for each DA and the distance between that central point and the shoreline was calculated. This distance was then combined with the work mentioned above to determine how much real estate value was lost per dissemination area with distance. A flat rate of 0.18% of household value was applied at 1km and a value of 0.00054% was added for each meter closer to the water, as per the study by Walsh and others. This study was used as the basis because it takes into account both shoreline properties and more distal ones, as well. That value was then multiplied by the average household value and the number of household in each dissemination area to determine what each individual dissemination area loses in real estate

value for a 10% decrease in Secchi disk depth.

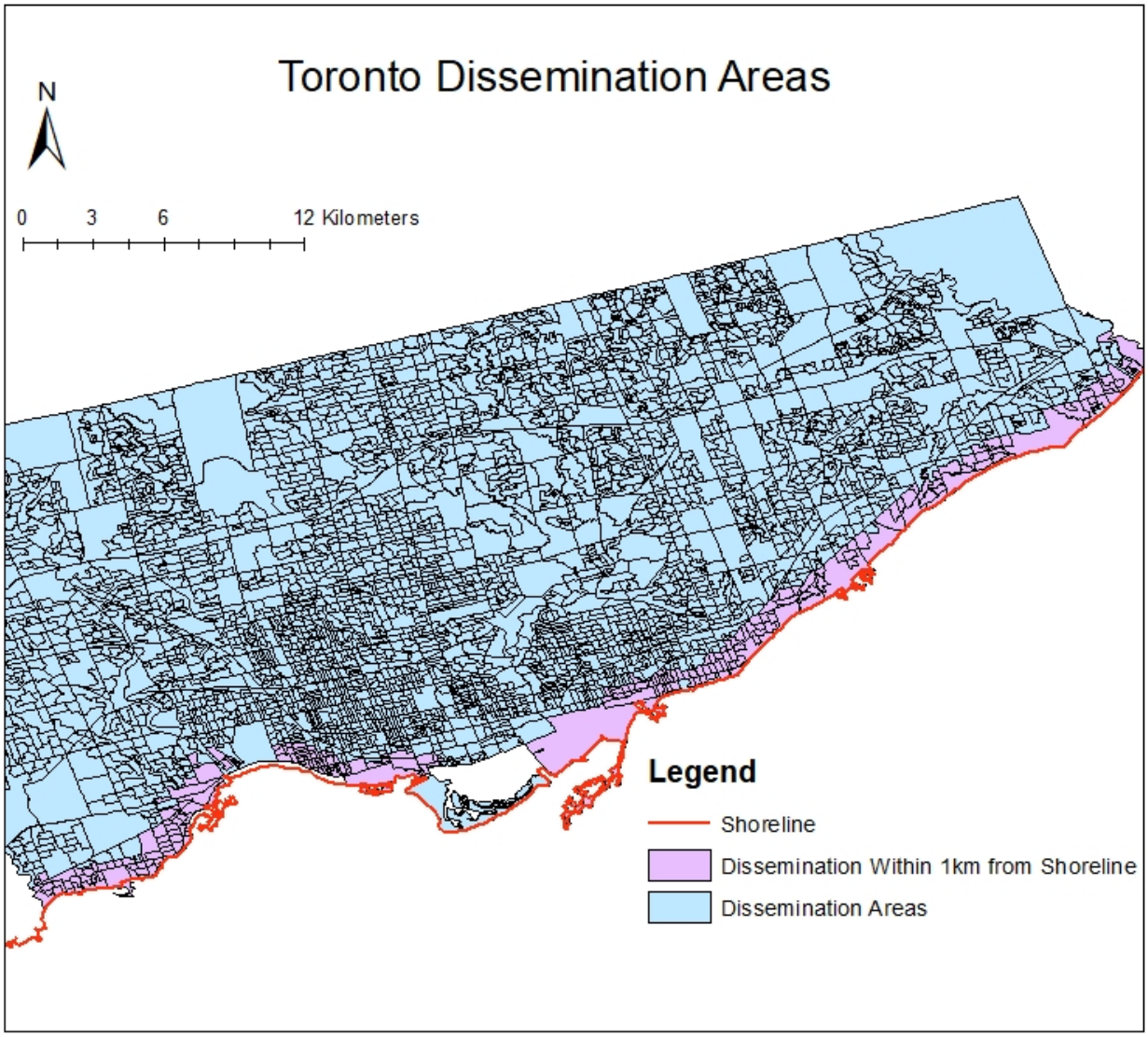


Figure 8: Toronto Dissemination Areas

With a total number of households in the 1km range of concern at a 94,801 and a total average home value as of 2018 of 807,871 (Canadian Real Estate Association, 2018), the model output determined that a 10% reduction in secchi-disk clarity would result in a loss of roughly $316,755,739.

Now, it is a bit tricky to say definitively that the secchi-disk depth measurements in the Toronto waterfront areas are a direct result of stormwater. There could be any number of other influences affecting the results. However, the source from which this data will be taken states in no uncertain that stormwater is a very important component in nearshore turbidity in the water surrounding Toronto.

According to this report, published by the TRCA, they squarely state that "stormwater infrastructure improvement, as well as wet weather flow projects and dry weather flow reduction measures [ie: stormwater controls] have contributed to further decline in nutrient concentration along the waterfront" (TRCA, 2015). Littered throughout the paper are constant references to stormwater being a primary driving factor between not just turbidity, but a great degree of water quality woes.

That paper did not publish the exact values anywhere, so they must be pulled from a chart depicting the values of different surveys. Some inaccuracy should be expected in this translation.

