LAND USE AND RIVER SYSTEMS: IMPACTS OF SUBURBAN RESIDENTIAL DEVELOPMENT ON CHANNEL STABILITY AND WATER SUPPLY, OAK RIDGES MORAINE, SOUTHERN ONTARIO

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ABSTRACT

To better understand the impacts of suburbanization on rivers and with the sensitivity of the Oak Ridges Moraine in mind, this study examined the geomorphology and hydrology of streams running through small primarily residential developments in the Humber River headwaters. Local scale impacts were analyzed by comparing paired upstream reference reaches to reaches downstream of developments in Caledon East, Palgrave, and Bolton. Channel morphology was assessed via bank soil strength measurements, vegetation cover, quantification of large woody debris, and visual assessment, allowing for inferences about potential downstream bank degradation symptomatic of streams in urban areas. Hydrology was evaluated using continuously measured water level and empirically estimated discharge, comparing hydrograph features between paired sites. Caledon East exhibited changes in morphology and hydrology symptomatic of the urban stream syndrome. Similar changes were seen at Bolton, but anomalously lower flows downstream confounded results. Palgrave did not exhibit impacts characteristic of urbanized streams.

DEDICATION

For Kendall Brownlee, whose mentorship nurtured my curiosity and whose guidance brought me to the discipline of Geography.

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CHAPTER ONE: INTRODUCTION

1.1 Introduction to fluvial geomorphology

River systems are complex in their nature, acting as conduits for carrying water and sediment, and are both shaped by and have a significant role in shaping the landscape that surrounds them. As such, field studies of river dynamics are complex and consider a great number of factors. Any fluvial geomorphic study conducted in a field setting inherently must take into consideration land uses that surround the channel and exist within its catchment area, as these impact the water that flows through that landscape.

The 1950's saw the rise of process-based geomorphology, a significant change in the methodology and approach to studies in fluvial geomorphology (Roy and Lane, 2003), which remains the prevailing way of thinking in modern fluvial geomorphic research. Prominent geomorphologist Arthur Strahler's 1952 publication, *Dynamic Basis of Geomorphology,* called for the principles of physics, chemistry, and statistics to be applied to the study of weathering, erosional, transportation, and depositional processes. This shift towards quantitative methods brought geomorphology to its modern iteration. Following the pioneering work of Leopold and Maddock (1953), the study of hydraulic geometry has become an important field in fluvial geomorphology, and field studies are commonplace (Williams, 1978; Richards, 1973; Rhodes, 1977; Parker, 1979; etc.). Despite a modern shift toward interdisciplinary scientific research, there remains a need to continually pursue river science and deepen our knowledge of fluvial processes.

Geomorphologist and hydrologist Luna Leopold concluded his 1994 book, *A View of the River*, with the statement, "The river, then, is the carpenter of its own edifice." Modern fluvial geomorphology acknowledges that rivers are physical systems with a relevant history (Schumm, 1977) and that their current form is shaped in tandem by past and present conditions and their immediate and regional surroundings (Knighton, 2014). The prominence of those historic and present impacts coupled with the ability of each system to respond and adapt to changes dictates the proportional significance of the historic and present physical and environmental influences (Knighton, 2014).

Land use acts as a major driver of geomorphic change, and as such, land cover assessments have long been an integral component of field studies in fluvial geomorphology. Even before the coining of the term "urban stream syndrome" (Walsh et al., 2005_a), fluvial studies commonly accounted for drainage area land use (e.g., Dunne and Leopold, 1978; Moscrip and Montgomery, 1997; Paul and Meyer, 2001; Konrad and Booth, 2002) and land-use change (e.g., Buttle, 1995; Lewis et al., 2000; Burns et al., 2005) in explaining the causes of a swath of ecological, geomorphic, and hydrologic alterations. Some of the latter two changes will be discussed in Section 2.4 regarding the urban stream syndrome and its symptoms.

1.2 Geographic context

It is known that land-use change and the construction of impermeable surfaces for anthropogenic use have profound effects on river systems including direct implications on channels at the local scale. Research has brought attention to the fact that intense and extensive urbanization in southern Ontario poses a significant threat to the health of the region's river systems (Paul and Meyer, 2001). With population increase in the Greater Toronto Area (GTA) intensifying pressure for residential development, population is sprawling onto the Oak Ridges Moraine. This holds the potential to further degrade the rivers draining the GTA's watersheds, as the Moraine is both a critical groundwater recharge zone and the headwaters for four of Toronto's major rivers.

Population in the City of Toronto has grown steadily over the past decade. The city's population increased by 4.5% from 2006 to 2011 (Statistics Canada, 2012) and again from 2011 to 2016 (Statistics Canada, 2017$_e$). Additionally, population density increased 4.3% between 2006 and 2011 (Statistics Canada, 2007; Statistics Canada, 2012) and by the same amount between 2011 and 2016 (Statistics Canada, 2012; Statistics Canada, 2017$_e$). Coupled with the common housing preference for single-family dwellings outside the main core of the City of Toronto, the demand for residential development has amplified demand for suburbanization of the fringes of the GTA. This has prompted pressure for new low-density residential development in Toronto's surrounding municipalities and regions. Cities such as Brampton, Mississauga, Vaughan, and others have been largely to entirely developed, primarily with low-density suburban-type dwellings. With demand for this housing type persisting, pressure has been shifted to regions further from Toronto proper, such as Milton to the west, through Durham region in the east, and a variety of suburbs to the north, including Caledon, Bolton, King, and so on. Some of these towns and suburban communities are located atop the subterranean Oak Ridges Moraine.

1.3 Primary goal of study

Land use varies over a developed area in part due to the degree of urbanization or builtness (Pauleit and Duhme, 2000). Spatial constraints act as the driving factors behind urban infrastructure sprawl from the confines of the dense urban core into surrounding spaces (Ferreira et al., 2012), allowing for lower density development to propagate outward into rural or undeveloped city fringes, hence, producing suburbs. Few field studies have been conducted specific to suburban land use or are defined as suburban fluvial geomorphology (Burcher and Benfield, 2006; Burns et al., 2005; Curran and Hession, 2013; Ferreira et al., 2012). While some studies have equated the presence of residential subdivisions with urbanization more broadly (Arnold et al., 1982; Hamilton and Waddington, 1999), it seems useful to make a distinction between urbanized and suburbanized land. In this way, focus can be directed to the lower density and less intense development associated with suburban land use and its features. In the North American context, specifically in Canada, there is a marked distinction between the typically dense urban and sprawling suburban land covers. Suburban land use in Canadian cities is characterized by comparatively lower population density than its nearby urban centre, having a high proportion of single-family dwellings and other low-density residences, and more open, non-residential areas such as parks and woodlands.

There is an apparent need for further knowledge of the impacts of suburbanization and other smaller scale, lower impact developments on stream health. This study sought to examine the impacts of the impermeability of suburban areas in the city's headwaters and characteristics on the stream morphology of the river it drains, linking impacts of low-intensity development seen downstream to the well-known symptoms of the urban stream syndrome. This was done through a case study approach, analysing local scale impacts of low-density residential development on downstream channel morphology and flow characteristics. The GTA's present environmentally precarious housing situation and the environmental sensitivity of the Oak Ridges Moraine combine to illustrate an apparent need for study of this nature in this area. While this study was conducted in suburban and small town-type contexts, it does not seek to better define the term "suburban" within the context of fluvial geomorphic studies. Rather, with the lack of scholarly focus on specific suburban studies of this nature, this research aims to contribute to broader work in an understudied land use context in fluvial geomorphology.

This thesis is organized into six main sections. The first section introduces the field of study, relevant background information, and the primary objective for this research. The second section provides a review of scientific literature discussing relevant themes, concepts, and previous research conducted in the application of the urban stream syndrome. The third section describes the methodologies used to carry out the project. The fourth section details the results of the study. The final sections, five and six, provide a brief discussion and some overall conclusions derived from the research.

CHAPTER TWO: LITERATURE REVIEW

2.1 Oak Ridges Moraine

The Oak Ridges Moraine is a large, continuous ridge of glacially deposited sand and gravel. Impressive in size, the linear moraine is the largest stratified moraine in Canada (Barnet et al., 1998). Covering approximately 11 000 km^2 (Edey et al., 2006), it is a maximum 200 m in thickness (Gerber and Howard, 2002), an average of approximately 13 km wide, and roughly 160 km in length (Sandberg et al., 2013). The subterranean landform is situated north of the City of Toronto, spanning from the Niagara Escarpment eastward to beyond Rice Lake and the Trent River. Roughly 65% of the moraine lies within the boundaries of the GTA. It has been estimated that presently, over 90% of the land on the Moraine is privately owned (Sandberg et al., 2013). All of the study sites are situated atop the moraine, with Bolton on drumlinzed till plain, Palgrave on kame, and Caledon East on a glacial spillway (Chapman and Putnam, 1984).

The precise origins of the Moraine are poorly understood (Barnett et al., 1998). The landform was created at the southern margin of the Laurentide Ice Sheet during the Wisconsinan glaciation, approximately 12 000 YBP (Shaw et al., 1996). Formed by episodic drainage processes during the retreat and demise of the Laurentide Ice Sheet (Russell et al., 2003), the Moraine was emplaced in four stages of glacial sedimentation: subglacial, subaqueous, fan to delta, and ice-marginal sedimentation (Barnett et al., 1998). The Niagara Escarpment was likely key in the creation of the Oak Ridges Moraine. A system of meltwater channels across and along its surface presumably provided pathways for glacial meltwater drainage and is thought to have acted as a control for regional water levels during the emplacement of the Moraine (Barnett et al., 1998). Additionally, the role of the drumlins in its formation is not well known. The drumlin channels terminate at the margin of the moraine and so are thought to hold significant to its origin (Barnett et al., 1998).

The Moraine is comprised of complex and porous glacial till sediment. It lies on Paleozoic strata along a margin of exposed shield to the north and directly atop the Newmarket Till, also deposited during Wisconsinan by the Lake Simcoe ice lobe (Barnett et al., 1998). The presence of the till on a sloping erosional surface created a local glacial unconformity (Russel et al., 2003). The high, sandy ridge acts as the present-day drainage divide between Georgian Bay to the north and Lake Ontario to the south (Barnett et al., 1998). Drumlins and a network of deep, steep valleys comprise the uplands of the landform and the Niagara Escarpment sits at its western fringe (Barnett et al., 1998). South of the moraine and through the GTA, the land slopes southward toward Lake Ontario and is considered part of the Peel Plains physiographic region, comprised of low-relief till material and the Lake Iroquois Plains (Chapman and Putnam, 1984).

The geographic extent of the Moraine is both complex and contested. A combination of surface and subsurface investigation techniques including studies of landscape geomorphology have been used to refine understanding of the Moraine (Sharpe et al., 1996; Barnett et al., 1998). Due to its composite origins and its subterranean setting, it has proved difficult to accurately and comprehensively define (Sandberg et al., 2013). While the variability and sheer thickness of the Moraine have made it difficult to locate with precision, accuracy in our understanding of its extent has improved with advancements in mapping techniques, such as GIS and remote sensing technologies (Shaw et al., 1996). Even still, it has been suggested that the Moraine may not truly be continuous, but rather, a network of smaller interconnected depositional features of glacial origin (Barnett et al., 1998).

Beyond its connotation as a notable landform, the Oak Ridges Moraine is of acute environmental significance and provides great anthropogenic value. The moraine acts as a critical groundwater recharge zone (Gerber and Howard, 2002). Its hummocky surface and porosity promote water collection and absorption from the surface (Barnett et al., 1998; Gerber and Howard, 2002) and its stratified sands and gravels filter the absorbed water (Sandberg et al. 2013). The Moraine acts as one of the most heavily relied upon groundwater sources in Canada (Cheng et al., 2001). Its aquifers feed baseflows for more than 65 rivers and streams that drain from its surface and provides water supply for more than a quarter of a million people (Sandberg et al., 2013). However, regional groundwater supply and flow patterns in southern Ontario are poorly understood. Few studies have been conducted to monitor groundwater levels regionally (Gerber and Howard, 2002). With many relying on the aquifers for water and a lack of real-time knowledge of the supply, there are concerns about local groundwater across the Moraine (Sharpe et al., 1996).

Land use on the moraine has varied greatly over the past decades, as with attitudes and efforts towards its conservation. From the 1990s onward, the Moraine has been challenged by suburban sprawl primarily from the northward creep of development from the oversaturated City of Toronto (Sandberg et al., 2013). Pressure from residents of the Moraine well informed of its hydrologic and ecologic significance coupled with extensive media coverage of planning hearings and technical details of plans culminated in the creation of the Oak Ridges Moraine Conservation Act in 2001 and the Oak Ridges Moraine Conservation Plan the following year (Sandberg et al., 2013). While wide acclaim for the Conservation Plan gives the impression of a seemingly tight legislative framework, arguably, development allowances within the Oak Ridges Moraine Conversation Plan are quite permissive. In the legislation, the Moraine is divided into four main areas: natural core areas, natural linkage areas, countryside, and settlement areas. Protections vary for each (Ontario Ministry of Municipal Affairs and Housing, 2002). The plan imposes strict restrictions on residents and landowners presently residing on the Moraine, but various permissions and loopholes allow for development within all four of the areas defined by the Plan (Sandberg et al., 2013). Even within the natural core areas, those zones defined as most hydrologically and ecologically vital and susceptible to impact, a long list of commercial, infrastructure, and residential developmental initiatives are considered acceptable. In natural linkage areas, also deemed to have considerable environmental significance, additional allowances are made. Development allowances are more liberal still in countryside and settlement areas.

At present, development of the Oak Ridges Moraine continues as is permitted within the Conservation Plan's jurisdiction (Government of Ontario, 2002) despite shifts in the Moraine's water balance and a notable decrease in groundwater recharge (Barrett, 2007). To date, only approximately 30% of the Moraine's surface remains in its natural, forested and vegetated form and this proportion is shrinking. Data show that population continued to grow on the Moraine between 2006 to 2011 at a rate faster than in the previous census (Statistics Canada, 2007; Statistics Canada, 2012), demonstrating that the Conservation Plan has not succeeded in slowing growth.

2.2 Stream channel morphology

In the context of river studies, morphology refers to channel function, form, including topographic and bathymetric shape and dimensions, and changes in these over time. Stream channel morphology is influenced by a range of factors with varying degrees of significance that affect channel form. Flow conditions largely influence morphology and control other aspects that influence form, making them arguably the most significant factor determining channel morphology and alterations to morphology over time.

Flow conditions shape channel form both over long periods of time and in short term, catastrophic events. Sediment transport rates are governed by flow conditions and bed and bank particle size distributions, which are unique to each river and even to individual reaches (Andrews, 1980). While peak flow conditions are large drivers of geomorphic change (Arnold et al., 1982), the concepts of the frequency, magnitude, and duration of forces significant to channel form (Poff et al., 1997) are critical to understanding the significance of a broader range of flows on channel morphology. The frequency with which discharge rates occur is illustrated by the distribution of flow events of varying magnitudes for a given stream. While short, catastrophic peak flows occur relatively infrequently, longer and more moderate flow events with correspondingly moderate sediment transport rates occur most frequently and transport smaller amounts of sediment but over a more significant proportion of the year (Andrews, 1980). In rare circumstances where channels have high resistance to erosion, those uncommon flow events with very high discharge play the most significant role in driving geomorphic change (Baker, 1977). More commonly, the more frequent and less intense flow events are most significant in shaping the channel, especially in that of the channel size and meander length (Walsh et al., 2005_a). In this way, all flow events causing bed or bank erosion and capable of sediment transport are significant in studying changing morphology.

In 1953, Leopold and Maddock asserted the existence an equilibrium condition between channel morphology and the independent variables of discharge and sediment load. Equilibrium here refers to the state within which the same amount of sediment is entering a system as there is being discharged from it, where the volume of sediment remains equal and produces no resultant change in channel morphology. This equilibrium between the independent variables of sediment input and outputs and discharge results in morphological stability of the bed and banks (Petts, 1979). Channel shape is adjusted during individual flood events, where observations of bed scour and aggradation during floods that cause widening and deepening of the banks and bed, respectively, occur simultaneously with changes in the suspended-sediment load, leading to the conclusion that the alterations to channel morphology are the result of modification in sediment load supplied from upstream to the reach and not purely the impacts of local flow conditions on its immediate geomorphic setting (Leopold and Maddock, 1953). In 1964, Langbein added to the concept of equilibrium that channels "possess five degrees of freedom," with the ability to alter their gradient, bed roughness, width, depth, and planform in response to flow and sediment inputs to remain in state of quasi-equilibrium. Additional studies added further variables that channels can adjust to maintain some level of equilibrium (Hey, 1978), adding further depth and complexity to the concept of channel adjustment to quasi-equilibrium (Petts, 1979). Absolute equilibrium rarely occurs; rather, channels adjust their size, geometry, and configuration to match the prevalent flow conditions and sediment supply (Langbein, 1964). Degradation takes place when sediment transport capacity exceeds the sediment supply, where flow competence holds the potential to initiate geomorphic change as it drives erosion. This results in channel size increase and reduced flow capacity, doing so until erosion can no longer be sustained by the flow (Petts, 1979). Dynamic equilibrium refers to the mutual adjustment of a drainage area with underlying geology and those streams that are drained from that surface area (Wiel and Coulthard, 2010). Equilibrium is not a static state, but rather, is flexible in responding to hydrologic and sediment regime shifts, such as those caused by alteration of catchment land use.

Channels with the presence of trees in the riparian area are impacted by the effects of large woody debris (LWD), which is debris comprised of fallen trees, trunks, stumps, root wads, and large branch accumulations (Keller and Swanson, 1979). LWD loading can create notable changes in channel morphology, having a direct impact on the channel’s form and the sediment movement through the system (Bilby and Ward, 1989). Channel form is influenced in a number of ways. LWD pieces and accumulations can cause the formation and stabilization of gravel bars (Lisle, 1986) and its inclusion can generate forced steps (Curran and Wohl, 2003). Pools are formed as the LWD directs the flow, either by concentrating the stream so as to scour the bed or bank or by acting as an obstacle to the flow (Lisle and Kelsey, 1982) and the resultant pool area correlates to the volume of LWD pieces that were its cause (Bilby and Ward, 1989). LWD can also create small waterfall structures, causing a drop in the bed elevation (Bilby, 1981). Sediment movement is mainly influenced by the LWD as it acts as a flow obstruction. Pieces and accumulations impede flow and cause a loss of potential energy over short distance resulting in the deposition of entrained sediment (Bilby, 1981; Megahan, 1982). This results in a significant volume of sediment retention, responsible for adding to channel complexity (Bilby, 1981) and an increase in the proportion of fines accrued (Zimmerman et al., 1967; Megahan, 1982). LWD also acts similarly with regards to the retention of organic matter, where LWD pieces and accumulations serve as a flow obstruction causing a trap and store for suspended organic particulates (Naiman and Sedell, 1979; Bilby and Likens, 1980).

2.3 Land-use change and river systems

The hydrologic characteristics of a drainage area are directly impacted by changes in land use (Hamilton and Waddington, 1999). Various land uses and vegetation covers have a range of impacts on the hydrology and the resultant morphology of the drainage channels. This is largely a result of the range in characteristic permeabilities associated with different land cover features.

Agricultural land covers a significant proportion of southern Ontario and the Oak Ridges Moraine. Agricultural areas have the hydrologic capacity to hold greater soil moisture than that of other land uses, including forested and developed land (Ferreira et al., 2012). While such land use causes considerable impact on biota, a shift from forested to agricultural land cover has not been consistently shown to significantly produce hydrologic or geomorphic effects (Burcher and Benfield, 2006). As a result, historically forested catchment area that has been converted to agricultural land has not been given any attention in this study, as the stream characteristics of interest would likely not have been transformed significantly with this specific change in land use.

Forested areas are often used in studies of fluvial geomorphology to reflect land cover that produces natural channel conditions (Niezgoda and Johnson, 2005), unimpacted by anthropogenic land use. Wooded areas decrease the proportion of water that contributes to surface runoff, where the denser the vegetation and tree cover, the greater infiltration is facilitated, and as such, surface runoff is proportionally decreased (Ferreira et al., 2012). Loss of forested area on a catchment can lead to channel degradation, as it is a key land cover for water retention producing increased lag time to stream input from precipitation events (Buttle, 1994). LWD loading is greatly impacted by the density of trees in an area, as trees in the immediate riparian area act as the source of LWD. As such, forested areas input LWD via natural tree mortality and external factors such as bank instability and failure, bank incision, flooding, and blow down by strong winds (Curran, 2010). The outcomes of LWD loading include bank stabilization, increase in sediment deposition, and increase in flow resistance (Curran, 2010). Due to the greater supply and potential for loading, these impacts are most significantly seen in wooded areas. While the impacts of a loss of forest cover in a catchment may be relatively straightforward, the same cannot be said for reforestation, as the process does not produce a simple inverse effect and takes much longer to cause an observable alteration to flow regime and generate geomorphic response (Buttle, 1994).

With these in mind, it must also be acknowledged that land uses with comparatively high permeability are not entirely permeable and can still produce surface runoff. Whether in agricultural, forested, or other land uses with high proportions of vegetation cover and what is understood to be permeable ground, overland flow can still occur with varying water repellence, soil saturation, vegetation type and volume, and surface litter conditions and characteristics. Nevertheless, vegetation features and pervious ground make for a less direct route for precipitation to reach stream channels. The two increase resistance, direct a greater proportion of the volume of precipitation into the ground, and allow for the uptake of that water by the vegetation to remain in storage or directed away via evapotranspiration. These combined effects provide a slower pathway and increase the lag time for the precipitation to reach its terminus in the streams. This broadly results in decreasing peak flows in response to precipitation events (Ferreira et al., 2012).

2.4 Urban stream syndrome

Urban and suburban land uses can be argued to be the most impactive on river morphology since their effects are apparent for many kilometers downstream (Vietz et al., 2015). With the world's population becoming increasingly urban and that migration toward urban centres projected to continue for the foreseeable future (Cohen, 2003), more land is expected to be developed for residential, commercial, industrial, and other anthropogenic uses. Consequently, the hydrologic impacts associated with urban and suburban land uses are expected to persist, all the while, humans living near stream systems habitually rely on them for valuable and sometimes essential natural resources (Meyer et al., 2005).

In 2005, Walsh et al. coined the term "urban stream syndrome" to describe the impacts of catchment urbanization on river channel morphology, hydrology, water chemistry, and ecology (Walsh et al., 2005_a). A summary of the characteristic symptoms can be seen in Table 2.1. It has long been understood that undisturbed, natural channels are shaped by prevailing conditions of the flow regime and surrounding environmental conditions over the span of many years (e.g., Mackin, 1948). In contrast, urban stream morphology has long been attributed to peak flow conditions with increased flashiness, magnitude, and frequency as a result of urban land cover (Walsh et al., 2005_a). Development of land typically results in deforestation, vegetation loss, and decreasing agricultural land cover (Ferreira et al., 2012), which have important implications for hydromodification, or alteration to the hydrology of a catchment area causing stress to the system triggering divergence from the usual hydrologic regime (Hawley et al., 2012).

Table 2.1: Basic urban stream syndrome symptoms, from Walsh et al., 2005_a

Feature	Consistent response	Inconsistent response	Limited research
Hydrology	↑ Frequency of overland flow ↑ Frequency of erosive flow ↑ Magnitude of high flow ↓ Lag time to peak flow ↑ Rise and fall of storm hydrograph	Baseflow magnitude	
Water chemistry	↑ Nutrients (N, P) ↑ Toxicants ↑ Temperature	Suspended sediments	
Channel morphology	↑ Channel width ↑ Pool depth ↑ Scour ↓ Channel complexity	Sedimentation	
Organic matter	↓ Retention	Standing stock/inputs	
Fishes	↓ Sensitive fishes	Tolerant fishes Fish abundance/biomass	
Invertebrates	↑ Tolerant invertebrates ↓ Sensitive invertebrates		Secondary production
Algae	↑ Eutrophic diatoms ↓ Oligotrophic diatoms	Algal biomass	
Ecosystem processes	↓ Nutrient uptake	Leaf breakdown	Net ecosystem metabolism Nutrient retention P:R ratio

The primary cause of this hydromodification is directly linked to the increased efficiency of storm and meltwater transport to river channels. The construction of urban features on the land surface results in less permeable ground surface in the catchment and consequent increase in surface runoff. With a decrease in subsurface storage, the route taken by rainwater into river systems becomes more efficient, and hence, produces a more rapid and intense hydrologic response (Walsh et al., 2005[a]). For instance, due to the decrease in surface permeability, a higher proportion of overland flow has been observed in built areas than in forested (Ferreira et al., 2012). Additionally, systems for stormwater drainage in which pipes carry water drained from urban surfaces directly into river systems further exacerbate the rapidity of input (Dunne and Leopold, 1978). The combined effects of decreased subsurface storage and stormwater management infrastructure channeling precipitation to streams produce an efficient pathway for stormwater to river systems and act as the driver of hydromodification in urbanized catchments. Typical stormwater management standards have sought to regulate and mitigate the impacts of surface runoff from storm events larger than those with one- to two-year recurrence interval (Roesner et al. 2001). However, climatic alterations to storm recurrence intervals mean that current infrastructure may not be built to withstand rain events becoming typical in our modern climate and are forcing a shift in standards for stormwater infrastructure capacity to accommodate more frequent and intense precipitation events (Walsh et al., 2005[b]).

In response to this hydromodification, channel width and depth exhibit consistent increases due to bank instability and incision, respectively, as well as consistent intensification of bed scour (Booth, 1990). Bank retreat and proportional channel widening occurs because of bank-toe erosion due to altered flow conditions coupled with bank mass failure (Simon and Collison, 2002). Storm water management approaches at the channel reach level have commonly been employed. More recently, catchment-wide flow regime management practices have been incorporated. Each method has shown limited success in combating the effects of urbanization on stream degradation (Booth and Jackson, 1997; Vietz et al., 2015; Walsh et al., 2005_b). As such, an in depth understanding of the precise impacts of varying degrees of development on streams is of the utmost importance for planning and the success of conservation efforts within, in close proximity to, and downstream of not only urban but also suburban communities.

Much scientific research has focused on the impacts of the urbanization of drainage area on stream channel health, however, the overwhelming majority of previous studies have focused on strictly high-density urban development settings. As a result, literature on the urban stream syndrome is quite literally focused on high-density urban centres. Human populations concentrate in urban centres, and as such, focus on preservation of streams in these contexts is given heightened importance because of the potential social, economic, and safety concerns (Annable et al., 2012). There exists a great body of literature spanning a range of spatial and temporal scales on the impacts of catchment development on stream features over past half century focusing on high-density urbanization (e.g., Carter, 1961; Wolman, 1967; Leopold, 1968; Hollis, 1975; Packman, 1979; Whipple et al., 1981; Dyhouse, 1982; Booth, 1990; Booth, 1991; MacRae and Rowney, 1992; Henshaw and Booth, 2000; MacRae, 1997; Doll et al., 2002; Bledsoe and Watson, 2001; etc.). However, less intense impermeable-type developments have been shown in some cases to contribute to river degradation, as well (Rose and Peters, 2001; Hawley et al., 2012). This illustrates the usefulness of the study of river responses to smaller scale development practices such as suburbanization. Across a wide range of scales, land-use change causes the most significant impacts seen in the hydrologic system (Bhaduri et al., 2000) and even relatively low concentrations of development have been shown to induce geomorphic change, for instance, at as little as 2% catchment imperviousness (Hawley et al., 2012). Some suburban land uses, specifically lawns, parks, and woodlands, allow for infiltration and groundwater recharge similar to pre-development rates (Lerner, 2002). However, suburban development largely entails constructing surfaces that are impermeable, thus, decreasing infiltration, increasing surface runoff, and intensifying peak streamflows (Rose and Peters, 2001). With this in mind, the principles of urban stream syndrome may be tentatively applied in the context of smaller scale, lower intensity developments.

Complexities and inconsistencies inherent to studies of suburban-type developments under the heading of "urban stream syndrome" research reinforce the argument that these land uses and scale of development, which have been given considerably less scholarly attention, require further study. Suburban stream response is perhaps more complex than that of its urban counterpart. Such development exerts influence on catchment hydrology and channel morphology in ways and to degrees far less understood than in much researched urban areas. In some cases, suburban land cover may produce no significant geomorphic response at all (Burcher and Benfield, 2006). Additionally, within the literature on land-use and river systems, terms such as "urban," "suburban," and "sprawl" are used inconsistently and interchangeably (Theobald, 2004). This introduces further vagueness into the understanding of the influences of suburbanization and other assemblages of low intensity developments on flow regimes and resultant river morphology.

2.5 Riparian vegetation

Riparian vegetation, that which is along the immediate- and near-bank surfaces of a watercourse, is both spatially and temporally dynamic and heterogeneous (Auble et al., 1994; Tabacchi et al., 1998). The prospect of a species and type of vegetation thriving on a particular landform is governed by the suitability of that site. This includes soil type, slope, aspect, climatic conditions, and so on, for the germination, establishment, and long-term growth to reproductive age of the individuals (Hupp and Osterkamp, 1996). Characteristic vascular plants found in riparian zones are predominantly species that are relatively disturbance tolerant and thrive near watercourses or frequently flooded areas (Richardson et al., 2007). Despite their proximity, these criteria usually result in riparian vegetation that is unique from adjacent or nearby terrestrial assemblages (Ellenberg, 1988).

Stabilization of banks occurs because of soil reinforcement, and water retention and physical stabilization by roots. Generally, soil is weak in tension. Conversely, fibrous roots, such as those of trees and other vasculars, are strong in tension. Therefore, soil permeated by roots is a more complex medium with enhanced strength compared to that of pure soil (Thorne, 1998). The roots protect soil from hydraulic scour by regulating soil moisture through ‘hydraulic redistribution’ (Burgess et al., 2001; Hultine et al., 2004). This results from evapotranspiration by the plants themselves and interception by their canopy, hence, increasing soil cohesion (Thorne, 1998; Simon and Darby, 1999; Abernethy and Rutherfurd, 2001). The effects of erosional processes are significantly exacerbated on non-vegetated banks (Beeson and Doyle, 1995). For this reason, vegetation is often employed in river restoration, emplaced along riparian corridors for its stabilization properties (N.R.C., 1992; U.S. E.P.A., 2004; Bernhardt et al., 2005). For instance, in the case of single threaded channels, vegetated banks add stability to help maintain meanders and broader patterns of channel planform complexity (Perucca et al., 2009; Curran and Hession, 2013). Though counterintuitive, it should be noted that riparian vegetation can in some cases cause minor adverse effects on bank strength (Durocher, 1990; Collison and Anderson, 1996), including during certain periods of hydrologic conditions when collapsing trees and upheaval of roots result in bank destabilization (Simon and Collison, 2002). However, this is not the general outcome, nor the desired outcome when vegetation is used in stream restoration efforts. This scenario should be considered exceptional with regards to vegetation impacts on the stability of streambanks.

Vegetation in and on the near bank and immediate bank surface of a channel increases surface roughness and intensifies the trapping of loose sediment (Curran and Hession, 2013). Removal of vegetation, especially in the riparian area, causes an increase in the removal of surface sediment and soil material and ensuing potential transport and incorporation of this sediment into channel flow (Sheridan et al., 1999; Lee et al., 2003; Mankin et al., 2007). Great volumes of sediment can be seized in riparian areas, making riparian vegetation a noteworthy filter and storage of sediment for river systems (Curran and Hession, 2013). While some studies have suggested that in exceptional circumstances severely reduced sediment loading can lead to channel erosion (Kondolf, 1997), riparian vegetation is largely seen as a sediment stabilizing feature and does not generally contribute to channel erosion. Such circumstances are not present in the context of this study. In the sites present in this study, riparian vegetation cover is recognized to be an effective trap for sediment on and near the banks and transported overland, as well as a contributor to increased near-channel surface roughness.

Land use has broad, regional impacts on general catchment permeability, but on a smaller scale, the impact of changing land use on successional stages of riparian vegetation can be discussed. Vegetation disturbance on or near the streambanks can be caused by changes in fluvial processes (Hupp and Osterkamp, 1996). Bank undercutting can cause the exposure of in-soil roots and destabilization of trees, hence, causing them to fall into or towards the channel and become incorporated as LWD. Since land-use changes and decreased permeability often are the drivers of the hydrologic changes that perpetuate geomorphic change, urban development is commonly attributed to causing a negative feedback loop with regards to impacts on riparian zones: urbanization further exacerbates channel bank erosion and degeneration by damaging and removing riparian vegetation, causing bank soil destabilization and the potential for further bank erosion. Flow conditions in equilibrium act as a control for the stability of the associated riparian trees and vegetation cover (Hupp and Osterkamp, 1996), though such conditions are rarely or never achieved in streams situated in urbanized catchments. When hydrologic change driven by human activity leads to a loss of equilibrium conditions and alters the geomorphic state of stream channels, the relationship between riparian vegetation and their associated fluvial landforms can collapse (Hupp and Osterkamp, 1996). During the phase of recovery and reestablishment of the equilibrium state, it is characteristic for ruderal and invasive species to colonize and play a role in aiding the reestablishment of channel equilibrium (Osterkamp and Costa, 1987; Hupp, 1992). Due to disturbance and the creation of new sites for plant establishment, invasive and ruderal species are often found along recently degraded riparian corridors (Hupp and Osterkamp, 1996). Native species are often absent or less abundant, as the invasive individuals outcompete and hinder the success of native ones (Scott et al., 1997). Note that some species and vegetation types, both native and invasive, are more resistant to hydrologic degradation (Hupp, 1983; Hupp and Osterkamp, 1996).

CHAPTER THREE: METHODOLOGY

3.1 Research questions

Comparison was drawn between the geomorphic characteristics and flow dynamics assessed in pairs of channel reaches, each pair with one site situated upstream and one downstream of low-density suburban-type developments. This allowed for qualitative and statistical comparison between those channels unaffected (upstream) and affected (downstream) by reduction in catchment permeability. The two-pronged primary research question was whether a selection of the geomorphic and hydrologic symptoms outlined by the principles of the urban stream syndrome would be apparent in the context of low intensity suburban-type development. On the geomorphic side, it was hypothesized that banks would be visibly more eroded and lack vegetation, that vegetation assemblages present would be composed of a higher proportion of ruderal and invasive species, and that there would be a higher percentage of LWD per unit area of channel at those downstream sites impacted by impermeable development because of bank degradation. On the hydrologic side, it was hypothesized that a significant difference in storm hydrographs and hydrograph features, specifically that of amplified rising limb slopes and greater peak magnitudes during stormflows, would be observed at the downstream sites compared to paired upstream sites. Additionally, a broad trend toward greater variation in discharge over the entire study period at downstream sites was hypothesized.

The use of a pocket penetrometer for assessing soil strength in mass per unit area in this study is described in 3.8 Bank Stability Assessment. The application of this instrument in this context is novel and is the source of another avenue of exploration. In addition to the core research questions, this study sought to test whether a pocket penetrometer, a handheld device commonly used for attaining soil strength measurements at a range of depths through series of soil horizons down a profile, could be used to asses the strength of riverbank soil. This was done with the intention of testing a potential new method to lend to more quantification in studies involving geomorphic assessments of bank strength.

3.2 Locations and sites

To examine the potential impact of suburban land use on a given reach, sites were sought in various locations with the following criteria. Firstly, channels were chosen that run through pockets of relatively low-intensity residential development with predominantly agricultural or forested areas comprising their upstream catchment, hence, having as little development as possible upstream from the suburban community to affect the catchment hydrology. The study considered areas large enough to encompass their small developments, hence, situating this work at the local, sub-watershed scale. For the purpose of this study, low-intensity refers to exurban developments; those that are outside of the urban core of the city. There, residential land use is dominated by low-density dwellings such as single-family, detached homes and also including semi-detached houses, townhouses, and occasional low-rise medium density condominium style housing. High-density, high-rise dwellings such as apartments are not present or are very uncommon in these areas. As such, the terms suburban and low-density are not used in a strictly quantitative, concrete sense. Rather, they are employed in a contextual and perhaps discursive sense within the spatial situation of the dense and growing metropolis of the GTA.

The streams were also chosen based on the criteria that they were headwater streams originating from the surface of the Oak Ridges Moraine. Consistency between the origins of sites, where their subwatersheds all exist within the bounds of the same subterranean geologic feature, provides better uniformity in the geologic underpinnings of each of the channel reaches, reducing variability between them in their origins (Annable, 1996). In addition, all were single thread, slightly meandering channels. Keeping the stream type uniform across the channels studied allows for an additional level of consistency and facilitates better comparison between them (Annable, 1996).

Six sites were chosen, with three sets of upstream and downstream pairs. Sites were defined by a channel reach and associated cross-section. The reaches were relatively straight sections of channel (Richards, 1982) extending for a standardized length of five times the channel width at the cross-section. Site cross-sections were located at the downstream end of each of the study reaches. Reaches were chosen as the straight sections between the meander bends so that each reach was approximately straight with cross-sectional shape as close to rectangular as was naturally available. Upstream sites contained reference reaches, not impacted by the developed catchment area downstream. These sites had relatively undisturbed land upstream, ranging from protected lands within conservation areas to rural land covers, representing the relatively stable natural form and conditions of their channel thread to simulate the control conditions for the study. Downstream sites were along the same channel as their upstream pair but were affected by the development, with the impervious town or suburb located within its specific catchment area. This allowed for comparison and contrast to be drawn between sites with similar characteristics and origins, as impacts of the development would be potentially exhibited downstream after the channel passes through the developed land.

Reference reaches, often used in fluvial studies, are stable reaches of channel that illustrate natural channel form (Rosgen, 1998; Kondolf, 1998; Niezgoda and Johnson, 2005). Reference reaches are those thought to be naturally stable (i.e., not reinforced or engineered for enhanced stability) and approximate natural conditions (Rosgen, 1997). Stability is assessed qualitatively using morphologic features, with visual markers indicative of ‘stable’ and natural conditions used to select the reference reach (Niezgoda and Johnson, 2005). In the case of comparative study with regards to impacts of development such as this one, a reference reach serves to approximate the pre-disturbance, predevelopment conditions for that particular river (Niezgoda and Johnson, 2005). In this way, the upstream reference reach does not necessarily possess the exact natural form of its downstream pair. Rather, the upstream reference reach suggests what the morphologic state and relative degree of stability the downstream reach would have possessed pre-development, as it is close in proximity, along the same thread of channel, and is less impacted or perhaps unimpacted by impermeable development. Since the upstream and downstream site pairs in this study are situated a short distance away from one another and share a common substrate, the concept of a reference reach can be applied. As such, it is not a temporal reference, but rather, a spatial reference that is thought to approximate the pre-disturbed character of its downstream counterpart. In order for a reference reach to be employed in a study to compare with other reaches of that river channel, all must be situated on similar land types. In this study, all paired upstream and downstream sites are intentionally very similar in their situation, with none on vastly different geological substrates or slopes.

Traditionally, it is suggested that reaches impacted by anthropogenic features, such as bridges, dams, weirs, etc., be avoided for the purpose of a study of channel morphology (Annable, 1996). These installations can be seen as modifying flow and morphology, hence, skewing any observations of the presumed natural channel. However, the nature of this study is to draw inferences about the impacts of small, low intensity development on streams. So, avoiding anthropogenic impacts entirely is not the purpose of this research. Nevertheless, while the impacts of impermeable surface features were sought, some features were avoided in an attempt to reduce the impacts of built structures and anthropogenic influence in the immediate vicinity of the sites. The process of site selection attempted to seek reaches to represent the sum of the conditions in the catchment area draining into the selected reaches and eliminate as much impact caused by their immediate surroundings as possible. For instance, while most sites are situated close to roads for ease of access, the impacts of the roads and bridges crossing the channels were avoided by sampling upstream of such crossings. In that way, the impact of the bases and foundations of these structures resulting in the channeling the flow beneath them was not present where sampling took place. Additionally, sites were chosen with riparian vegetation and greenspace in their immediate vicinities. This reduced the impact of very local land use on the reaches in an attempt to best illustrate the regional influence of land use on morphology and flow.

Sites set within this low intensity development criteria were chosen in the Town of Caledon, Ontario. The entire town, situated in the Municipal Region of Peel northwest of the City of Toronto, has a population of 66 502, area of 688.16 km^2, and population density of 96.6/km^2 (Statistics Canada, 2017_b), an area significantly more sparsely populated than neighbouring Toronto, which has a population of 2 731 571 and population density of 4 334.4/km^2 (Statistics Canada, 2017_e).

Each site was situated in the headwaters of the Humber River watershed feeding into the main branch of the Humber. Southern Ontario is largely divided into relatively small drainage basins with short rivers less than 200 km in length draining into either Lake Erie, Lake Huron, or Lake Ontario (Walker et al., 1997). The Humber River is no exception. The Humber watershed spans 903 km^2 and extends 126 km to its terminus in Lake Ontario (Toronto and Region Conservation Authority, 2008_b). In 2002, only 32% of the watershed's surface was protected by vegetation cover (Toronto and Region Conservation, 2007). At the time of this study, only 25% of the urban and developed areas in the catchment had any level of stormwater management (Toronto and Region Conservation, 2008_b).

Given the source of water in the Main Humber, a study centred on impervious surfaces and hydromodification is especially important. According to a report on surface water quantity from the Toronto and Region Conservation Authority (TRCA) from 2008, groundwater discharge is the primary source of water in the Main Humber subwatershed, feeding baseflows. This is due to a combination of the permeable nature of soil in the catchment, hummocky topography of the porous underlying Oak Ridges Moraine, high proportion of rural land use, and presence of aquifers, especially in the upper portion of the subwatershed. When considering the Humber River as a whole, 50% of the total discharge during baseflow originates from the Main and East Humber (Toronto and Region Conservation Authority, 2008_c), making the perviousness of the two subwatersheds of great significance for sustaining baseflows.

The three locations, each having a pair of up and downstream sites, were chosen for this study and named after the towns or neighbourhoods they were located in: Palgrave, Caledon East, and Bolton. The locations of these can be seen in Figure 3.1. The names of the sites reflect their geographic location and position upstream or downstream. As such, the names of the sites are as follows: BU (Bolton, upstream site), BD (Bolton, downstream site), PU (Palgrave, upstream site), PD (Palgrave, downstream site), CU (Caledon East, upstream site), and CD (Caledon East, downstream site). The basic information for these sites is organized in Table 3.1. As can be seen in the table, each channel was classified as alluvial with either sand or gravel beds, having median bed grain sizes of between 0.0625 mm and 2 mm and greater than 2 mm, respectively.

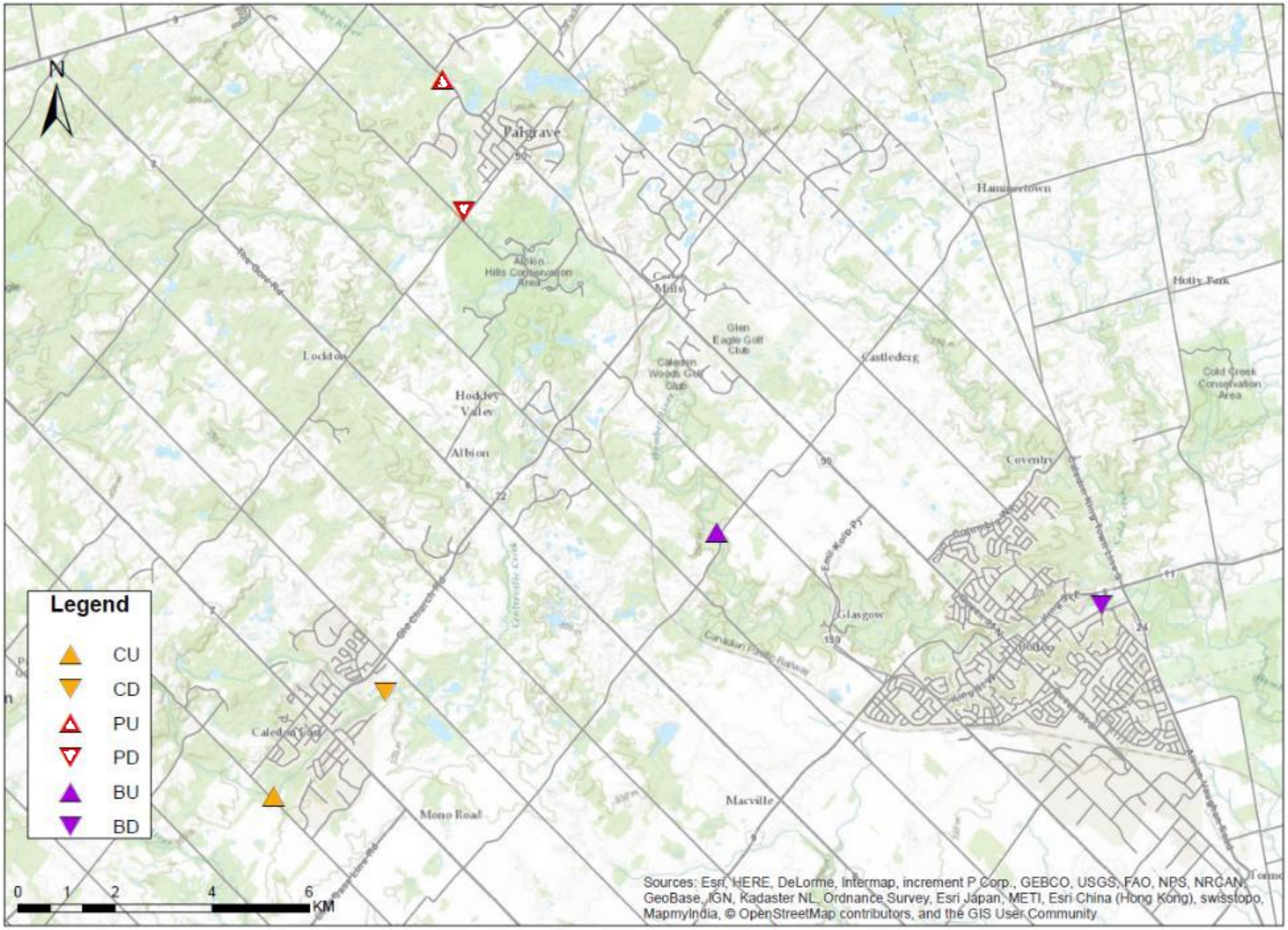

Figure 3.1: Location of study sites at Bolton, Caledon East, and Palgrave

Table 3.1: Basic site information

	Caledon East		Palgrave		Bolton	
	CU	CD	PU	PD	BU	BD
Easting (17T)	0590333	0592002	0592671	0593096	0596891	0602641
Northing	4856932	4858496	4867625	4865631	486094	4859955
Drainage area (km^2)	4.93	11.90	76.59	80.73	178.89	202.75
Drainage density (km/km^2)	1.52	0.93	0.44	0.48	0.30	0.37
Channel width (m)	3.25	2.44	10.00	13.30	13.50	10.00
Reach length (m)	16.25	12.20	50.00	66.50	67.50	50.00
Elevation (m a.s.l.)	291	281	280	253	238	225
Slope	0.010	0.003	0.004	0.016	0.014	0.005
Bed D_{50} (mm), grain size	0.74 coarse sand	0.89 coarse sand	1.20 very coarse sand	21.00 coarse gravel	5.90 fine gravel	3.40 very fine gravel

Each of the suburban communities in the study locations are unique in age and character. Palgrave is the smallest by population and oldest of the developments, comprised mainly of older single family, detached homes. It is situated in the northwest corner of Caledon in the upper Main Humber secondary subwatershed (Toronto and Region Conservation Authority, 2008$_a$). The 2016 census profile for the population centre indicates that 1 044 people were residing in 396 private dwellings (Statistics Canada, 2017$_d$). Spatially, it covers 1.86 km^2, slightly smaller than but comparable to Caledon East and much smaller than the larger city of Bolton (Statistics Canada, 2017$_{a;}$ Statistics Canada, 2017$_{c;}$ Statistics Canada, 2017$_d$). At the time of the study, Palgrave had a population density of 561.3 people/km^2 (Statistics Canada, 2017$_d$). Figure 3.2 shows the location of the Palgrave paired sites.