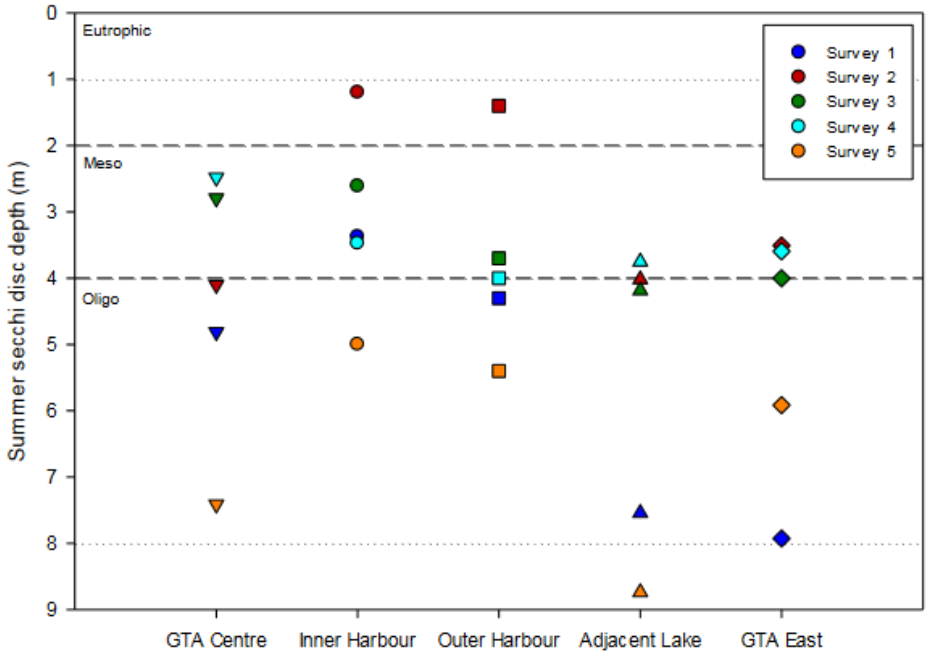


Figure 9: Great Lakes secchi disk depth, source: https://torontorap.ca/app/uploads/2013/01/Toronto-and-Region-AOC-Preliminary-Eutrophication-Assessment.pdf

The source materials for this section did not give a great direction as to how far to extend the water measurements for their effect on real estate values. So, a composite of the GTA Centre, the Inner Harbour, and the Outer Harbour will be used. Simply by eyeballing this chart, it appears that mean value for these three sites would be around 3.7m, give or take. The 'adjacent lake' entry provides a handy value from which to measure the difference between the two areas. This site appears to have a means secchi disk depth of roughly 5.7m. Therefore, there should be roughly a 35% reduction in secchi disk depth, most of which can be reasonably laid at the feet of the urban stormwater runoff, according to the source.

The 35% reduction represents a 3.5 times increase in the total real estate value that would be lost with 10% water clarity reduction. Using the value calculated above with the GIS model, it can be determined that the entire GTA real estate market down roughly $1,108,645,086 in value.

Using the volume of stormwater calculated in section 4.1 of 201,065,000m^3 (this includes both treated and untreated runoff), the estimated cost per volume of stormwater for lost real estate value in Toronto is \$5.51/m^3.

4.5.5 Vancouver

The same method with the same sources used in Toronto were also used for Vancouver.

There are 130,528 individual household scatted among 277 census dissemination areas that are within 1km of the Burrard Inlet shoreline in Vancouver. The average price for a household in Vancouver in 2017 was \$1,093,000. After running the model, it was determined that a 10% decrease in secchi disk depth in the waters surrounding Vancouver would lead to a loss of \$671,389,524.

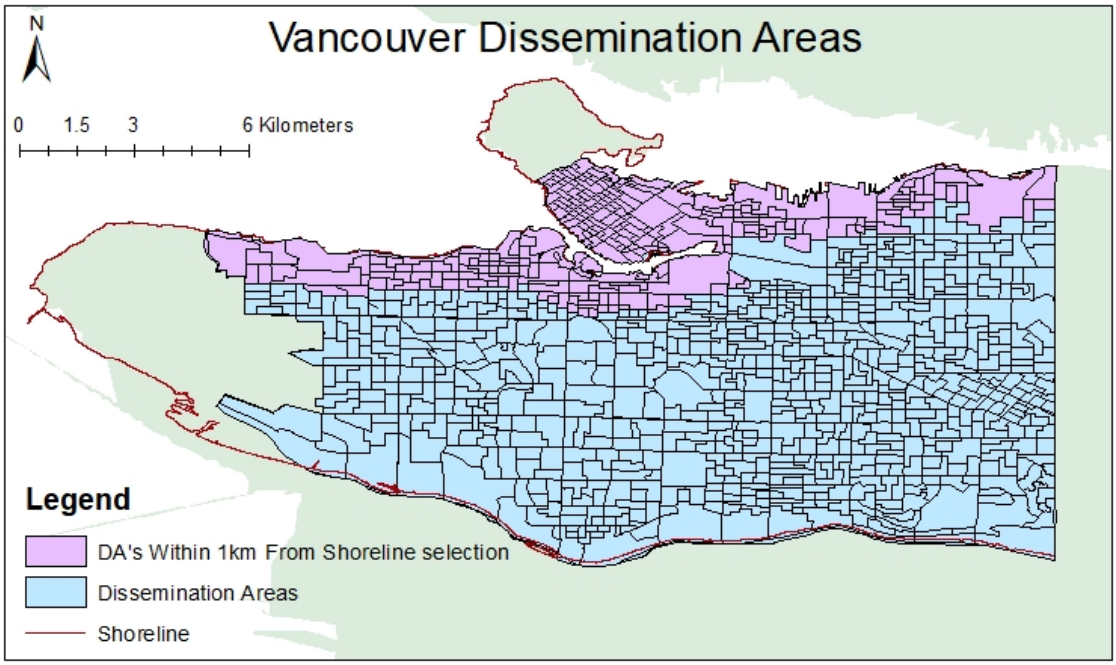


Figure 6: Vancouver Dissemination Areas

Unfortunately, there does not seem to be much available in the way of reliable Secchi disk measurements for Vancouver or the surrounding waters. However, a study conducted by the provincial government reported turbidity in the area in nephelometric turbidity units (NTU's).

NTU's are a measurement the light attenuation in water as determined by the degree to which a laser loses is power over a discrete distance within the water. The characteristics of the laser are variable and dependent on the type of monitoring device. NTU measurements will have to suffice as a stand-in for secchi disk depth here for want of a secchi disk based measurements.

The study showed that the average turbidity in the Port of Vancouver region, directly adjacent to the downtown city core, was 2.35NTU. Farther up the inlet and away from the urban runoff from Vancouver, values ranged between 0.17NTU and 0.77NTU, with a mean value of 0.52NTU (Government of British Columbia, 2001).

Converting between NTU and Secchi-disk depth is, at best, a rather speculative process. Secchi disks are a very subjecting measurement system to a certain degree of imprecision is to be expected. However, a general formula proposed by one paper indicated that near-surface depths, the relationship between secchi-disk depth and NTU was: NTU = -1.90252+15.013014/SD (Khattab and Merkel, 2015).

Using that value, it can be determined that the estimated Secchi-disk depth for the clear upper reaches of the Burrard Inlet is 6.20m. While the depth for the waters near Vancouver would be 3.62m. This represents a decrease in visible depth of 42%. Knowing that each 10% reduction in visible secchi depths results in a decrease of $671,389,524, it can be determined that the turbidity in the waters of the Burrard Inlet results in a real estate value loss of roughly $2,819,836,000.

Obviously, the amount of stormwater entering either the Burrard Inlet or the Fraser River is unknown. Thus, the best that can be done at the moment is a simple halving of the total stormwater volume. This is choice is backed up by the fact that both water bodies are serviced by roughly the same amount of stormwater infrastructure. Referring back to the map presented in section 5.2, it can be seen that both the Burrard Inlet and the Fraser River have 14 CSO-outlet points on their banks. An equal share of stormwater infrastructure at least hints at a roughly equal share of stormwater. This, clearly, is a rough estimation.

The same values for runoff and degree of impervious surfaces as calculated for Toronto will be used here. This makes the most sense as compared to, say, the values used in the calculations of runoff for stormwater management ponds, because they represent city-wide data from a similar form of urban development. Thus, a value of 45% for urban runoff will be used.

With a 45% runoff value applied to the 115km^2 of Vancouver, and a total annual average rainfall of 1815mm, there will be roughly 93,926,250m^3 of runoff. If it is assumed that roughly half of that is entering the Burrard Inlet and affecting its turbidity, then the volume of stormwater of concern is 46,963,125m^3.

If that amount of stormwater is responsible for a $2,819,836,000 loss in real estate value, then the cost per volume of stormwater in Vancouver is $60.04/m^3.

4.5.6 Calgary

The method for Calgary is similar to the other two, but the values are a bit different. Given that the city is situated on rivers and not a lake or ocean front, the value for e.coli was used as presented by Netusil, et al (2014). A map showing the affected dissemination areas, that is, all those within 1 mile of the river's edge follows.

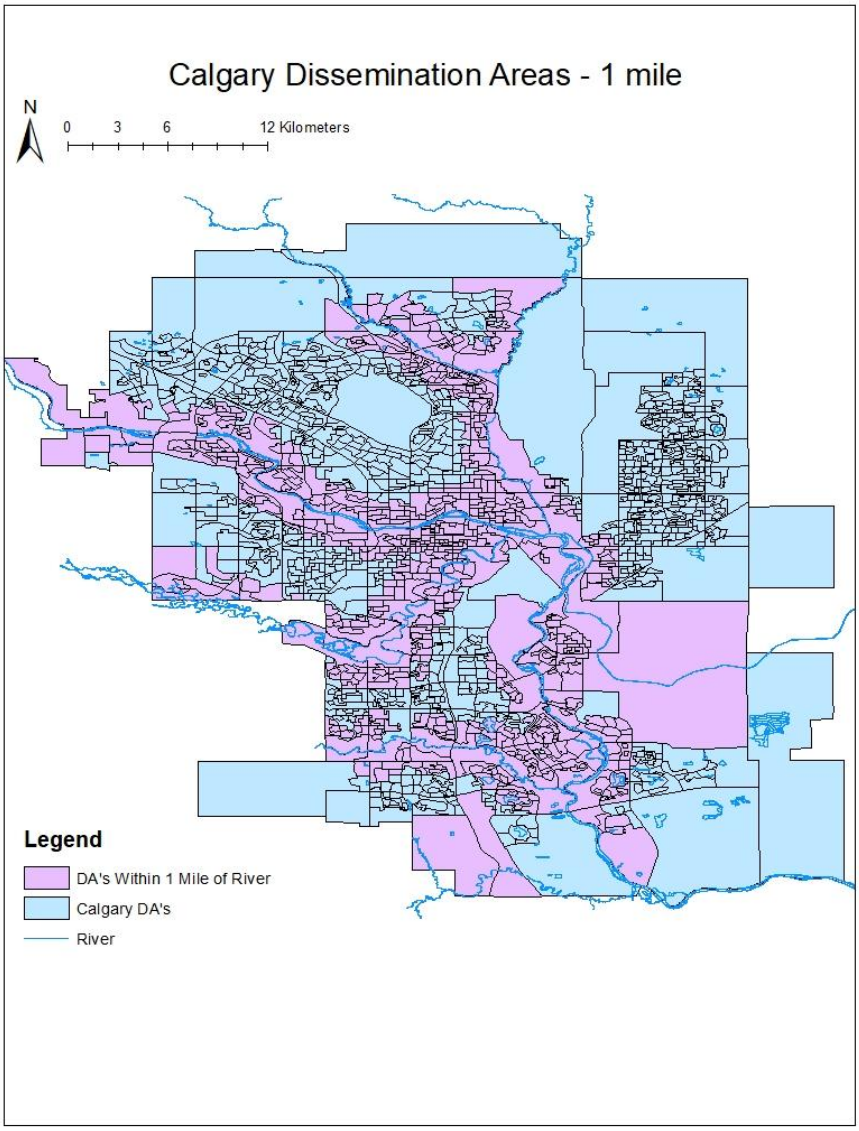


Figure 10: Calgary Dissemination Areas.