Caledon East, also classified as a population centre in the Canadian Census, had a population of 4 282 in 2016, nearly double its 2011 population of 2 214. It lies in the Centreville Creek secondary subwatershed of the Main Humber subwatershed (Toronto and Region Conservation Authority, 2008$_a$). The suburban community covers 6.29 km^2 and has a population density of 680.9 people/km^2 (Statistics Canada, 2017$_c$). The area, which would commonly be recognized as and referred to as a suburb, is comprised mainly of newer, single-family dwellings that have been built within the past five to ten years. Some older single-detached homes on larger lots exist. The location of the Caledon East sites are shown in Figure 3.3.

Finally, Bolton is the largest and most populous of the locations. While it only spans an area of 20.72 km^2 (Statistics Canada, 2017_a), covering approximately 3% of the entire Town of Caledon, it is home to nearly 40% of its residents, with 26 378 people calling Bolton home in 2016 (Statistics Canada, 2017_a; Statistics Canada, 2017_b). Its residential dwellings are mixed, with many newer subdivisions having popped up within the past five years or just reaching completion, as well as several older homes similar to those seen in Palgrave. Its population density of 1 273.0 people/km^2 is approximately double that of the other locations of study (Statistics Canada, 2017_a; Statistics Canada, 2017_c; Statistics Canada, 2017_d). This is also reflected in the density of impervious suburban development within the location. Figure 3.4 maps the upstream and downstream sites at the Bolton location. The sites were situated within the Palgrave to Bolton secondary subwatershed of the Main Humber (Toronto and Region Conservation Authority, 2008_a).

For Palgrave, the channel studied that ran through the residential area originated just upstream of the Palgrave Conservation Area, northwest of the main town, which is where the upstream site was located. After the channel crossed through the development, the downstream site was situated in the Albion Hills Conservation Area south-southwest of the core of Palgrave. The stream ran approximately north to south. For Caledon East, the upstream site was located off Mountainview Road and just southwest of Walker Road West, southwest of the suburb, with primarily rural surroundings in its catchment area. The downstream site was adjacent to the Caledon East Soccer Complex (~15 m away) on the eastern edge of the development. There,

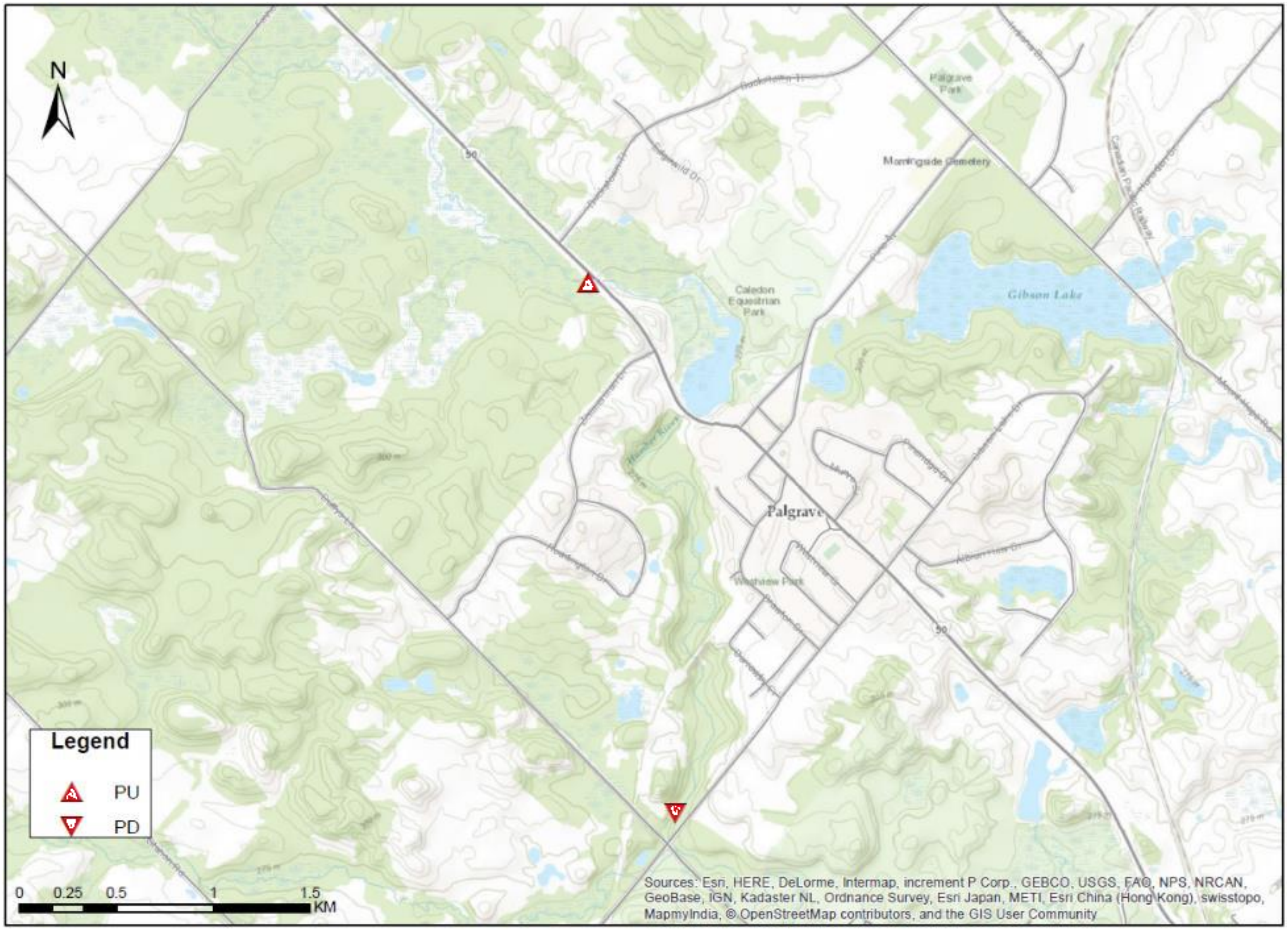

Figure 3.2: Location of Palgrave sites

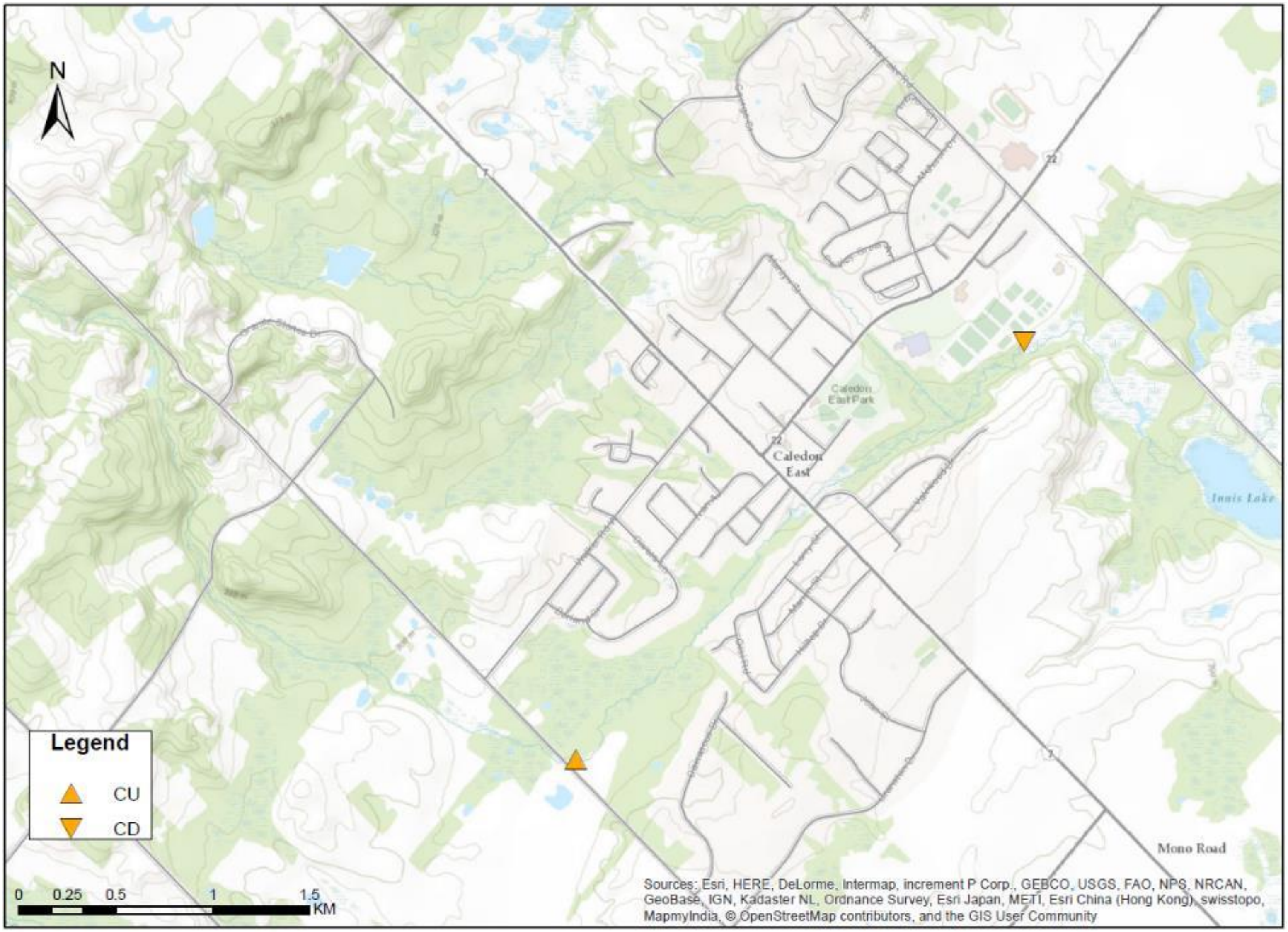

Figure 3.3: Location of Caledon East sites

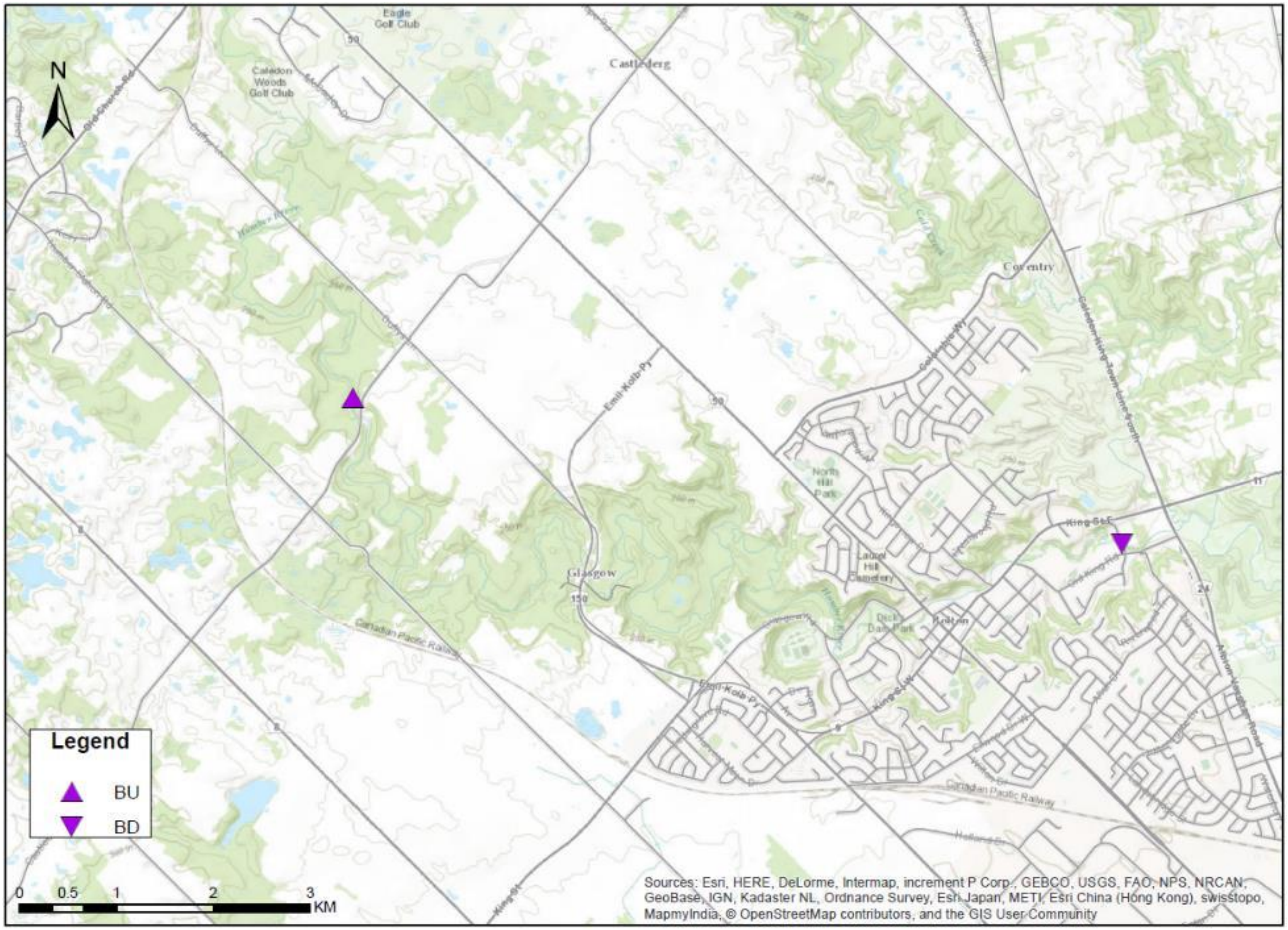

Figure 3.4: Location of Bolton sites

Centreville Creek ran approximately southwest to northeast. Finally, the Bolton upstream site was located approximately 100 m north of Castlederg Side Road between Duffy's Lane on the northeast and Humber Station Road on the southwest. After the channel crossed through a portion of the development, the downstream site was located just west of Sneath Road. Both sites were just off sections of the Humber Valley Heritage Trail, enabling easy access. The stream ran approximately west-northwest to east-southeast.

3.3 Primary site survey

As a precursor to the study, basic characteristics of each site were assessed. These characteristics provide a primary understanding of the geographic location of the sites and allow for spatial differentiation between them. A Garmin handheld GPS unit was used to record precise locations of the sites, specifically, the start and end points of the reaches. Elevation above sea level was noted at the upstream and downstream ends of the reaches. These can be seen in Table 3.1.

A two-part topographic survey of the channel reaches was conducted using a total station. An image of this can be seen in Figure 3.5. Firstly, using the survey equipment, a cross-sectional profile was created for each of the six sites. These cross-sections were located at the downstream end of the reaches. Latitude, longitude, and elevation was collected starting from approximately 1 m from the edge of the streambank, then down the banks, through the channel, up the opposite bank, and to approximately 1 m from the edge of the opposite bank. Since there is vagueness in the definition of where a streambank begins and a stream ends (Curran and Hession, 2013), the level of detail of these cross-sectional surveys was of the utmost importance to provide a detailed image of cross-sectional shape. As such, measurements were taken approximately every

Figure 3.5: Total survey station and equipment

centimetre. The survey took place at the beginning of the study period, in late May 2016. For practicality, the cross-sectional dimensions and shape were applied for the duration of the study and used in the estimations of discharge for the whole water level dataset. Visuals for the cross-sectional surveys can be found in Figures 3.6 through 3.11.

For the second part of the topographic survey, a survey was conducted of the channel beds from the cross-sections and extending to the upstream end of the reaches. Three points, one in the approximate centre of the channel and then two off to the left and right, respectively, were collected with the total station for bed height at the downstream location where the detailed cross-section was surveyed, then repeated every 1 m upstream to cover the whole reach. The three elevations were averaged, thus, giving a more accurate idea of bed height for each 1 m interval. A linear regression was performed on these averages, the slope of which indicates the slope of the channel bed, and thus, can be used to infer the slope of the water surface. The results of these regressions and resultant bed slopes can be seen in Table 3.1 and graphical displays of the longitudinal profiles in Figures 3.12 through 3.17.

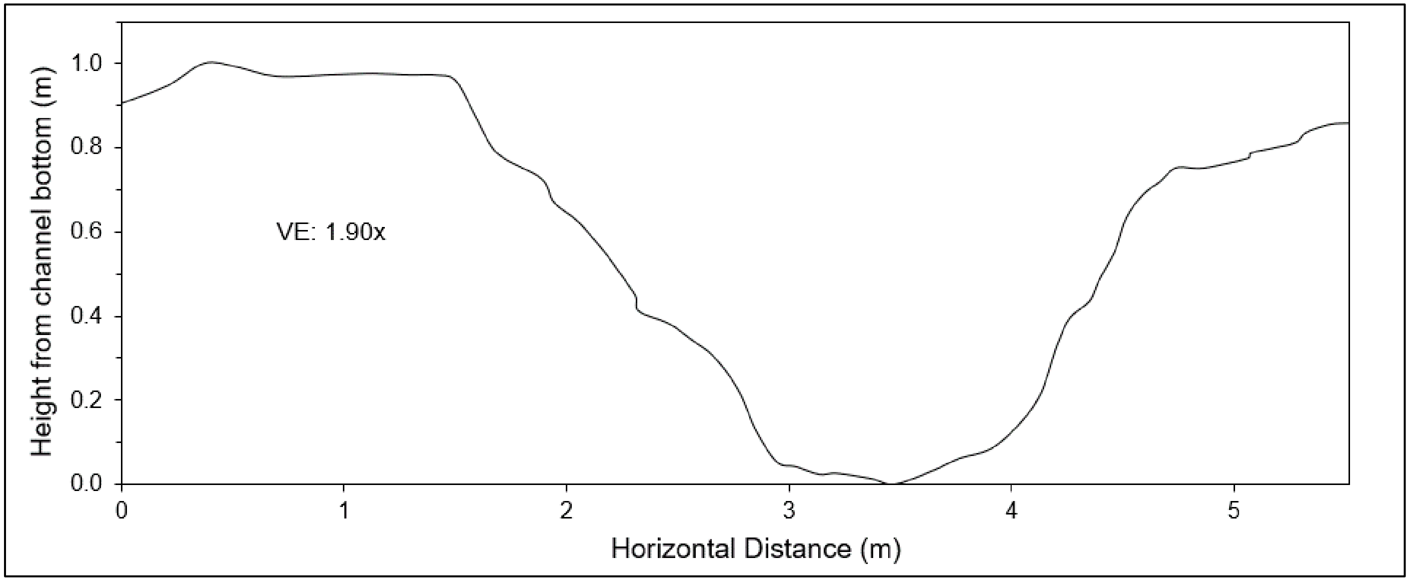

Figure 3.6: Cross-sectional profile, Caledon East upstream site

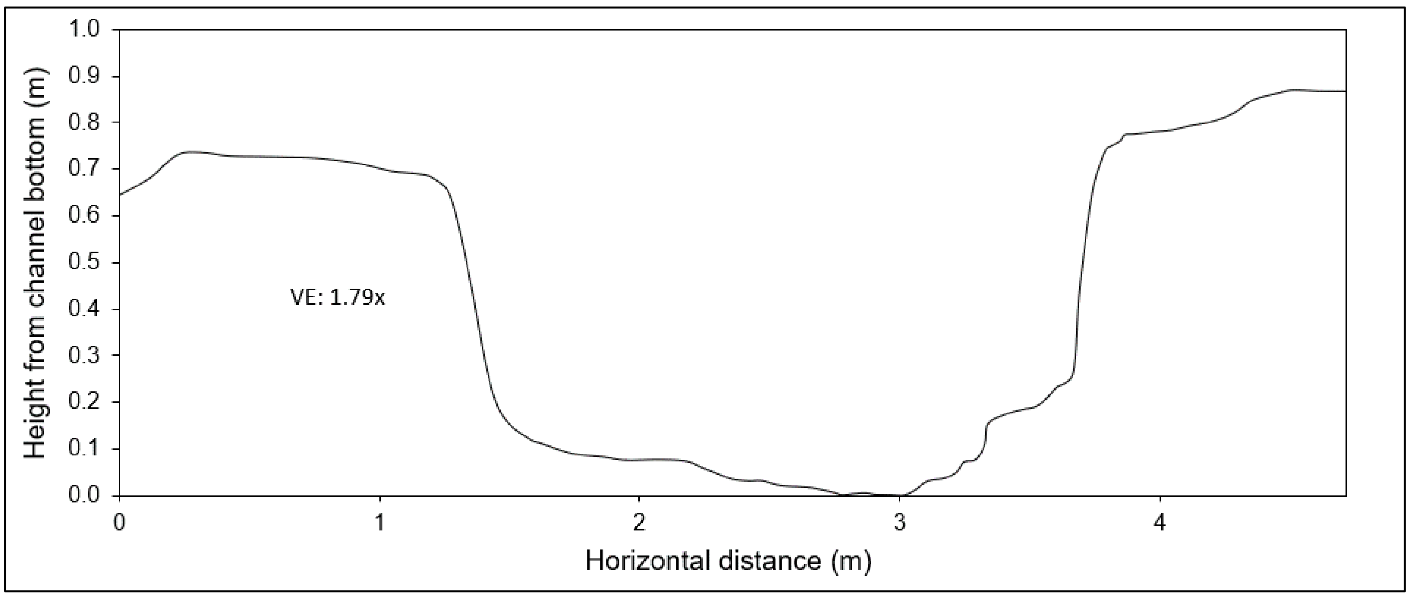

Figure 3.7: Cross-sectional profile, Caledon East downstream site

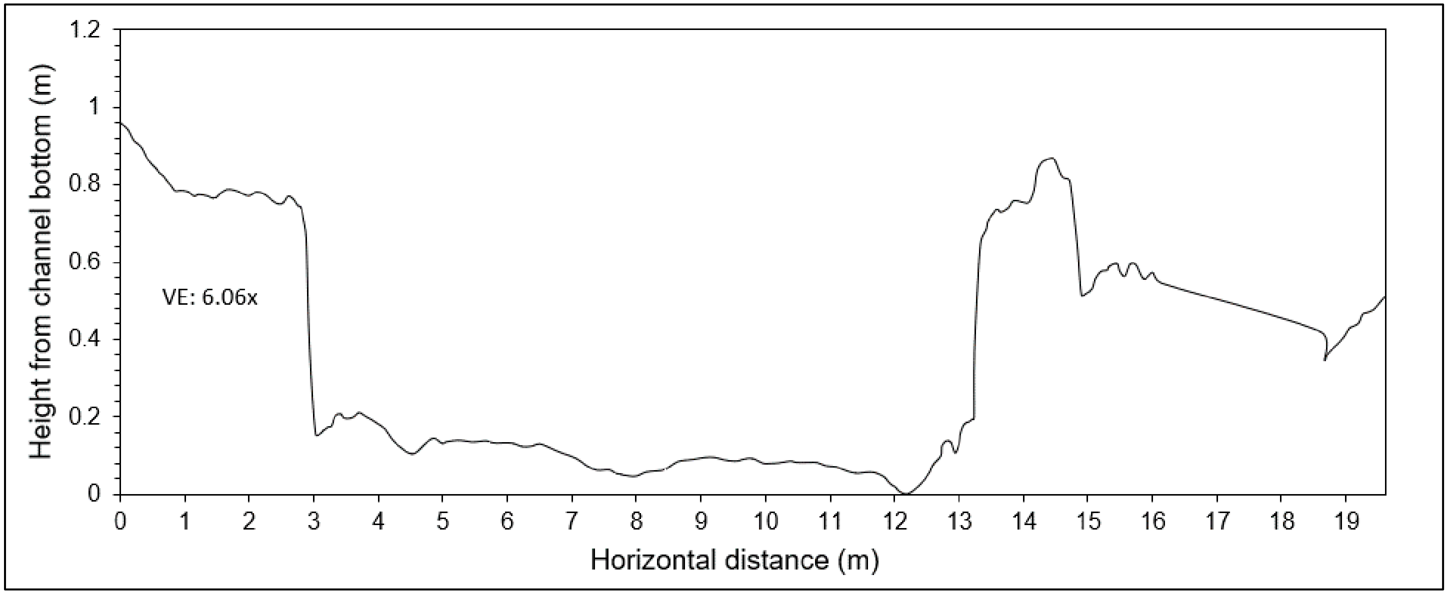

Figure 3.9: Cross-sectional profile, Palgrave upstream site

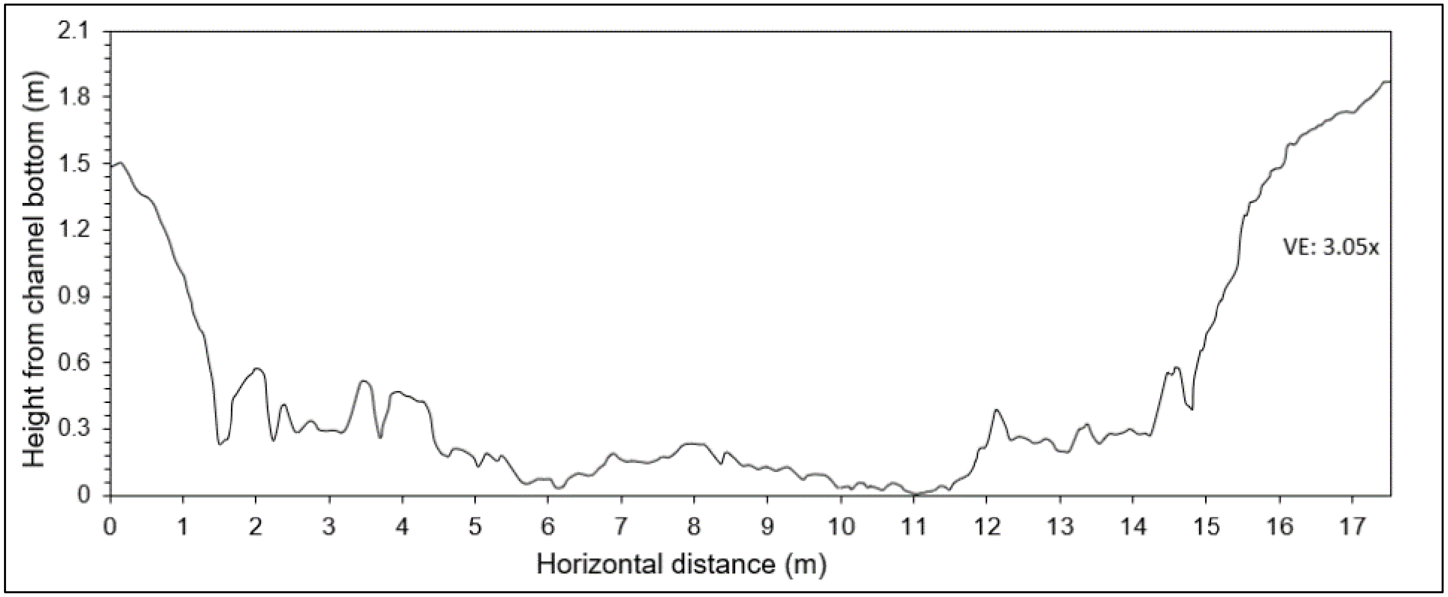

Figure 3.8: Cross-sectional profile, Palgrave downstream site

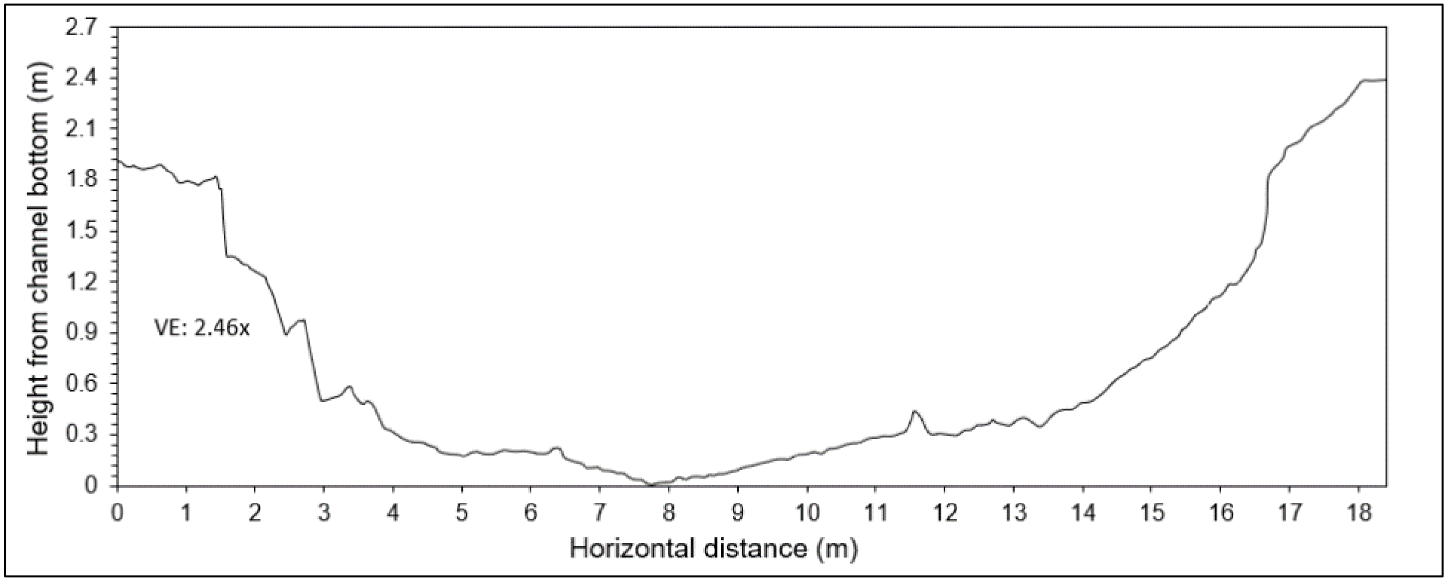

Figure 3.11: Cross-sectional profile, Bolton upstream site

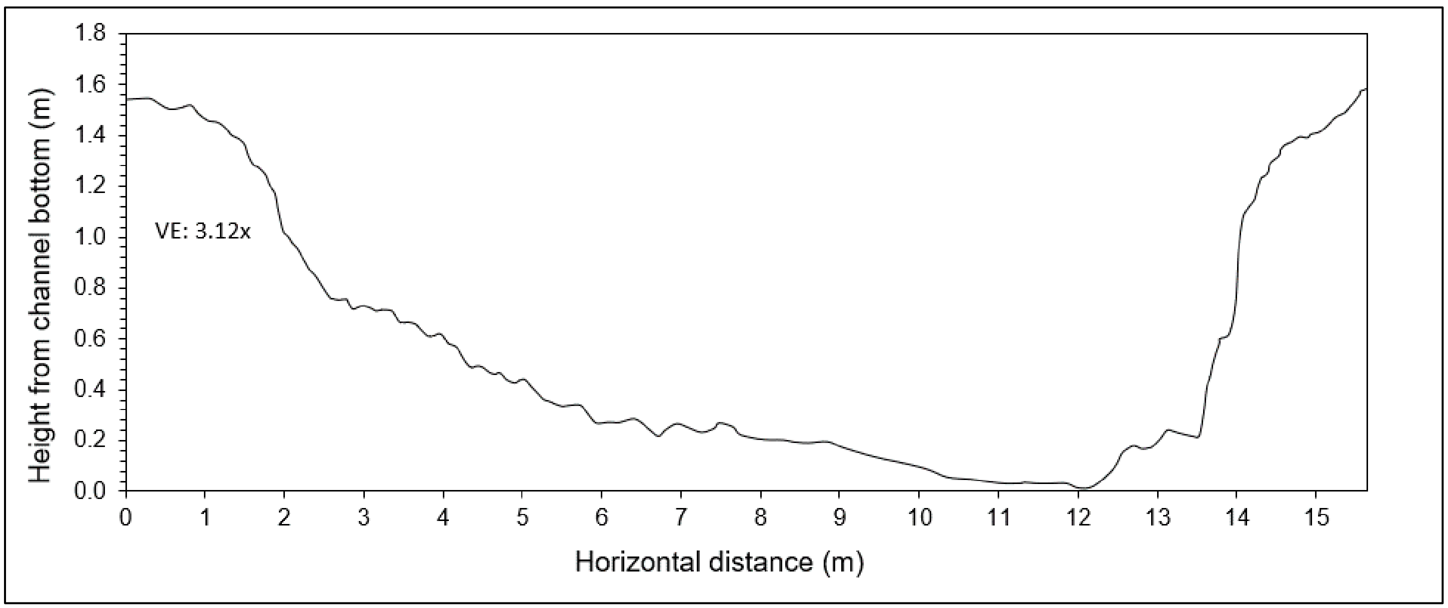

Figure 3.10: Cross-sectional profile, Bolton downstream site

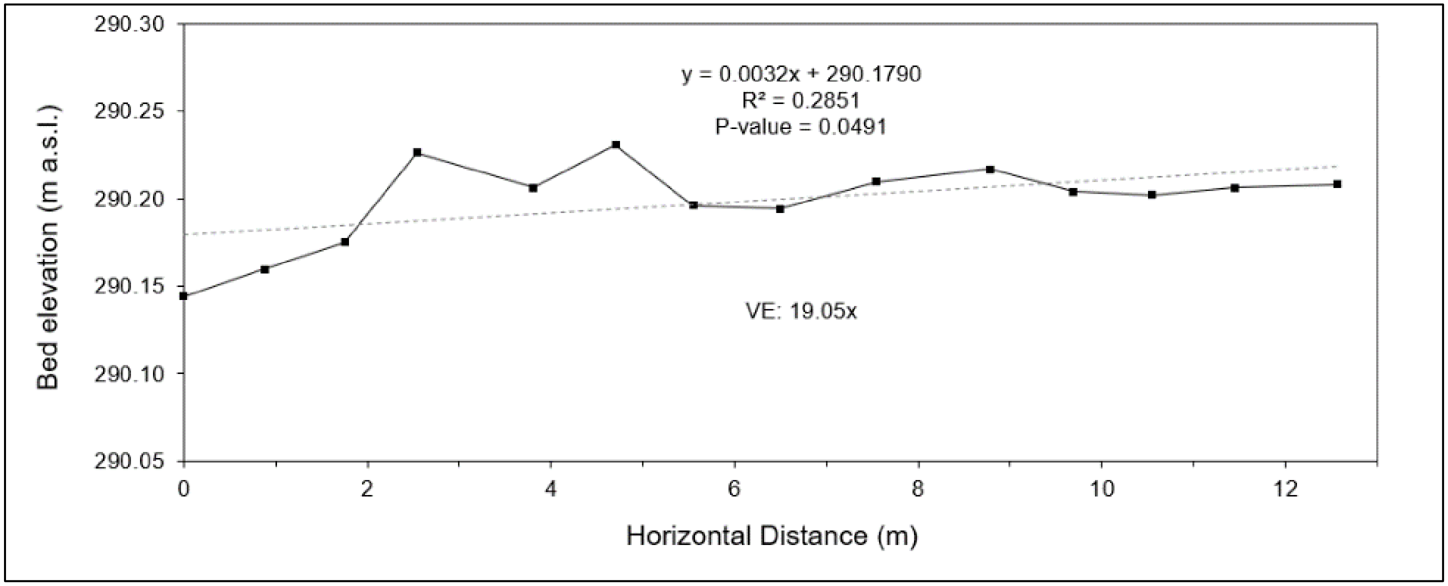

Figure 3.13: Longitudinal profile, Caledon East upstream site

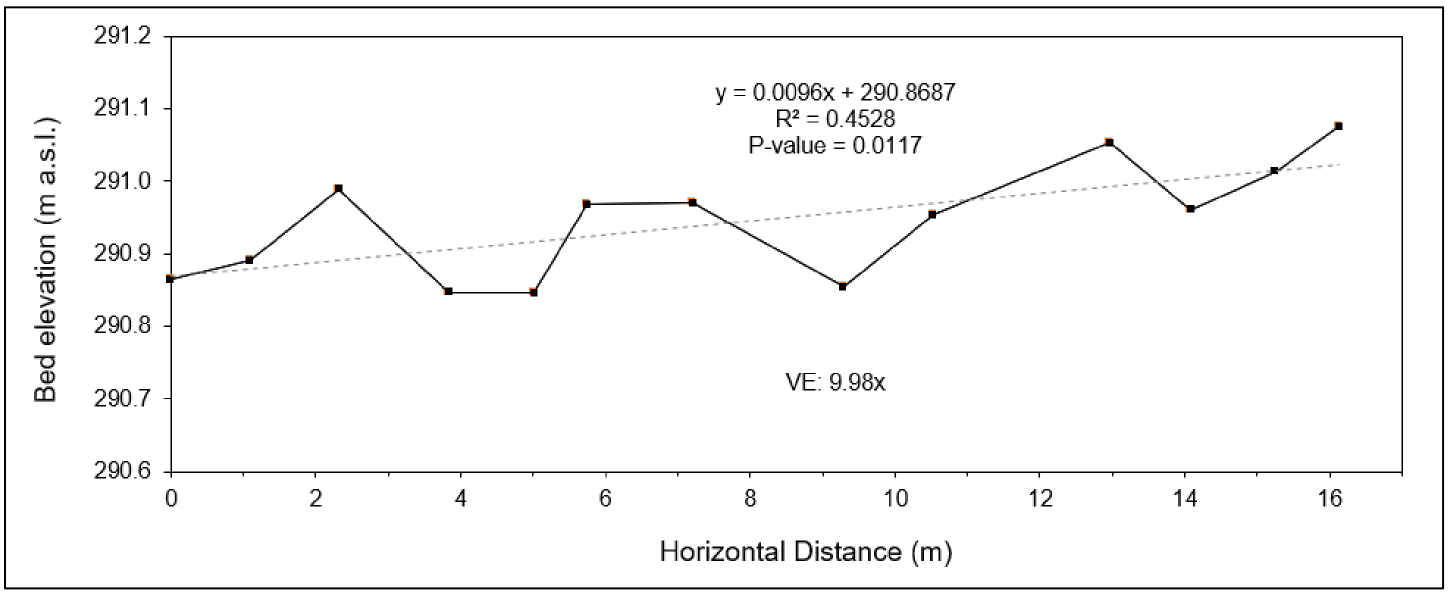

Figure 3.12: Longitudinal profile, Caledon East downstream site

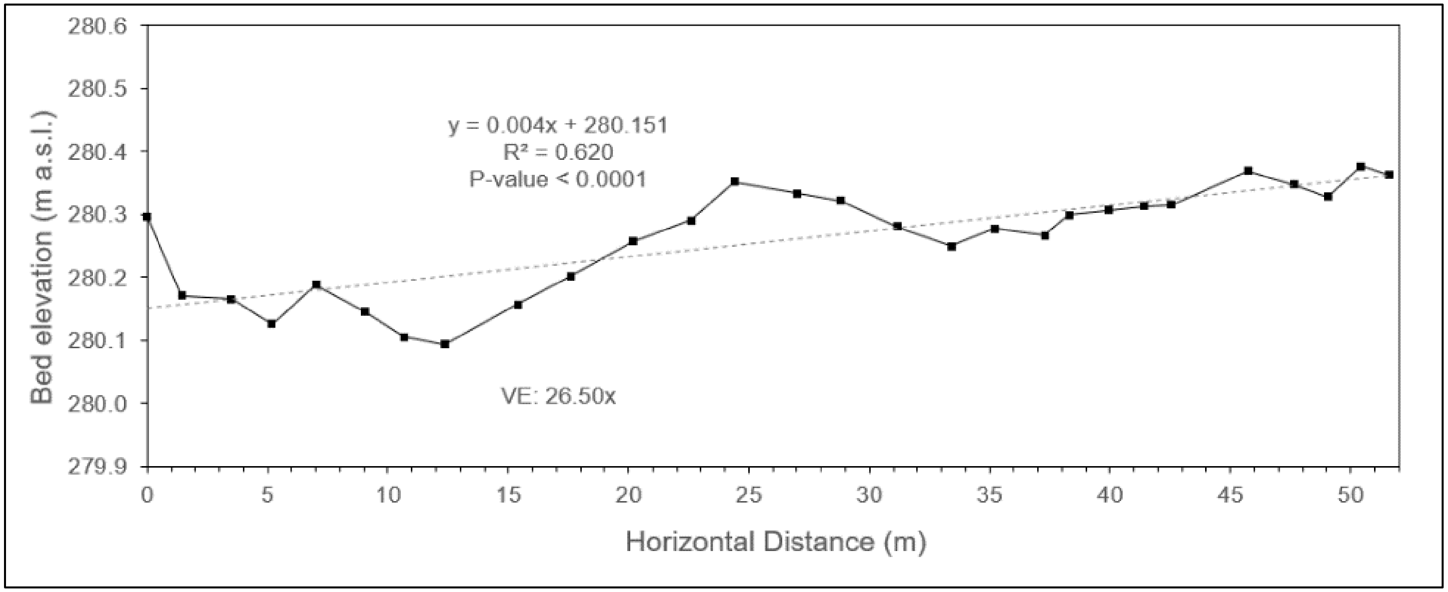

Figure 3.15: Longitudinal profile, Palgrave upstream site

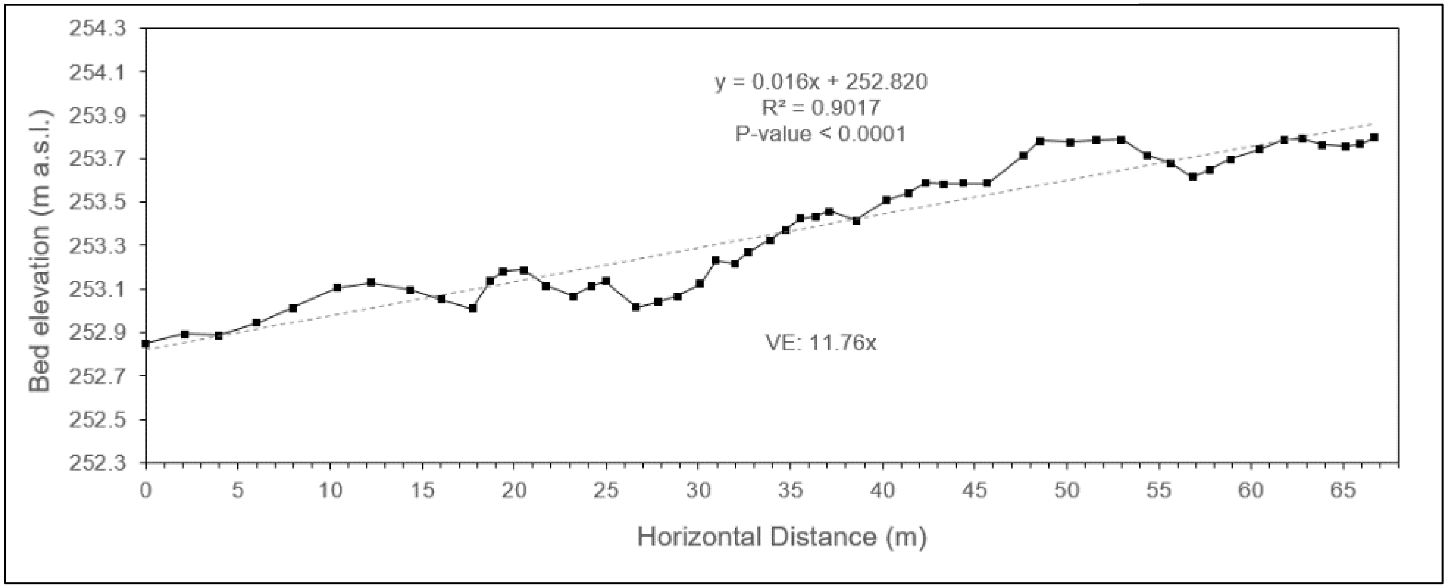

Figure 3.14: Longitudinal profile, Palgrave downstream site

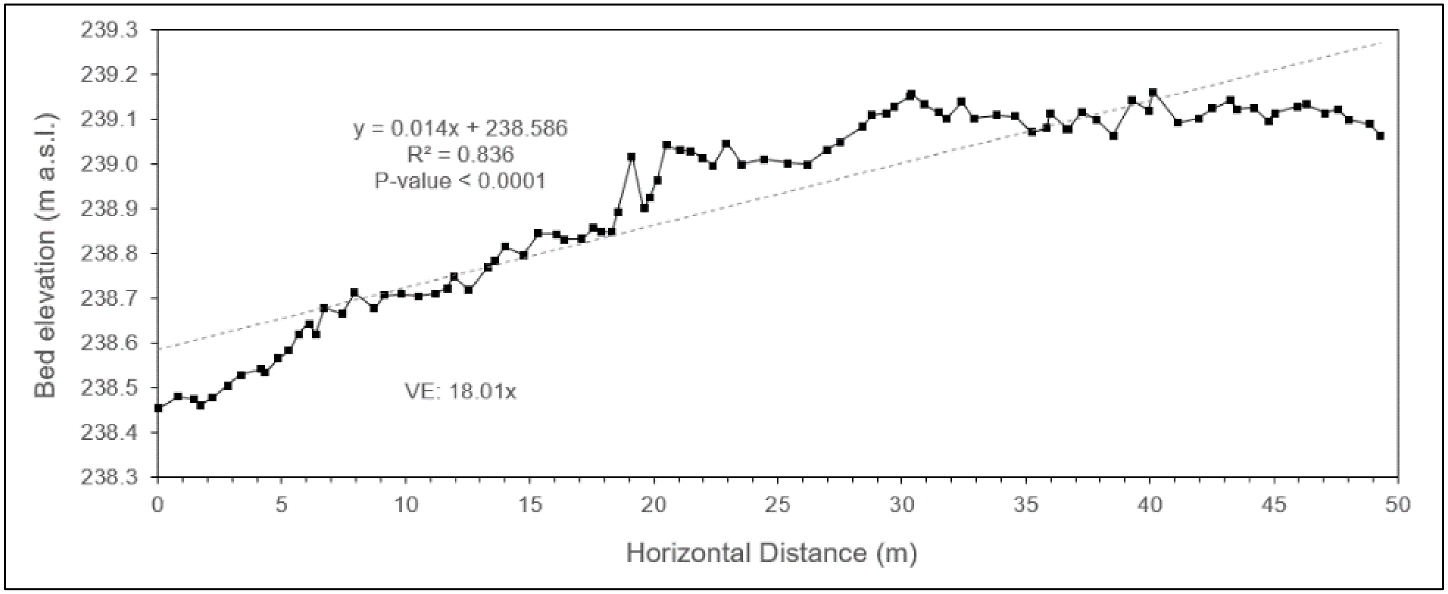

Figure 3.17: Longitudinal profile, Bolton upstream site

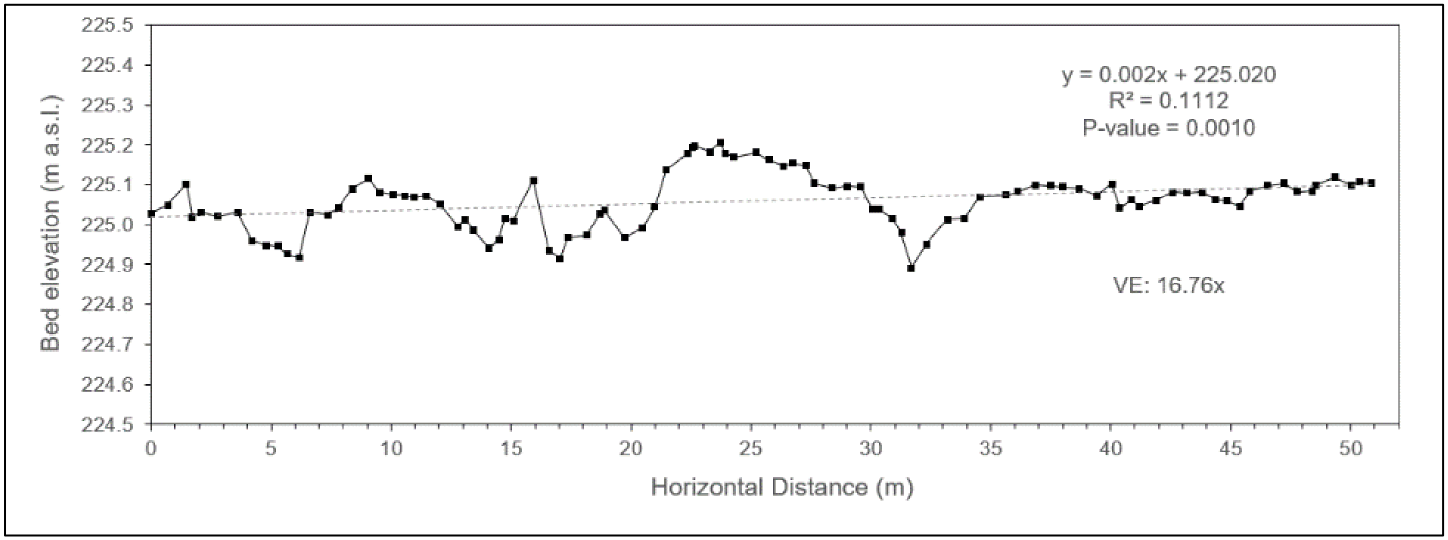

Figure 3.16: Longitudinal profile, Bolton downstream site

3.4 Land cover assessment and development quantification

To link changes between upstream and downstream sites and to exurban land use, the study generated an approximation for the proportion of impervious surface cover in the sites' subwatersheds. This was done through a land cover assessment using delineation of various land cover types with consequences for surface permeability. While the TRCA (2007) determined that 27% of Humber watershed is urbanized and that this will increase to 36% in coming decades, the spatial scale of this research demanded that the surface cover of the areas draining into the six reaches of study be more accurately determined. In this way, a better resolution of potential imperviousness data and more accurate illustration of catchment land use could be linked to varying degrees of impact. This was performed using Geographic Information Systems (GIS) and remote sensing technology. A preliminary watershed analysis was performed using the Ontario Flow Assessment Tool (OFAT III) from the Ministry of Natural Resources and Forestry. One of the functions of the GIS tool is to create a specific watershed, where digital elevation models and spatial hydrologic data are employed to allow for the precise delineation of drainage area for a given point along a stream channel.

Following this, remote sensing technology was employed to conduct a land cover classification for use in the broader analysis of catchment land use. The United States Geological Survey (USGS) online Earthexplorer tool was used to gather Landsat images for use in the land cover classification. The images with 30 m spatial resolution with atmospheric correction applied were gathered for the greatest level of accuracy for the classification. In addition, the images were taken from April 2016, a month before the fieldwork commenced for this research to ensure that the classification was performed on the most recent land cover conditions possible, so as to not exclude recent developments and alterations to land use. PCI Geomatica software was used to conduct an ISODATA classification, an unsupervised classification that groups pixels in the satellite imagery into clusters based on their spectral reflectance, then the groups were manually aggregated into the following land cover classes: water, forest, developed, field, and marsh. These five categories were selected to provide a differentiation between developed and non-developed land and as a way to ensure a simple and accurate land cover assessment given the spatial resolution of the satellite imagery and to assemble pixels into groups with distinct hydrologic significance. Differentiation between the developed area and broad categories of undisturbed land (water, forest, field, marsh or wet ground) allows for comparison between natural surface cover and those altered to become impermeable or less permeable. While it may seem intuitive that more specific classification into further subdivided groups would allow for better specificity in land cover analysis, broader classification allows for better accuracy during the completion of the land cover assessment, where pixel differentiation into more numerous and specific classes leaves more room for potential error. For instance, while farmed fields and fallow fields have different impacts on regional hydrology, they are very difficult to differentiate between with regards to their spectral reflectance in satellite imagery, and as such, grouping them under a general category with an assemblage of land cover of similar hydrologic signatures is most effective. Though an accurate differentiation between them would allow for more precise analysis of catchment hydrology, this distinction would introduce significant error into the land cover classification itself. As such, though more general, the broader groupings selected for this classification have similar hydrologic significance and produce a more accurate representation of actual land cover in the study areas.

Those surfaces classified as impermeable as a result of anthropogenic use and development regularly include stormwater management infrastructure. This includes storm sewers, those that collect overland water from precipitation, snowmelt, and anthropogenic inputs and transport them directly into the natural hydrologic system. This efficient, channelized input of precipitation further exacerbates the flashiness of the urban hydrograph, which is discussed in the coming section. This project did not seek to quantify the proportion of precipitation inputs channelized by the stormwater systems in place at each of the developments, but rather, takes into consideration their presence in those areas that are developed. The land use classification and quantification of impermeable surfaces is also understood to include systems which deliberately increase the efficiency of stormwater transport.

3.5 Streamflow

The urban stream syndrome describes that urbanized catchments produce consistent changes in the lag time to peak flows and flashiness of the hydrograph and in the magnitude of high flows in the rivers they drain (Walsh et al., 2005_a). Hydrologic data were acquired to determine whether such consistent changes are also observed at the scale and intensity of developments seen in the Town of Caledon. This was done through continuous monitoring of the water level at each of the six sites over a six-month span. HOBO water level dataloggers were used to remotely record water level using temperature and pressure at seven-minute intervals. The instruments were secured to the channel beds at the downstream end of the study reaches where the cross-sectional surveys were conducted. A single datalogger was installed open-air to record pressure as well for the duration of the study. This dataset acted as a control, where the instantaneous atmospheric pressure values were subtracted from the pressure values in the other six water level datasets, leaving the remaining pressure values to represent water pressure so that the water temperature and water pressure could be used to derive precise water level values using HOBO software. This method for deriving water level was chosen because of its accuracy over alternatives such as the float method (Tsubaki et al., 2011) and is less destructive and intrusive than the installation of structures for long-term monitoring such as weirs (Annable, 1996).

While peak discharge is of great importance and often given most attention in studies related to symptoms of urban stream syndrome, analysis of the entire hydrograph gives a more comprehensive understanding of stream response to land-use change (Booth, 1990). Streamflow was monitored continuously over the course of six months at each of the selected sites to allow for clear illustration of alterations in the hydrograph downstream of developments, including that of the rising and falling limbs, which better illustrate the input rate of precipitation during an event and the impacts of amplified impermeability. Additionally, previous studies have noted inconsistent changes in the magnitude of baseflows, where various studies have shown the usual low flow conditions (i.e., not stormflows following a precipitation input) to increase or decrease (Konrad and Booth, 2002; Nilsson et al., 2003; Roy et al., 2005) from predevelopment rates. Since inconsistent changes have been found previously and to improve the focus of the project, variations in baseflow were not given considerable attention in analysis.

Manning's equation was employed to incorporate estimates of velocity to generate instantaneous discharge estimates from measured water level. Manning's n is widely used and accepted in fluvial studies as an empirically sound law for flow in rough, stable, and uniform channels (Finnegan et al., 2005). It is consistent with the fact that velocity tends to increase with greater water depth, and hence, discharge follows this pattern. The equation is as follows (Robert, 2003):

$$n = \frac{\left(d^{\frac{2}{3}} \cdot S^{\frac{1}{2}}\right)}{U} \qquad (1)$$

where U is velocity (m/s), n is the Manning's factor representing channel roughness and accounting for friction on the flow d, is the depth of water (m), and S is the slope of the water surface (dimensionless). The velocity estimates determined in Eq. 1 were then used for the final estimation of discharge, Q (m^3/s), using the following equation (Robert, 2003):

$$Q = U \cdot A \qquad (2)$$

where A is the cross-sectional area of flow (m^2). This was computed using the cross-sectional survey completed for each reach and the seven-minute interval water level dataset. As such, each seven-minute reading produced an area of flow value. The statistical package R was employed to compute A, where the "AUC" package was used to calculate the area under a curve. Here, the cross-sectional survey served as the curve function and the inverse of the function coupled with the maximum water depth, recorded from the datalogger, was used to determine the extent of the area of water flow. A visualization of this is shown in Figure 3.18.