The affected dissemination areas contain 323,118 homes. The average home price in the City of Calgary as of June 2018 is 493,793 (JoeSamson.com, 2018). The total amount of real estate value lost in a 100-count increase in the number of fecal coliform per 100mL is $3,909,152,807. This is notably more than the other two cities. It should be kept in mind that these are apples and oranges, one is measuring water turbidity and the other fecal coliforms. Both water quality metrics, yes, but with different responses to each. Furthermore, a very large chunk of the City of Calgary lays within 1 mile of the riverbanks, so a larger proportion of the city's total real estate value is affected here.

The Bow River flows through Calgary and is sampled at seven distinct locations. The seven sampling sites reported a cumulative average level of *e.coli* of 67 counts per 100mL (City of Calgary, n.d.). Comparatively, the average value of fecal coliforms (used interchangeably with *e.coli* as it is a fecal coliform) in stormwater is 49,000/100mL. Knowing that Calgary's annual stormwater discharge is 119,114,560m^3, a simple concentration calculation can determine the total percentage of fecal coliforms that stormwater places into the river annually and, therefore, the amount for which stormwater is responsible for the water-quality related degradation of real estate prices.

Annually, the stormwater systems places roughly 5.84x10^18 fecal coliform counts into the river. The river's average flow rate is 129m^3/s (Water Office, 2018), which makes for an annual discharge of 4,068,144,000m^3. At a rate of 67 counts per 100mL, the river holds roughly 2.73.10^17 fecal coliform counts. The amount of stormwater is likely taken into account when computing the average flow rates, so the total river volume remains the same. The combination of river water and Calgary stormwater then, should have a total of 6.11x10^18 fecal coliform counts in 4,068,144,000m^3 of water, for a total count number of 1501.7/100mL.

This means that the stormwater in Calgary raises fecal coliform levels by 1434 counts per 100mL. The total real estate value then would be 14.34 time the amount calculated above. Or are a thoroughly astonishing $56,057,250,291. This value, divided by the amount of stormwater in the system, returns a cost-per-volume amount of roughly $470/m^3.

This seems a bit much.

Perhaps a better method is to simply compare the amount of *e.coli* bacteria upstream from the city to the amount of *e.coli* measured downstream of the city. This is a bit less precise of a method because there are certainly other contributing factors to the e.coli levels in the water, but at the very least it can give a good value for comparison.

While the map detailing as such is eye-strainingly small and therefore, not worth displaying here, the measuring site at Bearspaw flats occurs on the Bow River upstream of Calgary and almost immediately on the municipal boundary. Similarly, the site at Policeman's flat occurs on the downstream boundary. The value at Bearspaw measures 5 counts per 100mL and the site at Policeman's flat measure 152 counts per 100mL. This represents, then, an average increase of only 148 counts per 100mL.

At an extra 148 counts, the economic cost to real estate then becomes $5,785,546,154. This comes out to a cost of $48.57/m^3. Not cheap, but substantially less than what was experienced in the prior assessment method. In fact, this compares well with the price determined for Vancouver.

4.5.7 Discussion

It was rather expected that the value for Calgary would be higher than the other two simply from the GIS modelling. The city itself is bisected by rivers so a greater proportion of the households fall within the affected area. Secondly, the information available on fecal coliforms seems to be that they have a drastic influence on housing prices when compared to secchi disk clarity.

Regardless, the value found in this section is so grossly out of proportion with the rest of the paper that it probably should not be used in the final calculations. Rather, let it be a good example of the dangers that lay in applying trends beyond their reasonable usefulness. The likelihood that a potential buyer would be so drastically swayed by poor river water quality that they would pay almost half of the otherwise expected price seems a bit farfetched. Additionally, this whole matter may be mitigated by a more intensive look at locations of the stormwater outfalls and the timings of the events; after all, stormwater tends to come in bursts, rather than an evenly distributed annual average as used here. The fact that these highly-polluted bursts of rainwater are swept downstream in a matter of days likely counters much of this calculation. A worthy topic of research of its own, but far in excess of what is proposed here.

Vancouver seems to be worst off in this section then. Which is not surprising, it has a substantially higher average price for homes and a greater proportion of the population lives within a short distance from the shoreline.

5. Advanced Stormwater Management / Treatment Calculations

All of the above work can be compressed down into the following table:

Stormwater Cost ($/m^3)			
	Toronto	Vancouver	Calgary
Water Quality, Transport, and Treatment	0.26	0.29	0.31
Beach Closures	0.31	0.006	0.00
Erosion, Suspended Sediment, and Treatment	0.19	0.013	0.00
Stormwater Infrastructure	21.39	3.74	2.12
Real Estate	5.51	60.04	48.57
TOTAL	**27.66**	**64.09**	**51.00**

Figure 11: Summary of Stormwater Cost Per Volume

These values, then, can be used to re-examine the return on investment for different forms of green infrastructure.

5.1 Green Roofs – Extensive

There is a very good reference point for the efficacy of green roofs in Toronto provided by Esri, the corporation behind the ArcGIS projections used in this very paper. In 2009, they, along with building owners Crown Property Management, installed an extensive green roof on the top of their Toronto corporate headquarters, located at 12 Concorde Place.