While Manning's n is commonly estimated using descriptions or images of a range of rivers in various situations and conditions with their associated *n* value (e.g., Dingman, 2002), there are a myriad of methods that can be used to obtain *n* for a given channel reach (see Wohl, 2000). For the sake of accuracy and level of detail, *n* was determined by employing the following equation using a base value and correction factors that increase *n* based on elements of channel friction from Arcement & Schneider, 1989:

$$n = (n_b + n_1 + n_2 + n_3 + n_4) \cdot m \qquad (3)$$

were n_b is the base value for a straight, uniform, and smooth channel in natural bed and bank material, n_1 is a correction factor accounting for bank irregularities, n_2 is a correction factor

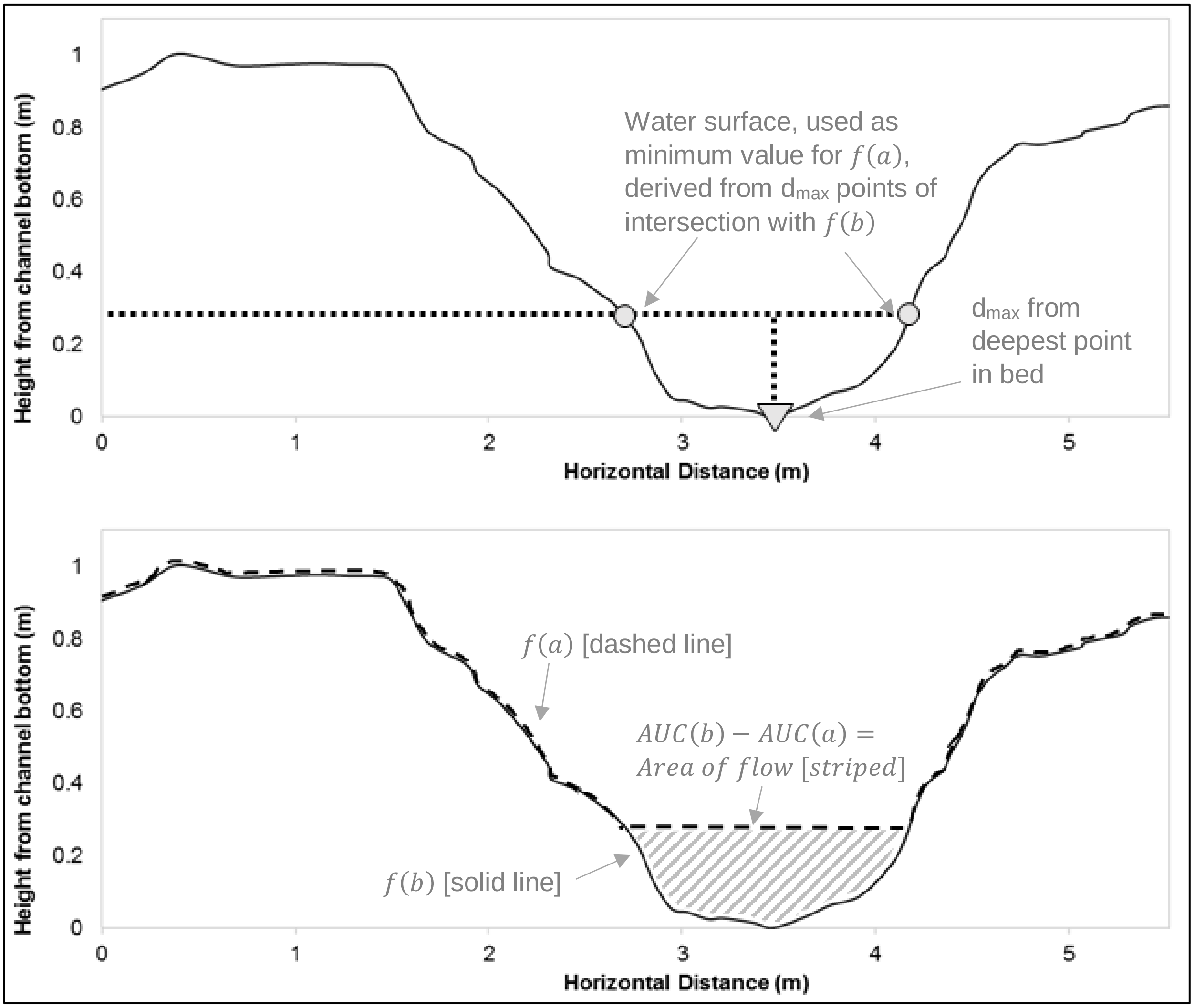

Figure 3.18: Illustration of method used to derive area of flow using cross-sectional survey, dmax, and area under a curve (AUC) function in R

accounting for cross-sectional variations, n_3 is a correction factor accounting for flow obstruction, n_4 is a correction factor accounting for in-channel vegetation, and *m* a correction factor accounting for section meandering. The selected base values, correction factors, and final *n* values for each site can be found in Table 3.2.

Table 3.2: Manning's n for study (using Arcement & Schneider, 1989)

	Caledon East		Palgrave		Bolton	
	CU	CD	PU	PD	BU	BD
n_b	0.03	0.03	0.03	0.03	0.03	0.03
n_1	0.01	0.01	0.01	0.02	0.01	0.02
n_2	-	-	-	-	-	-
n_3	0.01	-	-	0.04	0.01	-
n_4	-	-	-	-	-	-
m	0.01	-	-	-	-	-
n	*0.05*	*0.03*	*0.04*	*0.06*	*0.05*	*0.04*

Due to practical constraints, the Manning equation was chosen in lieu of attempting to determine the stage-discharge relationship for the reaches through velocity measurements. While the method is often employed for research of this nature (Braca, 2008), due to the comparatively short duration of the field season, where site visits and in situ data collection took place regularly for only approximately four months simultaneously across the six locations, velocity measurements taken during that time period would not necessarily represent a broad enough range of flow conditions. Additionally, this method was impractical, as the field work was undertaken chiefly by a single individual, and given the distance between sites and the time taken to accurately and thoroughly record velocity at each, recording velocity at all six sites during peak flow events, recording during the rising limb, peak, and recession limbs of the hydrograph, would not be achievable.

Graphical comparisons are often drawn between streamflow hydrographs taken at different times or locations, where urbanization is widely attributed to hydrograph alteration, including increased flashiness, more frequent large flow events, and steeper rising limbs (Walsh et al., 2005a). Visual comparison allows for broad inferences to be made about hydrologic response and further the processes that underpin those responses. However, visual assessment as the sole means of comparison between hydrographs is restrictive in the level of detail that can be ascertained about variations between hydrographs. In this study, hydrographs from upstream and downstream paired sites were examined visually for variations in shape to denote broad differences between streamflow responses at sites. In addition, statistical analyses were performed to understand in greater detail the variations in streamflow at the up and downstream sites for the three locations. Descriptive statistics, such as mean, maximum, minimum, standard deviation, and variance, were derived for each of the flow parameters for the entire six-month timeseries dataset.

Each of the flow components (water depth, area of flow, and discharge) were statistically analyzed. Water depth was measured, area of flow was derived from measurements, and discharge was estimated from a combination of measurements and empirical relationships. Statistical tests were performed on all flow components (measured, derived, and estimated) to compare results at single sites for a given test. This was done to eliminate the potential of error stemming from analysing discharge estimates alone and to bolster confidence in results. An F-test for sample variance was calculated for the flow components, comparing variance between the upstream and downstream paired datasets.

High temporal data resolution, with water level and consequent flow estimates at seven-minute intervals and rainfall at five-minute intervals, allowed for more detailed analysis of streamflow response to individual precipitation events. Analyzing hydrographs at the single precipitation event scale is appropriate in small catchments such as those studied in this research, as the lag time between rainfall input to stream response is small and the two can be easily correlated, unlike in large continental catchments where streamflow response may only be noted weeks later (Ward and Robinson, 2000). Since minor rainfall events, those of only a few millimetres, are likely to cause minimal impact on hydraulic stress, even in highly urbanized catchments (Walsh et al., 2005[a]), a minimum intensity precipitation event was chosen to delineate significant rainfall for the sake of individual storm hydrograph analysis. Storm events with at least 10 mm input over a twelve-hour period were selected for analysis. Storm hydrographs were isolated from the full six-month timeseries with their initial response, when consistent increase in discharge was observed in instantaneous discharge values (Linsley et al., 1975), acting as the beginning of the storm hydrograph. Since hydromodification resulting from urbanization can be seen in both larger flow events with higher hydrograph peaks and in flashier hydrographs with faster ascending rising limbs and quicker time from initiation to peak, it was hypothesized that both of these indicators would be observed in the storm hydrographs at the downstream sites. Faster rising limb ascension is associated with the time to peak, which is defined as the time taken from the beginning of the rising limb, or where flow begins a steadily ascent, to the peak of discharge, or the greatest flow recorded on the hydrograph. The time to peak is largely determined by drainage basin characteristics. Since the sites are close together in similar contexts and on similar geologic underpinnings, developed land cover can contribute to differences seen between time to peak at upstream and downstream paired sites. The rising limb of the hydrograph, the ascending portion representing increasing discharge via precipitation, ablation, or engineered water input, also depends largely on storm and basin characteristics. In this way, it is largely influenced by urbanization. The presence of greater impervious surface cover in a catchment area could contribute to steeper hydrograph rising limb slopes at the downstream sites.

To quantify differences between the up and downstream paired storm hydrographs in an attempt to illustrate possible effects of hydromodification, three metrics were used, expressed in Eq.4 through 6. Firstly, the percent increase from initial flow response to peak was computed. This test quantified the flow increase from baseflow, the last discharge estimate value before the flow steadily increased in response to precipitation, to the peak value and expressed the difference as a percent of baseflow using the following equation:

$$i_{PPT} = \frac{\Delta Q}{Q_b} = \frac{Q_p - Q_b}{Q_b} \tag{4}$$

where i_{PPT} is the increase (percentage) in response to precipitation, Q_p is peak discharge (m^3/s), and Q_b is baseflow discharge (m^3/s). In this way, upstream sites could be compared with their downstream paired sites, those which inherently have higher discharge simply because they have more catchment area providing them water supply. While comparing the quantified increase in baseflow to peak would be biased by the greater catchment area and consequently greater supply for flow during precipitation, using a percentage of increase illustrates the proportional increase and degree of response to precipitation input while eliminating the bias of greater flows due to basin size of the downstream sites.

Secondly, the rate of increase in the hydrograph rising limb was computed. Here, the extent of increase was expressed as a rate using the following:

$$i_{RLR} = \frac{\Delta Q}{t_{Pd}} = \frac{Q_p - Q_b}{t_{Pe} - t_{Ps}} \tag{5}$$

where i_{RLR} is the rate of increase in discharge $\left(\frac{m^3}{s}/h\right)$ and t_{Pd} (hours) is the temporal duration of the precipitation event, derived from the difference between the time the precipitation event ended, t_{Pe}, and the time the precipitation event started, t_{Ps}. Again, greater discharge estimates overall do not bias the results of the test in favour of downstream sites. Rather, the rate of increase illustrates the rapidity of response, a metric commonly observed to be greater at sites with greater proportion of impervious catchment surface cover.

Thirdly, the runoff coefficient was calculated for each site using Eq.6. The equation, rearranged from Dingman (2002), was as follows:

$$C_R = \frac{Q_p}{(u_R \cdot i_{eff} \cdot A)} \tag{6}$$

where C_R is the runoff coefficient (dimensionless), u_R is a unit conversion factor (0.278 when using metric measurements), i_{eff} is rainfall intensity (mm/hour), and A is the drainage area (km^2). Rainfall intensity is estimated simply as the quotient of the amount of precipitation recorded (mm) over the duration of time where rain was recorded (hour). Based on a five to ten-year storm, ranges for characteristic runoff coefficient values can be deduced for land uses typical in suburban and town contexts like those present in the areas of study for this research, including 0.70–0.95 for paved surfaces, and 0.05–0.35 for residential lawns (McCuen, 1989).

The coefficient is a component of a rational technique to model surface runoff from rainfall, using the proportional relationship between intensity of a rainfall event and peak streamflow (Dingman, 2002). The coefficient, ranging from zero to one, is commonly used in small and largely urbanized catchments as a way of illustrating the proportion of rainfall that enters the river system as overland runoff, where numbers closer to one represent a greater proportion of precipitation becoming surface runoff and numbers closer to zero represent a greater proportion absorbed (Dingman, 2002). Similar to the previous two metrics, the runoff coefficient incorporates basin area and uses equal rainfall intensity for each site for a given event. As such, observed differences in the resulting runoff coefficient could be a product of the impact of impervious ground cover on the downstream site.

3.6 Meteorological data

Beyond the fundamental measurements and assessments this project examined, additional data were collected to both contextualize and broaden the scope of the results. Weather data were collected, specifically, precipitation at 5-minute resolution. These data were obtained from TRCA meteorological station records at the Caledon East Soccer Complex, located nearby the Caledon downstream site. Table 3.3 shows the distance between each site and the TRCA meteorological gauging station. Such weather data were used in hydrograph analysis, as described in section 3.5. Because data were only available from the one site, comparisons between the time of initial response of corresponding upstream and downstream sites were not made. Rather, comparisons between the rising limbs, magnitude of peaks, and runoff coefficient of their hydrographs were analyzed, which are not significantly impacted by this resolution of meteorological data.

Table 3.3: Site distance from meteorological gauging station

	Caledon East		Palgrave		Bolton	
	CU	CD	PU	PD	BU	BD
Distance from met station (km)	< 0.5	3.5	17.0	13.0	10.0	19.5

3.7 Data quality control

For data quality preservation, the water level data were examined critically to ensure no errors were present in the final datasets or during the analysis phase of this research. The time series data for each parameter were plotted and visually assessed for anomalous periods or any seemingly unnatural changes that may be a result of error as opposed to actual flow variation.

A relatively short period of the Caledon East upstream water level dataset was omitted from data analysis, as well as the resultant flow components. On July 27, 2016, over a period of 180 minutes from 5:01 to 7:21, an irregular pattern of rapid increase and decrease in water level was recorded by the datalogger. Manned fieldwork was not being conducted at this time, so the anomaly cannot be related to the known presence of an individual entering and exiting the channel causing a false alteration to the actual water level. Following this, the water level steadily increased over the span of five days from 0.138 m (d_{max} = 0.225 m) to 0.320 m (d_{max} = 0.571), an approximately 250% increase. From 6:00 on August 1, to 10:07 August 9, the datalogger recorded that water levels remained relatively steady and abnormally high, with average water level of 0.305 m (d_{max} = 0.558 m), much higher than the average water level of 0.156 m (d_{max} = 0.246 m) in the three days before the anomaly began. The time period during which this anomaly occurred does not correspond to any precipitation events and field notes from July 28, 2016 do not note anything out of the ordinary with regards to the flow or equipment.

The most likely explanation for the flow anomaly is debris build up on the water level datalogger. As can be seen in Figure 3.19, the channel at CU is small and considerably vegetated. More than any other site, a great deal of organic debris flows through the cross-section regularly. The build up of organic debris around the datalogger and the post it was secured to on the channel bed could cause the pressure readings to be deceivingly high, unrepresentative of the actual water level. This could be exacerbated if the built up organic material additionally caused an accumulation of bed sediment and organic matter just upstream and potentially overtop the datalogger. At some point during the field season, the datalogger was swept of debris to remove the build up of organic matter and other materials from the device, though the date of this cleaning was not noted.

Figure 3.19: Datalogger emplacement at Caledon East upstream site

It can be said with confidence that this anomalous period in the flow record is not the result of the actual channel flow, but rather, an error caused to the equipment to produce skewed water level values. Analysis of this period in itself is not helpful for the purpose of this project. Its inclusion in analysis performed on the entire dataset results in skewed statistical results, such as a greater mean water level and resultant mean discharge for the site. For these reasons, the values were excluded from data analysis.

A similar period of anomalous flow was noted at the Palgrave upstream site midsummer, however, due to a lack of probable explanation for potential error, the data were deemed to be acceptable and remained for analysis. The period started before and ended after the CU anomaly, and since the sites do not share any catchment area, it is not logical that the same phenomena caused each anomaly period. At 9:18 on July 26, water level at PU jumped from 0.322 m (d_{max} =

0.462 m) to 0.386 m (d_{max} = 0.579 m) in over span of seven minutes. This occurred on the recession limb from a rainfall event the previous day. The water level remained elevated, with estimated discharge well above PD, making sudden spikes and drops; for example, at 1:31 on July 27, discharge fell 0.711 m^3/s (4.788 to 4.077 m^3/s) in one recording. At 2:37 on August 1, after falling to relatively normal level, just below PD, the water level continued in a regular wave-like pattern uncharacteristic pattern for the rest of the dataset, where readings were lower in morning, lowest around 6:00, then increased to peak around 18:00 before decreasing and beginning the pattern again. This pattern remained from August 1 to 11. At 16:15 on August 11, the water level readings did not decrease with previous wave-like pattern but instead remained steady to late morning August 12, then increases until 17:20 reaching a high of 0.381 m (d_{max} = 0.557 m) before immediately dropping to 0.367 m (d_{max} = 0.533). When presented graphically, the slope of the dataset decreased again until 10:50 on August 13, then began increasing with PD during a recorded rainfall event. From the peak of the flow response at PU at 23:12 onward, the flow record returned to its normal, pre-anomaly pattern and mirrored the water level at PD.

No conclusion can be made about the cause of this anomalous period. The hypothesized build up of material on the datalogger that likely caused the previously mentioned CU anomaly cannot be attributed to causing the PU anomaly. While a precipitation event instigating greater flows could clear the blockage atop and around a datalogger and this anomaly ends during such an event, the pattern during the anomaly is much different to that of the Caledon East site. CU remained at a much higher recorded water level and relatively steady through the period, whereas PU largely fluctuated in a cyclic diurnal pattern. A potential explanation for such a sinusoidal recurring daily anomaly in a water level dataset such as this could be the process of evaporation. If a stream were very small and evaporation a very significant component of water loss, water level could hypothetically reach a low late in the day because of evaporation during sunlight hours. However, it can be presumed that due to the size of the PU channel and the fact that the pattern for such phenomenon is out of phase, with the lowest water levels occurring in the morning and peak in the evening, evaporation is not at the root of the anomaly. Logically, the most likely explanation to the anomaly is that the flow was anthropogenically regulated during the period in question. The rhythmic pattern is unnatural for streams of this type and does not match the rest of the dataset. While the flow could have been heavily modified, there is no obvious explanation for why the flow at the upstream site seemingly exceeded its downstream counterpart for an extended duration. This is abnormal, especially for these two sections located close together along same channel. Since the period was initiated by a precipitation event on July 25 and ended by one August 14, it would lead one to believe that this could have been the product of natural events. Without a strong reason to believe that the anomaly was the result of an error caused by or to the datalogger and without the confidence to know that this was not the actual flow pattern, data from this anomaly period were kept in the PU flow time series.

3.8 Bank stability assessment

Consistent changes in channel width, complexity, and pool depth and scour are seen as a result of urban stream syndrome (Walsh et al., 2005_a). This study sought to better understand the alteration in frequency and intensity of erosive flows downstream of development and their consequences. The limited success of bank failure models in predicting bank instability in field settings renders modelling bank instability in situ ineffective (Darby and Thorne, 1996), so this project employed the use a variety of indicators to infer bank stability, largely through detailed observation and qualitative assessment. The use of qualitative indicators of bank stability in descriptive case studies of the impacts of catchment urbanization is quite common (Doyle et al., 2000), and in this study, employing multiple indicators bolstered the results of streamflow analysis.

The importance of preserving near-channel vegetation for the purpose of bank stabilization has gained increasing recognition in recent years, especially its value in stabilizing single-thread channels, shedding light on the importance of channel ecogeomorphology (Curran and Hession, 2013). This study considered the abundance of vegetation, diversity, and growth of vegetation, both vascular plant and tree, to infer about bank stability. A qualitative assessment of bank vegetation was conducted for the abundance of riparian vegetation or relative vegetation cover. This included the naming and description of vegetation types and description of relative concentrations along the reaches' riparian zones, extending 5 m inward from the edge of the bank. The assessment was carried out in late in the growing season, specifically, from late August and into early September. This allowed for the majority of the full extent of vegetation growth to be accounted for. Banks without vegetation cover can be many times more likely to be eroded during flood events. Denser and more complete vegetation cover decreases the rate of bank erosion and increases overall bank stability (Beeson and Doyle, 1995). Broadly, the presence and abundance of ruderal and invasive vegetation can be used as an additional clue to bolster the case for the visually observed impacts of bank erosion and instability. While the presence of invasive species are common in southern Ontario where the study was conducted, a noticeably high proportion of invasive plant species can act as an additional potential marker of urbanization impacts on channel bank conditions. As mentioned in section 2.5, in addition to non-vegetated and freshly eroded banks, invasive and ruderal species are typically seen outcompeting native species along banks of streams outside their range of equilibrium conditions. As such, particular attention was given to assessing the presence of disturbance tolerant species as a marker of bank instability. Additionally, the relative growth of vegetation was assessed. Larger, and hence, older plants indicate greater stability (Arnold et al., 1982).

Description of bank character and notable failures is employed widely across studies of bank erosion (Goudie, 1990). This qualitative approach was taken to bank assessment, where the banks were observed regularly over a span of approximately four months from end of May to early September. Photographs were taken and detailed notes on the character of the bank, including descriptors such as “stable,” “loose,” “raw,” “overhanging,” and so on, were made. Since bank retreat and channel widening occurs as a result, in part, of bank mass failure (Simon and Collison, 2002), descriptions of noticeable bank failures and significant erosion were made. There are a number of qualitative rating scale methods that can be employed for bank stability (e.g., Pfankuch, 1975; Simon and Downs, 1995; Myers and Swanson, 1996; Johnson et al., 1999). Elements of the visual channel stability assessment set forth by Pfankuch (1975) were used because it is the most commonly employed (Doyle et al., 2000).

Another technique was employed in an attempt to bring quantification of bank stability into the project. Soil strength was measured using a pocket penetrometer, shown in Figure 3.20, on both sides of the channel at the furthest downstream point in each of the reaches, i.e., at the location of the cross-section. Measurements were taken at the top just inside of the bank, mid bank, and near the water surface. These bank strength measurements were repeated every 10 cm upstream a total of twenty-one times, hence, covering the bank soil strength of the 2 m furthest downstream in each of the six reaches. Measurements were taken once a month a total of four times over the study span between June and September. While the use of penetrometers is widely used for soil strength measurements, this technique has not been widely employed across research of bank erosion and stability. This work made use of soil strength measurements in an attempt to

Figure 3.20: Pocket penetrometer

complement existing, widely used methods also employed in this study while being critical of the collected data and comparing them to trends seen in the other factors to determine its validity as a method.

While incorporation of measured soil strength is of great importance, the erosional characteristics of an urban stream are often best revealed by visual clues (Doyle et al., 2000) such as the inclusion of LWD, which are pieces of organic remains greater than 0.1 m in diameter (Keller and Swanson, 1979; Ward and Aumen, 1986; Hogan, 1987; Andrus et al., 1988; Gippel et al., 1996). LWD acts as an obstruction lying across a portion of the channel while not impeding the entire width (Lisle, 1986). The transfer of LWD pieces into a channel is controlled by three main processes. Firstly, trees die naturally and if they are in close proximity may fall into the channel. Secondly, environmental conditions and events may promote the inclusion of LWD, such as blowdown by high winds or icy winter storms. Finally, and most pertinent to this research, bank instability can cause the tipping of trees often towards the channel, thus, bringing in LWD due to geomorphic conditions (Keller and Swanson, 1979). This was detailed in section 2.5. While the quantity is controlled by forest, tree, and environmental characteristics and can be affected by human interference (intentional inclusion or exclusion), in riparian areas, the inclusion of LWD in a stream channel is largely dictated by the geomorphic conditions of the banks (Piegay, 1993).

Erosive flows and resultant unstable banks effectively increase the inclusion of LWD into the channel by causing trees to slump inwards towards the channel. Since this input method is the most significant in riparian areas and bank stability is impacted by flow conditions and debris concentrations are highest in headwaters streams (Keller and Swanson, 1979), LWD was used to infer about geomorphic impacts of catchment suburbanization. Quantification and measurements of LWD pieces, as well as descriptions of accumulations at each site, provide insight into the stability of soils in the channel banks. A census approach was employed. Every piece present was measured and recorded (Gippel et al., 1996). While there is no standardized method for quantifying LWD, comparative inclusion of debris can be employed to make inferences about bank stability (Piegay, 1993). Along the transects, in-channel LWD and root wads fallen partially in the channel were considered. These pieces were measured for width and length, specifically, length falling within the channel area (i.e., not the portion resting on the bank or in the near bank area). In this way, the volume of LWD was estimated (Spetich et al., 1999) so comparisons could be made between up and downstream paired reaches. Within the timeframe of this study, all LWD pieces and accumulations documented remained in place through to the end of the field season.

3.9 Sediment sampling

Sampling of bed and bank material was conducted at each of the six study sites. Sampling was performed once at the end of August 2016 during baseflow conditions.

For bank sampling, a soil corer was inserted into the bank at the location of the downstream end of the reach where the cross-sectional survey was conducted. Similar to the pattern of sampling for soil strength, three samples were taken from each of the left and right banks, respectively; near the water surface, mid-bank, and near the top of the bank where it began to slope back to horizontal.

While there are obvious difficulties in defining where the riverbank is located precisely, in this study, the term bank is employed to define the walls of the river that extend close to vertically up from the bed and the more horizontal terrain that extends immediately out from either side of the channel. Grain size analysis was conducted in a laboratory. Grain size distributions were averaged from the three samples for better precision analyses for each bank.

To sample bed material, the bulk sampling method was employed. A plastic cylinder 27 cm in height and with openings on the top and bottom 20 cm in dimeter was used to confine and excavate bed material, the cylinder acting as a barrier to flow and preventing the loss of fine material. Though the standards set out for bulk sampling lack consistency between authorities (Mosley and Tindale, 1985), standard guidelines were sought for bed sampling procedures. The British Standards Institution (BS 812: Part 1, 1975) requires that samples with a nominal grain size of 10 mm be collected with a minimum sample material of 500 g for sieve analysis. This was considered during field sample collection and all samples exceeded the minimum mass. Cobbles were collected by hand then a trowel was used to extract finer sediment that was added to the sample. The ISO standards (ISO 4364-1977(E)) for bulk sediment samples recommended a sample for every cross-section. This requirement was exceeded, where a sample was collected 1 m upstream of the cross-sections at the reaches' downstream ends, as well as 2 m and 3 m upstream, totalling three bulk samples per site. Like the bank sample grain size distributions, these three bed samples were analysed for their particle size distributions, then the values for the three samples were averaged for each site. This provided a single grain size analysis per site. It should be noted that for bed sediment in gravel bed streams, accuracy in grain size analysis and characterization of bed material is exceptionally labour and resource intensive (Mosley and Tindale, 1985). Due to labour constraints, samples were collected satisfying basic guidelines.

Samples were analyzed for particle size in a laboratory at the Keele Campus of York University. Samples were removed from their plastic bags and placed in labelled tins where they were oven dried at 40º C for 72 hours (ISO 11464). Dry samples were gently crushed with mortar and pestle (Ryżak and Bieganowski, 2011). The material was then run through sieves with mesh sizes 9.51 mm (medium pebbles and larger), 4 mm (fine pebbles), 2 mm (very fine pebbles/granules), 1 mm (very coarse sand), 500 µm (coarse sand), and 250 µm (medium sand and finer) in accordance with the Wentworth scale (ISO11277) using a mechanical shaker for 20 minutes (ISO11464). Samples larger than 5 cm (b-axis) were removed from the bed and measured and weighed in the field. Using the weights for associated particle size groupings, averages were calculated, giving one grain size distribution for each bank and one for the bed material at each site. Grain size parameters D_{10}, D_{16}, D_{30}, D_{50}, D_{60}, D_{84}, and D_{90} were assessed and cumulative frequency curves created for all average samples for each site.

CHAPTER FOUR: RESULTS

4.1 Streamflow: entire time series

A visual assessment of the time series and statistical analyses were performed to compare the paired upstream and downstream time series. Figures 4.1 (Caledon East), 4.2 (Palgrave), and 4.3 (Bolton) show the instantaneous average water level, cross-sectional area of flow, and estimated discharge on three separate graphs. Graphically, all sites show a similar, fairly mirrored pattern between their up and downstream sites. This is to be expected from paired sites that lie along the same channel thread. Peaks occurred nearly simultaneously, indicating similar forces are at play in causing the flow pattern at each. Both the upstream and downstream paired sites for each location show a trend toward increased discharge over the time series, moving from the dry 2016 summer into the wetter autumn season. Upon closer examination, the Bolton sites show a slightly greater delay, with the downstream site taking the most time to respond to precipitation events. This is because the catchment area for the BU and BD sites are comparatively greater than those at Caledon East or Palgrave, and the additional delay is due to their position further downstream in the catchment. Despite the slight lag time, both show mirrored flow patterns.

Overall, Caledon East and Bolton consistently showed that flow components at their downstream sites had had more flashy response to precipitation and more variability overall than their paired upstream sites. Results from the full time series for Caledon East lend toward the potential explanation of greater impermeable surface cover affecting flow components at the CD site. Due to the oddity of greater flow at BD than BU, nothing significant can be surmised about the Bolton location. Palgrave did not show consistent results when comparing up and downstream both graphically and statistically, not lending toward the explanation of developed land surface impacting channel flow.

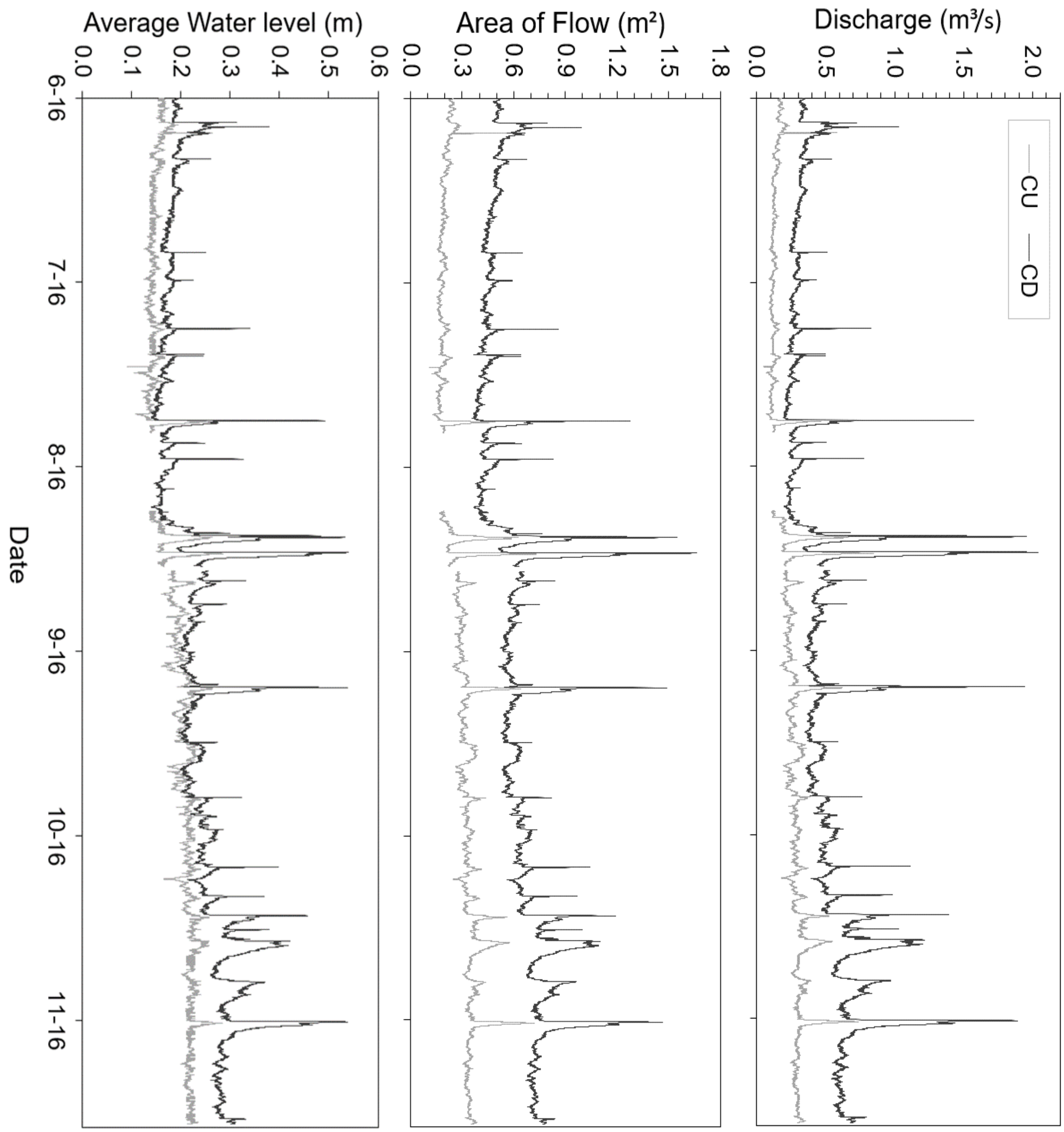

Figure 4.1: Time series of average water level, area of flow, and discharge at Caledon East sites, June to November, 2016