Figure 12: Esri's Green Roof, source: https://www.theglobeandmail.com/report-on-business/industry-news/property-report/its-growing-on-us---more-green-roofs/article4435865/

While the builders have been a bit ambiguous on the total cost of the project, they have stated the price per square meter for design and installation ranged between $285 and $372. This is notably higher than the average costs for an extensive green roof. While highly variable based on the individual project, the Environmental Protection Agency of the American Government found that, on average, an extensive green roof will cost about $\$10/ft^2$, or about $\$142/m^2$ in Canadian Dollars. As one can see in the picture, this example roof has clearly been furnished with some quality-of-life accessories that would drive the price up.

This roof is $704m^2$ in total (Esri, 2012). They go on to state that the roof is estimated to prevent about $393m^3$ of stormwater from entering the municipal sewers on an annual basis. So, each square meter of this roof reduces stormwater by about $0.56m^3$ per year, equating to a

stormwater attenuation rate of 79%. Using the stormwater price calculated for the city of Toronto ($27.66/$m^3$), each square meter of this green roof provides roughly $15.44 of benefits annually. If the average cost per square foot was $328.50, then through stormwater savings along, this roof pays itself off in roughly 21 years.

Using the 79% attenuation rate as a guide for the other two cities, we can see that a similar roof in Vancouver would capture 1.43m^3/m^2, resulting in annual savings of $91.65 and payback period of roughly 3.6 years. Correspondingly, this roof in Calgary would attenuate about 0.26m^3/m^2, saving $13.26 annually and paying itself off in a few months short of 25 years.

For an interesting point of comparison, the Government Services Administration of the US published a study on the cost-benefit ratio of green roofs (finding they compare very favourably to the usual asphalt/shingle roofs) and noted that every square foot of green roof space in Washington DC saved $11.00 American over a 50-year period for benefits due to stormwater attenuation. According the GSA, this accounts for "savings from reduced infrastructure improvements and/or stormwater fees" (GSA, 2011).

Another report, by the American Department of Energy and the Environment, found that an extensive green roof in Washington DC will capture and hold, on average, 15 gallons of stormwater per foot per year (DOEE, 2009). Over a 50-year span that comes out to 750 gallons or 2.84m^3. This means that the estimated cost per stormwater from this region is about $3.87/$m^3$ American or about $5.07/$m^3$ Canadian. The majority of this cost appears to come from the deferred stormwater infrastructure that would have otherwise had to be installed due to local regulations.

5.2 Green Roof – Intensive

As stated much earlier in the paper, the main technical difference between an intensive and extensive green roof is the depth of the growing medium, with 6" (15.24cm) being the dividing line. However, what this means in practice is that intensive green roofs tend to support a much higher variety of plant life because the deeper medium allows for larger root systems that can support larger plants.

Intensive green roofs, much like extensive ones, can range in price by quite a margin depending on the nature of the project. However, several sites, both from green roof installers and those advocating for green roofs, indicate that intensive ones start in the $\$352/m^2$ range (Apex Green Roofs, n.d.) and scale up to roughly $538/m^3$ (Canadian Contractor, 2015).

While the average rate of annual water retention seems to vary considerably based on the local conditions and the construction of the green roof (Carson, et al., 2013), an average value of about 65% of total annual rainfall retention for intensive green roofs seems about appropriate given the information at hand (Speak, et al., 2013). Again, though, it should be stressed that the values range quite considerably.

So, with an assumed retention rate of 65%, an intensive green roof should on average absorb about $0.46m^3/m^2$ in Toronto (709mm average annual rainfall), $1.18m^3/m^2$ in Vancouver (1815mm average annual rainfall), and $0.21m^3/m^2$ in Calgary (326.4mm average annual rainfall). This equates to annual stormwater savings per square meter of $12.73 in Toronto, $75.62 in Vancouver, and $10.71 in Calgary. Using the mean price of $445/m^2$, intensive green roofs have a stormwater-only payback period of 35 years in Toronto, 5.8 years in Vancouver, and 41.5 years in Calgary.

5.3 Green Facades

Calculating the costs and benefits for this particular form of green infrastructure gets a little tricky because there appears to be only one article published, ever, that looks at that the actual measured effective rate of stormwater retention. It just so also happens that that article is hidden behind a paywall inaccessible through the York University library system (Kew, Pennypacker, and Echols, 2014) Despite the lack of measured results, there has been some work on the theoretical retention rate of green facades.

One paper posited, rather reasonably, that the retention rate of a green facade would be roughly equal to its evapotranspiration rate. Utilizing that value, they modelled the runoff reduction for a site in Seattle and found that on average, a green facade could be expected to reduce stormwater runoff by about 19%. Using this value, then, a green facade would retain roughly $0.135m^3/m^2$ in Toronto, $0.344m^3/m^2$ in Vancouver, and $0.062m^3/m^2$ in Calgary.

While, like all the other green infrastructure types mentioned, costs can vary greatly between one site and the next, green facades tend to be substantially more expensive than other forms of green infrastructure. At their more basic level, basically just planter boxes at the base of buildings, green facades can run up to the $30€/m^2$ range. At the higher end, with pre-planted vegetation blocks supported by a zinc-coated steel lattice, a green facade can cost as much as $1200€/m^2$ (Perini and Rosasco, 2013). In Canadian, that equates to green facades costing between $\$46.17/m^2$ and $\$1846.99/m^2$, give or take a few dollars depending on the exchange rate.

Green facades would save roughly $\$3.73/m^3$ in Toronto, $\$22.05/m^3$ in Vancouver, and $\$3.16/m^3$ in Calgary. On the low end, the payback period for green facades is 12.4 years, 2.1 years, and 14.6 years in Toronto, Vancouver, and Calgary respectively. On the higher end of the

price range, the payback periods become 495 years in Toronto, 84 years in Vancouver, and 584 years in Calgary. Not the best of use of one's money.

5.4 Rain Gardens

This may come as a shock, dear reader, but the price of installation for rain gardens is *also* variable. Given that they are often installed at a small scale on individual residential sites, a do-it-yourself approach can have costs as low as $\$42.30/m^2$. Alternatively, professionally designed and constructed rain gardens tend to range from $\$141.01/m^2$ up to around $211.51/m^2$ (Rain Garden Alliance, 2009).

The effective water retention rate of a rain garden (and indeed, all such green infrastructure forms) is dependent on the specific site, design, and construction. However, for what is deemed to be an average yet well-built rain garden, the Environmental Protection Agency, through a partnership with a local water authority based in Minnesota, found that a sample site rain garden was able to effectively retain 89-92% of the rainfall over a two-year period, reducing stormwater runoff by that same amount (City of Burnsville, 2006). Quite effective.

Extrapolating that value to the studied cities, there would be an estimated reduction of $0.645m^3/m^2$ in Toronto, $1.651m^3/m^2$ in Vancouver, and $0.297m^3/m^2$ in Calgary. This results in a per-square-meter savings of $17.84 for Toronto, $105.81 in Vancouver, and $15.15 in Calgary. This gives payback periods for a professionally designed rain garden (average cost of $\$176/m^2$) of roughly 9.9 years for Toronto, 1.7 years for Vancouver, and 11.6 years for Calgary. A self-

built garden would pay itself off in 2.4 years in Toronto, 2.8 years in Calgary, and just under 5 months in Vancouver.

Perhaps a good use of city resources would be to encourage homeowners to build their own rain gardens, considering the costs of that.

5.5 Swales

Swales, like rain gardens, can come in a variety of forms. One of the most common of which is the grass swale (sometimes referred to as an *enhanced* grass swale, ooh). Basically, these are ditches designed to both convey water as well as retain and treat it.

The Credit Valley Conservation Authority was so kind as to published a rather detailed look at using enhanced grass swales in their locale, which makes it an excellent source of information for Toronto and passably so for Vancouver and Calgary because it at least encapsulates the construction and design conditions unique to Canada.

The CVCA found that an enhanced grass swale complex will typically cost between $35,284 and $117,507 with a median price of $58,753 (Credit Valley Conservation Authority, 2012). This price is for a setup that will drain an entire hectare of impervious surface area. If the entire hectare of affected impervious surface is considered a green-infrastructure site with the addition of a grass swale, this results in a price per square meter of $\$5.86/m^2$, making it a very affordable option.

While the efficacy of a grass swale varies with local conditions, particularly the porosity of the soil, the study found that an realistic average would be a retention rate of about 20%. This

equates to 0.141m^3/m^2 in Toronto, 0.363m^3/m^2 in Vancouver, and 0.065m^3/m^2 in Calgary and presents annual cost savings of \$3.90/m^2, \$23.26/m^2, and \$3.32/m^2. The payback periods, then, would be 1.5 years for Toronto, 3 months for Vancouver, and 1.7 years for Calgary.

Quite a cost-effective tool.

5.6 Wetlands

There are two primary types of constructed wetlands, subsurface flow wetlands and free water surface wetlands. As the name implies, the primary difference between the two types is how water resides in the system. In free water systems, the water is exposed to the atmosphere while in a subsurface flow system the water in the wetlands is held within the soil substrate (Environmental Protection Agency, 2000).

The cost per hectare for a constructed subsurface flow wetland ranged between \$112,598 and \$155,890 with a mean value of \$135,964 (converted from 2007 American to 2018 Canadian). The cost for the same amount of land converted to a free water surface wetland was between \$3228 and \$101,328 with a mean value of \$34,607 (Manios, Fountoulakis, and Karathanasis, 2009). On a per square meter basis the prices are \$13.60/m^2 for the subsurface flow wetland and \$3.46/m^2 for a free water surface wetland. Given the rather large discrepancy between the two types of system, they will be considered separately for these calculations.

In terms of the efficacy of wetlands in reducing annual overland flow, it all comes down to how the particular site is designed; given that they are effectively naturalized cisterns, the amount a wetland can hold is determined by its dimensions and composition.

Many are designed to hold a 100-year flood event for their drainage area (Carlisle and Mulamoottil, 1991) and, as a result, retain the vast majority of the annual rainfall in any given year. However, perhaps a more reasonable annual retention level would be about 85%. This is derived from the requirements in some major metropolitan areas (California Stormwater Quality Association, 2003).

So, assuming a constructed wetland that is of decent quality but not built to contain all of a year's rainfall, the average amount of rainfall stored per area would be $0.598m^3/m^2$ for Toronto, $1.542m^3/m^2$ in Vancouver, and $0.277m^3/m^2$ in Calgary.

For subsurface flow wetlands, Toronto would save $16.54 annually and have a payback period of 10 months, Vancouver would save $98.83 annually and have a payback period of just shy of two months, and Calgary would save $14.13 annually and have a payback period of about a year. The payback periods for a free water surface wetland would be two and half months, two weeks, and 3 months for Toronto, Vancouver, and Calgary respectively.

5.7 Trees

Trees are actually quite effective at retaining and cleaning stormwater. This effectiveness, of course, varies greatly by species and size. As a result of this, perhaps the best method for ascertaining a relative efficacy of trees as stormwater management tools would be a large-scale analysis that helps to elide the differences between tree size and species.