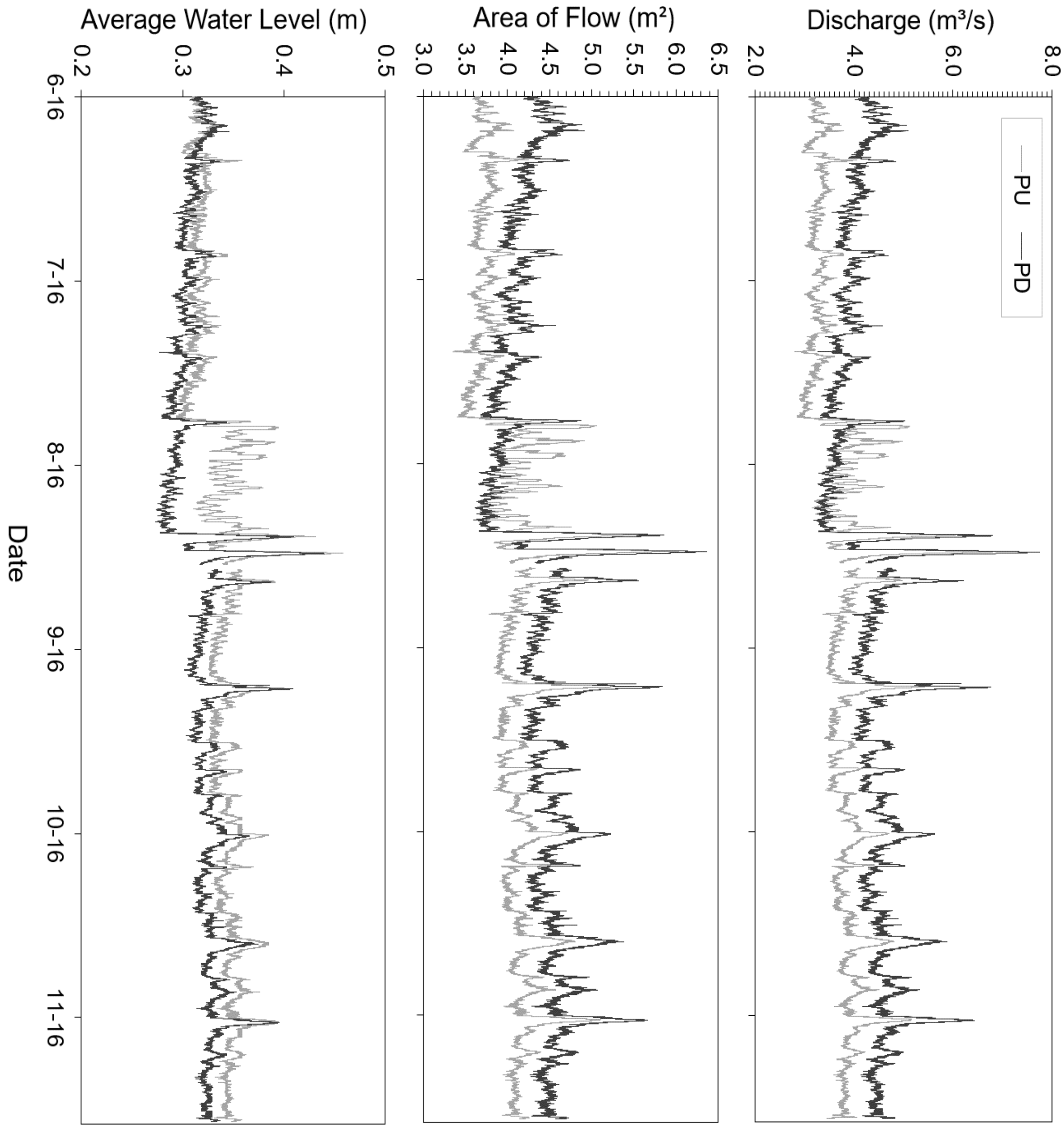

Figure 4.2: Time series of average water level, area of flow, and discharge at Palgrave sites, June to November, 2016

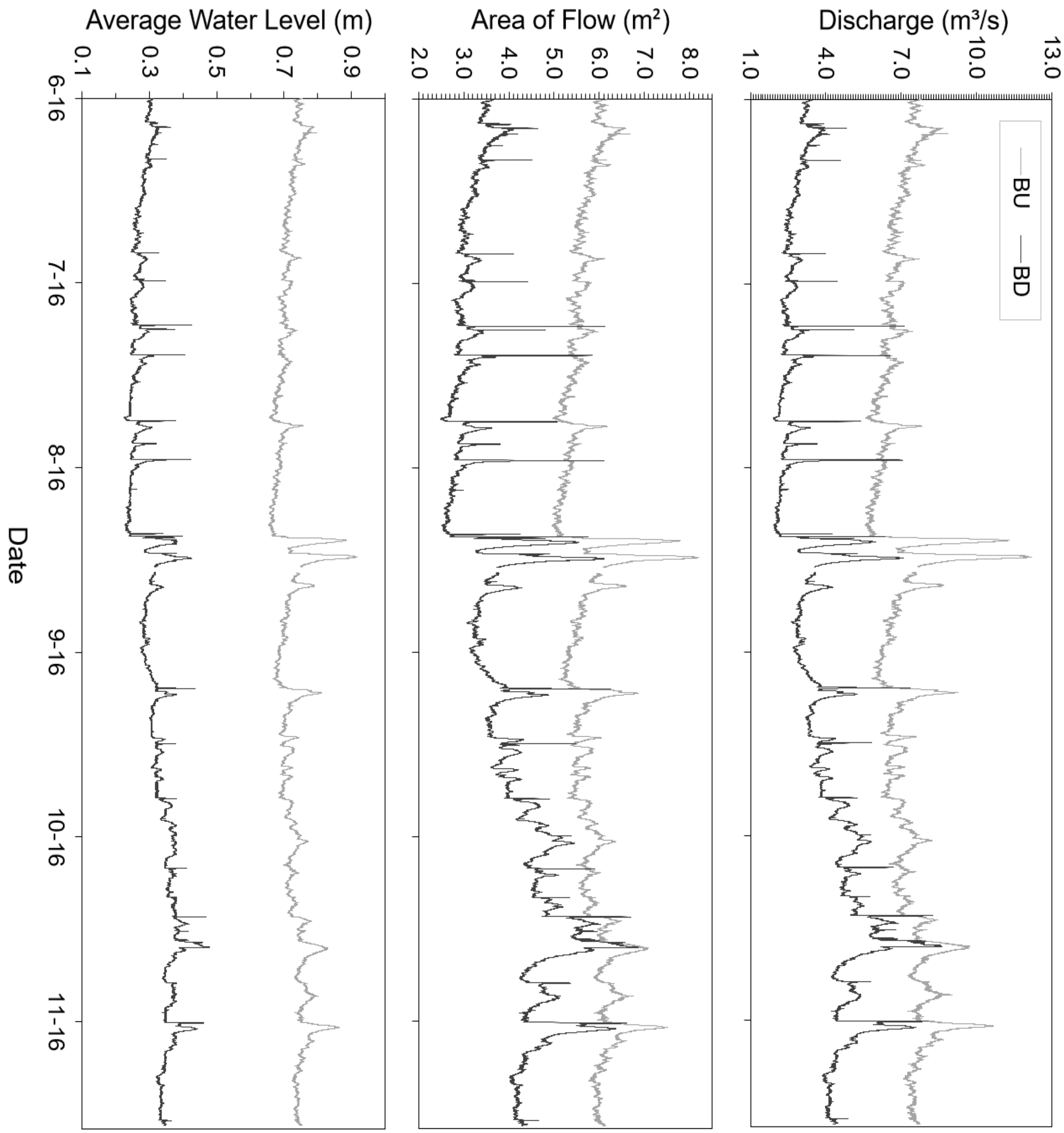

Figure 4.3: Time series of average water level, area of flow, and discharge at Bolton sites, June to November, 2016

Upon further examination of Figure 4.1, the downstream site (CD) shows more pronounced peaks in water depth, area of flow, and discharge in response to rainfall events than upstream (CU). The CD datasets show rapid, steep increases with sharp, high peaks corresponding to rainfall events. Those responses to precipitation are visually more significant at the downstream site than the upstream. The peaks are much higher and in greater contrast with the baseflow, and the CD time series graph is more jagged than that of CU. This is especially noteworthy, as the drainage density at CU (1.52 km/km^2) is much greater than CD (0.93 km/km^2). Nevertheless, CD produces consistently sharper and quicker peaks in spite of lower drainage density.

In Figure 4.2, the Palgrave sites do not show the same dramatic difference between up and downstream noted at Caledon East. Peaks in the flow metrics do not seem more pronounced at either site. Besides the expected greater flow at PD, approximately proportional to its slightly greater catchment area, there is no obvious visible difference between the two datasets. The sites' drainage densities are quite similar (PU = 0.44 km/km^2, PD = 0.48 km/km^2).

The third time series, shown in Figure 4.3, shows a flow pattern at Bolton more similar to Caledon East. The downstream site has noticeably more dramatic responses but with a complication. Though the site has greater catchment area and lies downstream along the same channel as BU, the BD time series show consistently lower water level, cross-sectional area of flow, and estimated discharge values. While the water level and even area of flow could hypothetically be lower at an upstream site, this is not typical. Possible explanations for this are discussed in Section 5.1. Despite lower values, peaks in the BD dataset are markedly sharper. Even during precipitation events generating little deviation from baseflow at BU, such as those seen through the month of July, sharp increases are produced in the water level, area of flow, and discharge downstream. Even though not reaching flow levels as high as those at BU, responses to precipitation are far more pronounced at BD. The downstream graphs for the time series are jagged, with stable baseflows and peaky high flow events, indicating much flashier flow regime overall at BD. This does not seem to be influenced by drainage density, as the Bolton sites are very similar (BU = 0.30 km/km^2, BD = 0.37 km/km^2).

Basic descriptive statistics for the flow time series are displayed in Table 4.1. Firstly, with the exception of velocity, the maxima, minima, and means for all flow components are greater at CD than CU. The reverse pattern seen with velocity is likely due to the greater slope at CU, as slope is a factor in velocity and the estimates using Manning's equation, as explained in section 3.5. The standard deviation was also greater for all flow components at the downstream site, showing greater variability in the CD data and more consistency at CU. The downstream section seems more sensitive to inputs with easily visible changes in water level, and hence, all other flow components. The range between the maximum and minimum value for each flow component was

Table 4.1: Descriptive statistics of flow components for entire time series

		Caledon East		Palgrave		Bolton	
		CU	CD	PU	PD	BU	BD
d (m)	Mean	0.19	0.23	0.34	0.32	0.46	0.31
	Max	0.32	0.54	0.46	0.44	0.62	0.48
	Min	0.09	0.14	0.29	0.27	0.40	0.23
	σ^2	0.04	0.06	0.02	0.02	0.03	0.05
A (m^2)	Mean	0.31	0.59	4.01	4.35	5.75	3.77
	Max	0.88	1.66	6.03	6.36	8.20	6.87
	Min	0.11	0.36	3.36	3.60	4.96	2.48
	σ^2	0.14	0.15	0.30	0.35	0.43	0.85
U (m/s)	Mean	0.77	0.73	0.92	0.98	1.22	0.94
	Max	1.09	1.31	1.12	1.22	1.49	1.26
	Min	0.47	0.53	0.83	0.89	1.12	0.76
	σ^2	0.10	0.12	0.04	0.04	0.05	0.10
Q (m^3/s)	Mean	0.26	0.45	3.69	4.26	7.05	3.61
	Max	0.94	2.04	6.79	7.75	12.22	8.62
	Min	0.05	0.19	2.80	3.19	5.56	1.91
	σ^2	0.17	0.20	0.43	0.52	0.84	1.19

greater at the downstream site. This is especially prominent when examining the range between the highest and lowest discharge estimates at Caledon East, which are nearly double at CD (1.85 m^3/s) compared to CU (0.89 m^3/s), and in the average water level measurements (CU = 0.23 m, CD = 0.40 m). Although their minima are comparable when at baseflows, as the primary source of flow at CD is from CU upstream nearby, the maximum at CD is far greater. This can be explained by the source of flow at the downstream site. CD is fed by a combination of upstream flow and an additional significant input is sourced from the specific catchment area feeding CD, as it is not a part of the CU flow.

Overall, differences seen between the Palgrave sites flow datasets are small and comparatively less pronounced than those seen at Caledon East. Similar to what was seen in the time series figures, descriptive statistics of flow components at Palgrave do not illustrate pronounced differences between up and downstream paired sites. While the maxima, minima, and standard deviations of water depth and velocity are similar, there are slightly more noticeable differences in area of flow and consequent discharge estimates between PU and PD. This can be accounted for by differences in cross-sectional shape and size between the sites. Discharge, the product of each of the flow components, is the factor with the greatest variability between up and downstream. Despite this, discharge values for the paired sites do not vary greatly. Discharge has a slightly larger range downstream (4.56 m^3/s) than at its paired upstream site (3.99 m^3/s), and its standard deviation was greater (CD = 0.52 m^3/s, CU = 0.43 m^3/s). However, recall the Caledon East sites the mean discharge: CD was 15.4% greater than CU, whereas the catchment area is only 5.4% greater. This illustrates that the increase in flow is more than proportional to the increase in area from upstream to downstream. This disproportional increase was not the case for Palgrave.

Table 4.2: Variability in flow components at Bolton sites

	Bolton			
	(Max – Min)		(Max – Min) / Mean	
	BU	BD	BU	BD
d (m)	0.22	0.25	0.48	0.81
A (m^2)	3.24	4.39	0.56	1.16
U (m^2/s)	0.37	0.50	0.30	0.53
Q (m^3/s)	6.66	6.71	0.94	1.86

Finally, the pronounced visual differences between the BU and BD time series are reinforced by the descriptive statistics of their flow components. With a greater cross-sectional area of water flow and consistently higher velocity estimates, discharge estimates produced at BU are greater than BD over the entire time series. Maxima and minima are steadily greater at BU, but the standard deviations and range between maxima and minima are greater for all components at the downstream site. This is extraordinary, since greater values would generally be associated with greater variability. However, the difference between the highest and lowest values here, as well as the ratio between this difference and the mean for each component, is far greater at the downstream site. This is shown in Table 4.2. It is clear that variability in the BD dataset is far greater than at BU. Because of the obvious issue of greater discharge at BU, caution must be exercised when making deductions from the differences between these datasets.

To further test for variation between the upstream and downstream sites, an F-test was performed to assess variance between the paired flow component datasets. d_{max} was chosen over d for added precision, as the datalogger measured instantaneous maximum water level. Results from this test are shown in in Table 4.3. The test resulted in very significant p-values for each of the flow components at the paired sites. This was to be expected at the Caledon East and Bolton sites following previous graphical and statistical analysis, where greater variance was observed between the upstream and downstream datasets. However, while visually the PU and PD flow

Table 4.3: F-test comparing flow components for entire time series at paired sites

	p-value		
Parameter	Caledon East	Palgrave	Bolton
d_{max}	< 0.01	< 0.01	< 0.01
A	< 0.01	< 0.01	< 0.01
Q	< 0.01	< 0.01	< 0.01

components were closely mirrored and looked almost identical graphically, the F-test showed a statistically significant difference between the variances in the up and downstream datasets. The time series were comprised of large datasets, with each flow component having over 35 000 data points. This likely influenced the outcome of the test. Additionally, ratios of instantaneous values to average values were computed for each of the components for all series (e.g., $\frac{Q_n}{\bar{Q}}$ where Q_n is the nth instantaneous value for discharge and $\bar{Q}$ is mean discharge) and the F-test was performed on these ratios. This was done because the range of values for each variable are different up and downstream, where downstream usually have greater values and greater ranges for their flow components than the paired site upstream. In this way, ratios between the instantaneous values and their respective means eliminate the inherent differences in datasets that may cause statistically significant results for differences between datasets not reflective of the potential suburbanization impacts. Again, p-values for the F-test were extremely significant for all components at all site pairings, showing that the differences between the up and downstream paired sites are not as a result of different water levels to begin with. Interestingly, the results were significant for Bolton. This showed that BD had significantly greater variance than BU though having lower values to begin with.

4.2 Streamflow: storm events

The results of these three assessments of the storm hydrographs were tested to determine whether there was a statistical difference between the upstream and downstream paired sites. A one-tailed paired t-test assuming equal variance was performed on the results of each test. A one-tailed test was chosen because the intent of the test was to determine specifically whether the downstream values were significantly greater than those upstream, rather than if one was merely larger than the other. Each yielded a unique result and provided insight into potential differences between the responses to precipitation at paired up and downstream sites, as well as the relative utility of tests in this context.

Table 4.4 shows the percent change in discharge for paired sites at the three study locations in response to precipitation events, rising from initial response to peak flow. At Caledon East, while all but one storm event produced a greater proportional increase from base to peak flow, this did not quite yield a significant result. While visual assessment of Figure 4.1 indicated a relative

Table 4.4: Percent (%) increase in discharge for select precipitation events, from initial response to peak

	Precipitation	Caledon East		Palgrave		Bolton	
Date	(amount/duration)	CU	CD	PU	PD	BU	BD
07/25/2016	15.8 mm/1 hr 40 mins	315.9	532.9	30.8	33.6	32.2	140.2
08/13/2016	4.4 mm/1 hr 10 mins	17.4	71.0	62.0*	96.1*	3.16	91.1
	11.2 mm/1 hr 40 mins	19.0	230.4			10.5	157.7
	12.4 mm/50 mins	38.8	154.5			64.4	96.6
08/16/2016	24.6 mm/8 hr 20 mins	318.4	400.6	86.6	96.6	70.3	132.3
09/07/2016	7.2 mm/1 hr 35 mins	95.9	296.7	21.2	40.6	35.5	99.1
	12.8 mm/1 hr 35 mins	44.2	102.9	22.7	26.6	10.1	17.0
10/20/2016	11.0 mm/13 hr	56.0	71.8	24.3	32.8	28.1	41.1
11/03/2016	16.8 mm/4 hr 20 mins	138.1	120.3	30.6	36.8	39.4	78.1
	p-value (one tailed t-test)	0.07		0.21		< 0.01	

difference in response, statistically speaking, the t-test showed the downstream responses were not quite significantly greater than those upstream. As such, it cannot be concluded that the degree of response to storm events was greater at the downstream site, though the majority of stormflow responses were greater downstream.

For the sake of accuracy in testing the Palgrave sites, the intermittent rainfall over the course of August 13 was recorded as a single storm event, i.e., 30.4 mm over 19 hours 10 mins (0:10 to 19:20). This was done because hydrographs for the storm at PU and PD did not show clear and observable responses to intermittent rainfall. Rather, the flow metrics all increased steadily over the storm as a whole, i.e., one defined rising limb and peak rather than three. Tabular data reveal that all responses were greater downstream than upstream, meaning severity of the storm's impact was greater downstream. However, this difference was by a smaller margin than seen at the Caledon East sites. Analysis produced a result that showed no statistical difference, and as such, it cannot be concluded that response to input was of greater magnitude from base to peak flow at PD.

At the Bolton sites, tabular data showed that BD had greater proportional increase in flow from base to peak in every instance. It is also notable that there was great variability in those increases, ranging from 6.9% to 147.2% greater proportional increase than BU. Statistically there is a very significant difference between the paired sites, where downstream certainly had a more significant response with regards to flow increase during storm events. This reinforces the notable spikes in discharge in response to precipitation seen at BD compared to BU in Figure 4.3.

Table 4.5 displays results from the comparison between rate of increase in discharge in response to storm events at up and downstream paired sites. Tentatively, this can be thought of as a quantitative comparison of the storm hydrograph rising limbs between sites.

Table 4.5: Rate of increase (m³/s per hour) in discharge for select precipitation events, from initial response to peak

Date	Precipitation (amount/duration)	Caledon East CU	Caledon East CD	Palgrave PU	Palgrave PD	Bolton BU	Bolton BD
07/25/2016	15.8 mm/1 hr 40 mins	0.056	0.666	0.274	0.231	0.093	1.716
08/13/2016	4.4 mm/1 hr 10 mins	0.028	0.373	0.120*	0.236*	0.395	3.468
	11.2 mm/1 hr 40 mins	0.072	0.678			0.898	5.572
	12.4 mm/50 mins	0.138	2.547			0.494	0.182
08/16/2016	24.6 mm/8 hr 20 mins	0.090	0.482	0.278	0.327	0.300	0.180
09/07/2016	7.2 mm/1 hr 35 mins	0.110	0.602	1.692	2.178	0.184	1.102
	12.8 mm/1 hr 35 mins	0.081	1.687	0.268	0.295	0.203	0.262
10/20/2016	11.0 mm/13 hr	0.016	0.182	0.073	0.099	0.081	0.097
11/03/2016	16.8 mm/4 hr 20 mins	0.033	0.279	0.087	0.096	0.138	1.599
	P-value (one tailed t-test)	< 0.01		0.40		0.04	

Caledon East produced very significant results, showing that CD had overall more rapid responses to precipitation input. This is indicative of a more direct incorporation of precipitation from the catchment surface into the flow at the downstream site.

At Palgrave, testing did not indicate that the downstream site responded significantly differently to the upstream. Again, the three rainfall episodes recorded over the day on August 13 were taken as a single storm event and a single response at each site was considered. These results agree with those in Table 4.4. The Palgrave paired sites do not respond significantly differently to storm events.

T-tests performed on the rates of increase in estimated flow to individual rain events at the Bolton sites produced a significant result. In some cases, the rate of response at BD was over an order of magnitude greater than the response at BU. This is despite having atypically lower discharge at its downstream site.

Table 4.6: Runoff coefficient (dimensionless) for select precipitation events

Date	Precipitation (amount/duration)	Caledon East		Palgrave		Bolton	
		CU	CD	PU	PD	BU	BD
07/25/2016	15.8 mm/1 hr 40 mins	0.035	0.050	0.022	0.024	0.017	0.010
08/13/2016	30.4 mm/19 hr 10 mins	0.319	0.373	0.179	0.191	0.144	0.071
08/16/2016	24.6 mm/8 hr 20 mins	0.209	0.209	0.107	0.116	0.083	0.043
09/07/2016	20.0 mm/4 hr 15 mins	0.094	0.125	0.054	0.064	0.040	0.028
10/20/2016	11.0 mm/13 hr	0.464	0.436	0.267	0.310	0.231	0.181
11/03/2016	16.8 mm/4 hr 20 mins	0.135	0.147	0.063	0.074	0.055	0.037
	P-value (one tailed t-test)	0.44		0.40		0.22	

Finally, Table 4.6 shows results from the calculated runoff coefficients for each site during precipitation events. Here, periodic rainfall events were combined into single storms, as they produced more reliable and comparable values for rainfall intensity in the calculation of the coefficients. Tabular data were very similar between the Caledon East sites, where in most cases, modelled proportions of surface runoff were slightly greater at CD. With drainage area taken into consideration, of which CD has over double the area of CU, testing showed no difference between the sites with regards to modelled surface runoff. Similarly, testing of Palgrave and Bolton pairs each do not yield significant differences, though p-values are smaller for the BD and BU pairing.

Results from the analysis of runoff coefficients were in stark contrast to those attained from analyses performed on the storm hydrographs, leading to further consideration about the nature of the tests themselves. As a metric, the runoff coefficient does not incorporate baseflow in computation, and consequently, it does not consider the actual degree of response to rainfall. Rather, it uses peak flow as its sole discharge component. Additionally, locations for agricultural and commercial water withdrawal, likely in addition to household subsurface extraction, were scattered throughout the catchment areas of these sites. It is reasonable to conclude that portions of the catchments and reaches were engineered with regards to stormwater management, as well. Manipulation of local hydrology in these ways means the lack of baseflow consideration in the runoff model could produce problematic results. As a metric, peak flow may not be reflective of the amount of precipitation generated as surface runoff when taken in isolation in this context. Some water may not have the chance to reach the channel, for instance, if it were diverted to a quantity control stormwater management pond, or may reach the channel via storm sewers and other direct means. Additionally, the lack of significant results in runoff coefficient testing does not seem reflective of the surface covers, as the runoff coefficient does not consider ground saturation.

Overall, the percent and rate of increase in flow in response to storm events seem to be the best measures to assess the potential impacts of impervious surface cover in suburbanized catchment area on channel response to precipitation. With this, the results suggest that flow downstream of Bolton is impacted by the development with regards to stormflows, and that Caledon East shows some sign of impact by the suburb in the catchment, where the greater rate of increase in flow to storm events is very significant downstream.

4.3 Bank stability indicators

The visual assessment of bank condition and LWD quantification comprise the bank stability evaluation. Banks displayed some scour resulting from flow erosion. No mass wasting was noted so it can be deduced that bank vegetation present had a positive effect on bank stability (Thorne, 1998).