Year Completed	i-Tree Reference City	Number of Trees Studied	Annual Stormwater Benefits (dollars)	Rainfall Intercepted Annually by Trees (million gallons)	Volume m^3	Rainfall per tree (m^3)	Stormwater CAD$/$m^3$
2006	Albuquerque, NM	4586	55833	11.1	42018	9.16	1.74
2005	Berkeley, CA	36485	215645	53.9	204034	5.59	1.38
2004	Bismarck, ND	17821	496227	7.1	26876	1.51	24.19
2007	Boise, ID	23262	96238	19.2	72680	3.12	1.73
2005	Boulder, CO	25281	357255	44.9	169965	6.72	2.75
2006	Charleston, SC	15244	171406	28.3	107127	7.03	2.10
2005	Charlotte, NC	85146	2077393	209.5	793044	9.31	3.43
2004	Cheyenne, WY	17010	55301	5.7	21577	1.27	3.36
2003	Fort Collins, CO	31000	403597	37.4	141574	4.57	3.73
2005	Glendale, AZ	21480	18198	1	3785	0.18	6.30
2007	Honolulu, HI	235800	350104	35	132489	0.56	3.46
2008	Indianapolis, IN	117525	1977467	318.9	1207168	10.27	2.15
2005	Minneapolis, MN	198633	9071809	334.8	1267356	6.38	9.38
2007	New York, NY	592130	35628220	890.6	3371288	5.69	13.84
2009	Orlando, FL	68211	539151	283.7	1073921	15.74	0.66
2003	San Francisco, CA	2625	466554	99.2	375513	143.05	1.63
2001	Santa Monica, CA	29229	110784	3.2	12113	0.41	11.98

Figure 13: Trees, Stormwater, and Moneys. Source: Derived from Environmental Protection Agency, Stormwater to Street Trees, 2015, retrieved from: https://www.epa.gov/sites/production/files/2015-11/documents/stormwater2streettrees.pdf

The first five columns in the above chart are from the sourced study, while the final three are calculations derived from the source material. The average amount of rainfall intercepted by each individual tree is 5.47m^3 per year (the values for San Francisco were discarded given that

they were such a distal outlier). While they will not be included in further calculations in this paper, the estimated value per m^3 of stormwater was also calculated to provide a bit of context. Given that the values range from \$0.66/m^3 up to \$24.19/m^3, there is clearly a lot of regional variation in the effects of stormwater (and perhaps, just as importantly, the manner in which stormwater costs are calculated). The average overall value for a unit of stormwater came out to \$5.76/m^3. As an interesting aside, the state of Indianapolis went a bit further and even calculated what the most economically beneficial trees were for a number of towns. Turns out, the maple is the consistently the top performer, whether that be sugar, red, or silver maple (Forestry Indiana, n.d.).

Unfortunately, this study does not provide an average area-per-tree so it is not possible to normalize the total retention coefficient for a tree. Therefore, it seems like the next best solution is to simply use the total volume retained value for the site which more closely resembles our sample cities. For Toronto, Minneapolis, MN, provides the best analogue, with an average annual rainfall value of 778mm to Toronto's 709mm. For Calgary, Boise, ID seems a likely pairing, with an average annual rainfall of 304mm to Calgary's 326.4mm. This means that the average tree in Toronto could be assumed in intercept roughly 6.38m^3 of stormwater a year while the average tree in Calgary would intercept roughly 3.12m^3. These values fall well within the range supported by a large-scale literature review that found that the average annual interception volume for trees ranged from 0.28m^3 to 11.3m^3 (Song et al., 2018).

The City of Vancouver does not have any direct analogues on this list, the closest in terms of annual rainfall would be Orlando, but that is clear on the other side of the continent and the dissimilarity in climate is so great as to effectively render any comparison spurious at best. Fortunately, a publication by a Vancouver suburb clears that issue up. In the city of North

Vancouver, it is estimated that a single street tree intercepts 2.08m^3 of stormwater a year (City of North Vancouver, 2004).

The City of Vancouver set aside 1.5 million in 2017 for park and street tree plantings, with a resultant 17,500 being planted. This results in a cost per tree of $85.71 (City of Vancouver, 2017).

In 2016, the City of Toronto allocated $1.6 million to tree plantings, which resulted in the planting of an estimated 27,000 trees across the city. This means that each individual tree planted in Toronto costs an estimated $59.26 (City of Toronto, 2016).

Following a destructive 2014 late-summer snowfall nicknamed "Snowtember," the City of Calgary undertook a vigorous tree planting program to make for the substantial losses suffered by urban tree canopy. In 2015, the Urban Forestry section of the Calgary Park Department was allocated a budget of 22.72 million, higher than usual due to the recovery from Snowtember. An audit of that same year's budget found that the role of planting /nursery/inventory was 15.4% of the Urban Forestry section's budget. This equates to a spending of roughly $3.49 million for 2015 (City of Calgary – City Auditor's Office 2016). In that year, the city managed to plant 7488 trees. If one were to assume that planting trees took up a third of that budget, then each individual tree planting would cost roughly $155.75. While this may be accurate, the fact that the other two cities are much less and much more closely matched in price was first a bit of concern. However, it seems that the price-per-tree planting is quite variable between different municipalities. The fine City of Vaughan (a bustling centre of culture and excitement) accords each tree $175 for planting costs in their budget (City of Vaughan, 2012). So it would seem that

the price for Calgary, while notably greater than either Toronto or Vancouver, is well within the expected margins.

In Toronto, each tree costs roughly $59.26 to plant and will absorb roughly 6.38m^3 of stormwater (averaged over its lifetime), resulting in annual stormwater savings of around $176.47. The payback period then would be roughly 4 months. Although, again, the first few years this would not be realized as the tree would need time to grow to that point.

In Vancouver, each tree costs $85.71 to plant and absorbs only 2.08m^3 of stormwater. This results in annual savings of $133.31 and a payback period of about 8 months.

Calgary's trees, coming in at maybe $155.75 each and attenuating 3.12m^3 of water a year produce annual savings of $159.12 and a payback period of a little over a year.

5.8 Permeable Pavement

There has been a lot of research conducted on the cost and benefits of permeable pavements so this is will be a relatively short section. The cost per square meter of permeable pavements ranges between $7/$m^2$ for porous asphalt up to $140/$m^2$ for the more expensive types of preformed interlocking pavers; the average costs being roughly $70.47/$m^2$. While the efficacy of permeable pavers depends on construction and rather critically on the infiltration capabilities of the underlying soils, the average site can expect between 45% to 75% annual runoff reduction, the average of that being 60% (Virginia Water Resources Research Centre, 2011).

Applying that 60% runoff average to the three cities results in a 0.425m^3/m^2 annual reduction in Toronto, 1.09m^3/m^3 reduction in Vancouver, and a 0.195m^3/m^2 reduction in

Calgary. The annual savings, then, are $11.76 in Toronto, $69.86 in Vancouver, and $9.95 in Calgary. This results in payback periods of 6 years in Toronto, 1 year in Vancouver, and 7 years in Calgary.

5.9 Summary

The values calculated in this section are summarized in the following tables:

Payback Periods (years, unless stated otherwise)			
	Toronto	Vancouver	Calgary
Extensive Green Roof	21	3.6	25
Intensive Green Roof	35	5.8	41.5
Green Facade	12.4 - 495	2.1 - 84	14.6 - 584
Rain Gardens	9.9	1.7	11.6
Swales	1.5	3 months	1.7
Subsurface Wetlands	10 months	2 months	1
Open Water Surface Wetlands	2.5 months	2 weeks	3 months
Trees	4 months	8 months	1
Permeable Pavement	6	1	7

Annual Savings ($/year)			
	Toronto	Vancouver	Calgary
Extensive Green Roof	15.44	91.65	13.26
Intensive Green Roof	12.73	75.62	10.71
Green Facade	3.73	22.05	3.16
Rain Gardens	17.84	105.81	15.15
Swales	3.9	23.26	3.32
Subsurface Wetlands	16.54	98.83	14.13
Open Water Surface Wetlands	16.54	98.83	14.13
Trees	176.47	133.31	159.12
Permeable Pavement	11.76	69.86	9.95

Figure 14: Annual Savings and Payback Periods for Green Infrastructure Projects

6. Discussion

Many municipalities in Ontario are already struggling to finance their existing stormwater infrastructure and the gap between what is built and what is needed is projected to only grow in the future (Ontario Environmental Commissioner, 2016). This paper has hopefully made the case that green infrastructure, when considering a more robust analysis of stormwater prices, is, in fact, an economically viable choice.

All across Ontario, the commonly stated goal of stormwater fees is cost replacement. That is, the fee is designed to draw in enough income to sustain the infrastructure for stormwater management. It is not intended or priced at a point that reflects the true cost that stormwater inflicts on a city. The entire 325-page Stormwater Financing Study conducted by the City of Mississauga does not actually ever give an amount at which to value stormwater's costs to the city (City of Mississauga, 2013). The price that the city implements as a stormwater fee is entirely disconnected from the actual harm that stormwater causes. It is solely to cover the funds for stormwater infrastructure. Calgary's stormwater management fee, detailed in section 5.3, operates on the same principal.

Because the city has a legal mandate to control stormwater, it would seem (and this is reading into things a bit) that they assume that some stormwater management is necessary, but the degree to which they could or should or are required to do so is open to interpretation. By placing a direct monetary cost by volume on stormwater, a city like Mississauga would know exactly how much resources should be devoted to the problem and will be able to make informed decisions on the costs and benefits of stormwater management. From there, a discussion on the

return on investment of different forms of stormwater management, including green infrastructure, can begin.

As the previous section's calculations show, a great number of green infrastructure forms are quite affordable when considering the costs of stormwater as calculated in this paper. The values, of course, are quite general, but it nevertheless indicates that green infrastructure offers a good return on investment when it comes to stormwater attenuation.

While the economics of green infrastructure seem to be quite favourable, once should not lose sight of the fact that green infrastructure initiative provides a host of hard-to-quantify ancillary benefits to the community in which they are placed. From improvements in health, happiness, and biodiversity, all the way down to a potential for reductions in crime (Montgomery, 2013). By embracing green infrastructure, knowing now that it reasonably affordable, cities can enjoy a whole host of other benefits in addition to stormwater maintenance. Making for better cities and better lives for the people in them.

7. Conclusion

The impetus behind this paper was the lack of available data on the subject at hand. This gap was made evident during an internship over the Summer at the Green Infrastructure Foundation. The work there was similar in nature, though different in scope, but greatly frustrated by the inability to find reasonable data on green infrastructure economics and stormwater pricing in particular.

There was a certain failure, then, to recognize the issues that would arise from this dearth of data while first formulating the proposal.

Ultimately, this paper suffered from this serious issue with data availability. In lacking the hard numbers for a host of factors, the paper was forced to rely on a series of extrapolations and assumptions that seriously reduced the veracity of any of the values presented here.

None of this serves to refute the central thesis of this paper, that stormwater is undervalued and green infrastructure is a cost-effective mitigation tool. Rather, it is to say that the numbers expressed here should be considered rather rough guides for stormwater pricing. Every value that was calculated was done with a great deal of generalization. There are so many variables possible with every single thing calculated that any one section of this paper could well be its own paper with a deeper look.

An astute reader of this paper has probably been asking questions along the lines of "but what about maintenance costs" or "is an average between two extremes actually representative of the situation as a whole?" These questions certainly cropped up while writing the paper. But, as stated way back in the opening pages, every time one looks deeper into the issue, even more questions and more potential factors arise. A cut off had to be put in place somewhere.

Despite these issues, this paper did accomplish the stated goal of demonstrating, at least in part, how the current view of stormwater pricing is undervaluing its costs and that green infrastructure is a cost-effective tool for attenuating stormwater and its inherent costs. Furthermore, this paper helped to shed some light on why the matter of stormwater pricing remains so nebulous.

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