Sites at Caledon East displayed markedly different bank characteristics up and downstream but with no significant LWD at either. Banks at CU appeared quite gradual. Vegetation from the banks bled seamlessly into the channel, making the banks less distinguishable. Vegetation was continuous from just inside the channel up onto the banks and into the riparian area. Banks downstream at CD appeared steeper over the reach. This is reinforced in by the cross-sectional shapes shown in Figures 3.6 and 3.7. Roots from grasses and other herbaceous vegetation was overhanging areas of pronounced erosion. While not over the entire reach, banks on either side regularly appeared scalloped at the downstream site. Some areas showed an arc pattern of bank profile, where bank material was carved further inward than overhanging vegetation and the extent of the water at baseflow. It should be noted that this is not fully illustrated by the cross-sectional profile diagram. Survey equipment used was not capable of measuring inside the bank when vegetation overhanging the scour was present above. Though the channel was quite small, scallops at CU were similar in size and intensity to those seen at the larger downstream sites.

Indicators of degradation were present at both PU and PD, making them visually similar with regards to bank condition and strength. PU banks were quite steep in the near-channel area. Some minor undercutting of the bank material was observed, with grasses and their roots extending outward over the channel in patches along the left bank. Banks at PU were vegetated over the entire reach with no areas bare and exposed. Scalloping was present on the right bank from midway through the reach to its upstream end. Minor scalloping was present along the left bank but less prominent and intense than that seen on the right. Despite having fewer trees near-channel than downstream, PU had many dead trees were noted slumping inward toward the channel. At PD, banks were steep from the water surface extending upward, but the riparian area and surroundings were steep, as well. Figures 3.8 and 3.9 show that immediately next to the channel, banks were similarly sloped at both sites. Much root material was overhanging the channel at PD, especially in scalloped areas. Exposed areas of bank were common, with raw soil exposed without vegetation coverage. Large scallops pocked both banks over the reach. Tree roots from near channel trees were often quite exposed, as many trees were present in the near channel and riparian zone. Many pieces and accumulations of LWD were seen also due in part to the abundance of trees. LWD concentrations were similar between the two sites. PD had twice as many as PU with regards to pieces and accumulations recorded per unit length of channel, approximately every 0.87 per metre compared to 0.40 upstream. However, the sites were nearly equal in the approximate volume of LWD per unit length of channel. PD had 0.08 m^3 of LWD affecting flow for every metre of reach, while PU had 0.06 m^3.

Banks appeared in better condition at the Bolton upstream site, but LWD concentrations were similar between the paired sites. At BU, the banks were quite gradual for the majority of the reach. Very little bank soil was exposed, noticeably less than at its downstream counterpart. Some areas appeared undercut but comprised a small proportion of the entire length of the reach. Banks at BU were consistently vegetated otherwise and did not appear raw, with exposed soil material being very rare. Few scallops were noted and banks ran smoothly and linearly. BU had the greatest number of LWD pieces and accumulations of any site, but much like PD, the reach itself was long and LWD were primarily fallen branches and not dead trees. At BD, banks were steeper, especially the left bank. This is illustrated comparatively in Figure 3.10 and 3.11. Some parcels of bank with grasses and roots exposed were observed slumping in toward the water. The right bank was noticeably undercut over a span of a few metres at the upstream end of the reach. Grasses were angled inward nearly to the water surface over the reach and soil appeared to slump in many places. Scalloping had affected both banks, especially the right. While BU (1.59) had nearly double the number of LWD pieces and accumulations per metre of channel that BD (0.84) had, the estimated volume of LWD was nearly identical per unit length; BU had 0.32 m^3 and BD had 0.31m^3 per metre of channel length.

4.4 Soil strength measurements

Compressive soil strength measurements were statistically compared. To test for difference between up and downstream soil strength, measurements from paired sites were compared using a t-test for sample means. To test for difference in compressive strength over time, a one-way ANOVA with post-hoc Tukey test was used in an attempt to show differences between groups. This was done by testing change over time (between months) at a given site with data compared as paired values. A one-way test was chosen for the purpose of showing difference over time, which is unidirectional. The post-hoc Tukey test was chosen as it accounts for all values in the dataset even when only comparing one pair at a time, hence, correcting for the family-wise error.

With regards to sites, results displayed in Table 4.7 show that there was a statistically significant difference between the up and downstream pairs at all three study locations. The compressive soil strength was significantly lower in the BD bank (0.71 ± 0.44 kg/cm^2) compared to its upstream counterpart, BU (0.87 ± 0.29 kg/cm^2, $p < 0.01$). The significant results seen at

Table 4.7: Descriptive statistics of compressive soil strength, all sites

	Caledon East		Palgrave		Bolton	
	CU	CD	PU	PD	BU	BD
Mean	0.40	0.57	0.34	0.69	0.87	0.71
Max	0.83	1.33	0.83	1.92	1.58	1.92
Min	0.08	0.08	0.00	0.25	0.25	0.08
σ^2	0.02	0.05	0.03	0.10	0.08	0.19
p-value (t-test, n = 168)	< 0.01		< 0.01		< 0.01	

Palgrave and Caledon East show the very opposite. PD exhibited nearly double the bank soil strength (0.69 ± 0.31 kg/cm^2) assessed at PU (0.34 ± 0.17 kg/cm^2, $p < 0.01$). CD also exhibited greater compressive soil strength (0.57 ± 0.23 kg/cm^2) than that of CU (0.40 ± 0.15 kg/cm^2).

Results from the ANOVA with post-hoc Tukey testing for change at a given site over time were more complex as displayed in Table 4.8. CU saw no significant changes in soil strength over time. The downstream site, CD, saw a significant difference between July and August. Table 4.9 shows that the soil strength decreased by 0.17 kg/cm^2 (July: 0.64 ± 0.22 kg/cm^2, August: 0.47 ± 0.18 kg/cm^2, $p < 0.01$). The test revealed that at PU, compressive soil strength was significantly greater in August (0.39 ± 0.12 kg/cm^2) compared with June (0.28 ± 0.18, kg/cm^2, $p = 0.01$), showing an increase over time contrary to the pattern seen at CD. PD showed several decreases in soil strength over time. Compressive strength reduced from June (0.81 ± 0.36 kg/cm^2) to August (0.51 ± 0.21 kg/cm^2, $p < 0.01$), June (0.81 ± 0.36 kg/cm^2) to September (0.58 ± 0.21 kg/cm^{2,} $p < 0.01$), July (0.86 ± 0.30 kg/cm^2) to August (0.51 ± 0.21 kg/cm^2, $p < 0.01$), and July (0.86 ± 0.30 kg/cm^2) to September (0.58 ± 0.21 kg/cm^2, $p < 0.01$). At the Bolton location, BU had one change in compressive strength between months. Bank soil strength decreased by 0.23 kg/cm^2 between

Table 4.8: One-way ANOVA with post-hoc Tukey showing change in compressive soil strength over time

Months compared		p-values					
		Caledon East		Palgrave		Bolton	
		CU	CD	PU	PD	BU	BD
June	July	0.34	0.82	0.13	0.81	0.44	0.75
	August	0.97	0.03	0.01	< 0.01	1.00	0.03
	September	0.94	0.84	0.84	< 0.01	0.13	0.03
July	June	0.34	0.82	0.13	0.81	0.44	0.75
	August	0.15	< 0.01	0.79	< 0.01	0.52	< 0.01
	September	0.12	0.33	0.52	< 0.01	< 0.01	< 0.01
August	June	0.97	0.03	0.11	< 0.01	1.00	0.03
	July	0.15	< 0.01	0.79	< 0.01	0.52	< 0.01
	September	1.00	0.21	0.10	0.68	0.10	1.00
September	June	0.94	0.84	0.84	< 0.01	0.13	0.03
	July	0.12	0.33	0.52	< 0.01	< 0.01	< 0.01
	August	1.00	0.21	0.10	0.68	0.10	0.21

July (0.97 ± 0.33 kg/cm^2) and September (0.74 ± 0.24 kg/cm^2, $p < 0.01$). More changes were noted at the downstream site, BD, similar to those observed at PD. A decrease in compressive strength was noted from June (0.81 ± 0.50 kg/cm^2) to August (0.56 ± 0.26 kg/cm^2, $p = 0.03$), June (0.81 ± 0.50 kg/cm^2) to September (0.56 ± 0.22 kg/cm^2, $p = 0.03$), July (0.90 ± 0.57 kg/cm^2) to August (0.56 ± 0.26 kg/cm^2, $p < 0.01$), and July (0.90 ± 0.57 kg/cm^2) to September (0.56 ± 0.22 kg/cm^2, $p < 0.01$). Generally, the downstream sites had more significant changes between soil strength measurements over time than the upstream sites.

Generally, extremely low values for compressive strength were attained for bank soil across the study sites, calling into question the validity of the experimental method. Mean values for strength never reached 1.0 kg/cm^2 along any of the sites' vegetated banks, though minimum strength required to support vegetation growth is between 1.5 and 2.5 kg/cm^2 (Clary, 1995). Typically, other studies employing penetrometers to ascertain soil strength present values well into the single and double digits (Drnevich et al., 1974; Adams et al., 1982), well beyond even the maximum strength value attained in this study, which was 1.92 kg/cm^2 at BD.

Table 4.9: Descriptive statistics for monthly compressive soil strength, all sites

		Caledon East		Palgrave		Bolton	
		CU	CD	PU	PD	BU	BD
June	Mean	0.39	0.60	0.28	0.81	0.88	0.81
	Max	0.83	1.33	0.67	1.92	1.33	1.92
	Min	0.17	0.08	0.00	0.33	0.25	0.17
	σ^2	0.15	0.29	0.18	0.36	0.27	0.50
July	Mean	0.45	0.64	0.36	0.86	0.97	0.90
	Max	0.75	1.17	0.83	1.58	1.58	1.75
	Min	0.17	0.25	0.00	0.42	0.33	0.25
	σ^2	0.14	0.22	0.20	0.30	0.33	0.57
August	Mean	0.38	0.47	0.39	0.51	0.88	0.56
	Max	0.75	1.00	0.67	1.00	1.33	1.33
	Min	0.08	0.08	0.17	0.25	0.33	0.08
	σ^2	0.16	0.18	0.12	0.21	0.27	0.26
September	Mean	0.38	0.56	0.31	0.58	0.74	0.56
	Max	0.75	1.00	0.75	1.17	1.58	1.08
	Min	0.08	0.25	0.08	0.33	0.33	0.17
	σ^2	0.14	0.16	0.16	0.21	0.24	0.22

The proximity of bank soil to water and the banks' ensuing soil moisture content limits the use of penetrometers in this context. What can be ascertained from the statistical analysis performed on compressive strength data is minimal. Higher moisture content is known to cause lower shear strength in soil (Yokoi, 1968). In this study, even the soil moisture of the highest of the three measurements taken inside the bank were visibly influenced by the water in the channel, with the soil being cool, damp, and dark with moisture. Wet soil can produce more inconsistent readings and one study found that 65 to 71% soil moisture equated to a range of 0.64 to 2.75 kg/cm^2 for shear strength (Yokoi, 1968). Since it is possible that much of the bank soil tested in this research contained more moisture than this, the occasional readings of 0 kg/cm^2 compressive shear strength make sense. While logically a reading of no strength would imply no stability and a state of erosion, this was not the case in places where zero readings were attained. As such, the readings were likely less influenced by the actual strength of the soil and more so by the moisture content, giving exaggeratedly low values for compressive strength. Based on this, it is not recommended that pocket penetrometers be used further in evaluating bank soil strength as conducted here.

4.5 Catchment imperviousness

Figures 4.4 through 4.9 show site drainage maps with land cover. The developed land classification serves an approximation for the proportion of catchment area with decreased surface permeability, or decreased capacity to allow for permeation of surface water. This land cover is a product of anthropogenic influence due to construction of residential, commercial, and other built surfaces and structures.

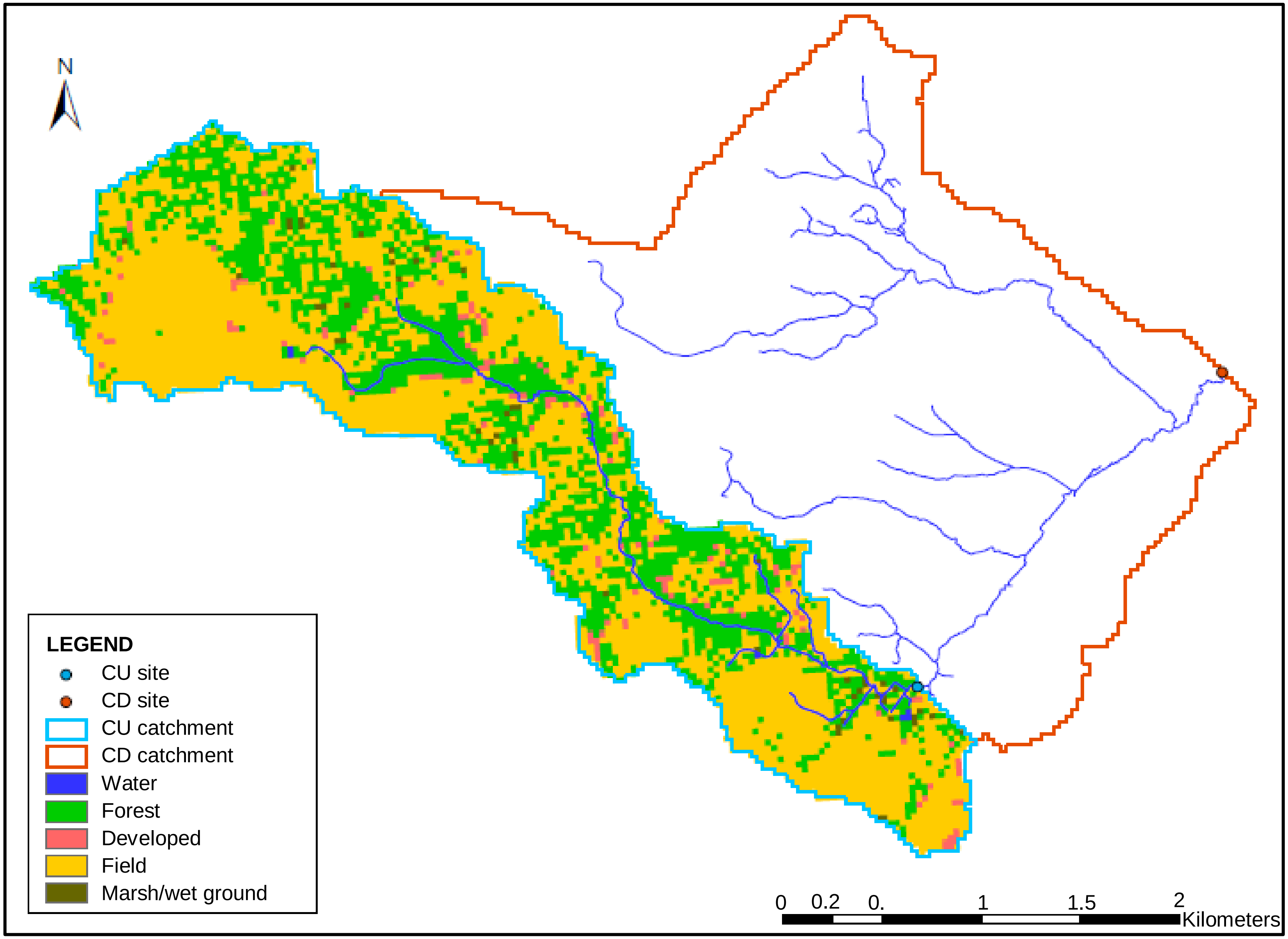

Figure 4.4: Land cover, Caledon East upstream catchment area

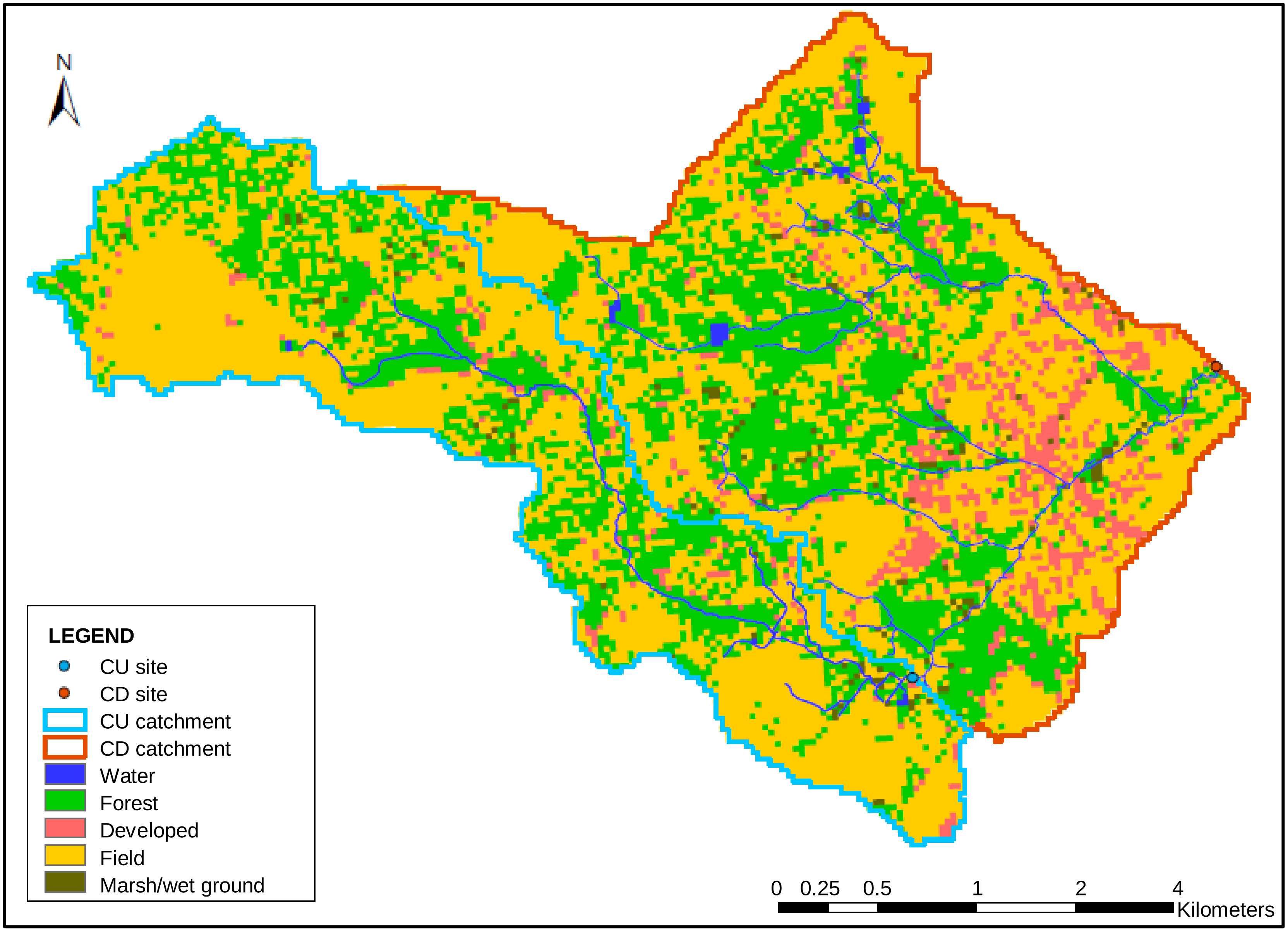

Figure 4.5: Land cover, Caledon East downstream catchment area

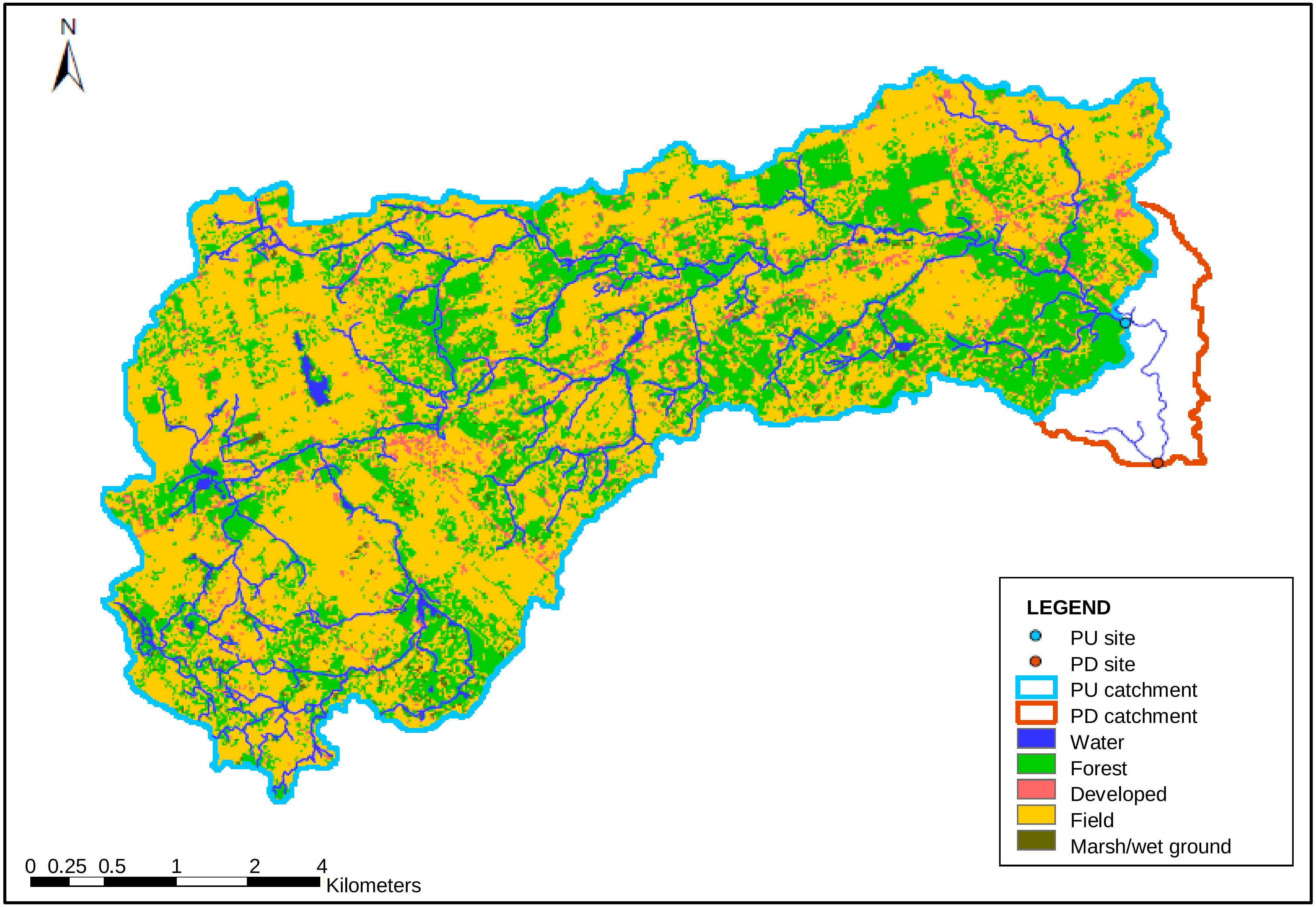

Figure 4.6: Land cover, Palgrave upstream catchment area

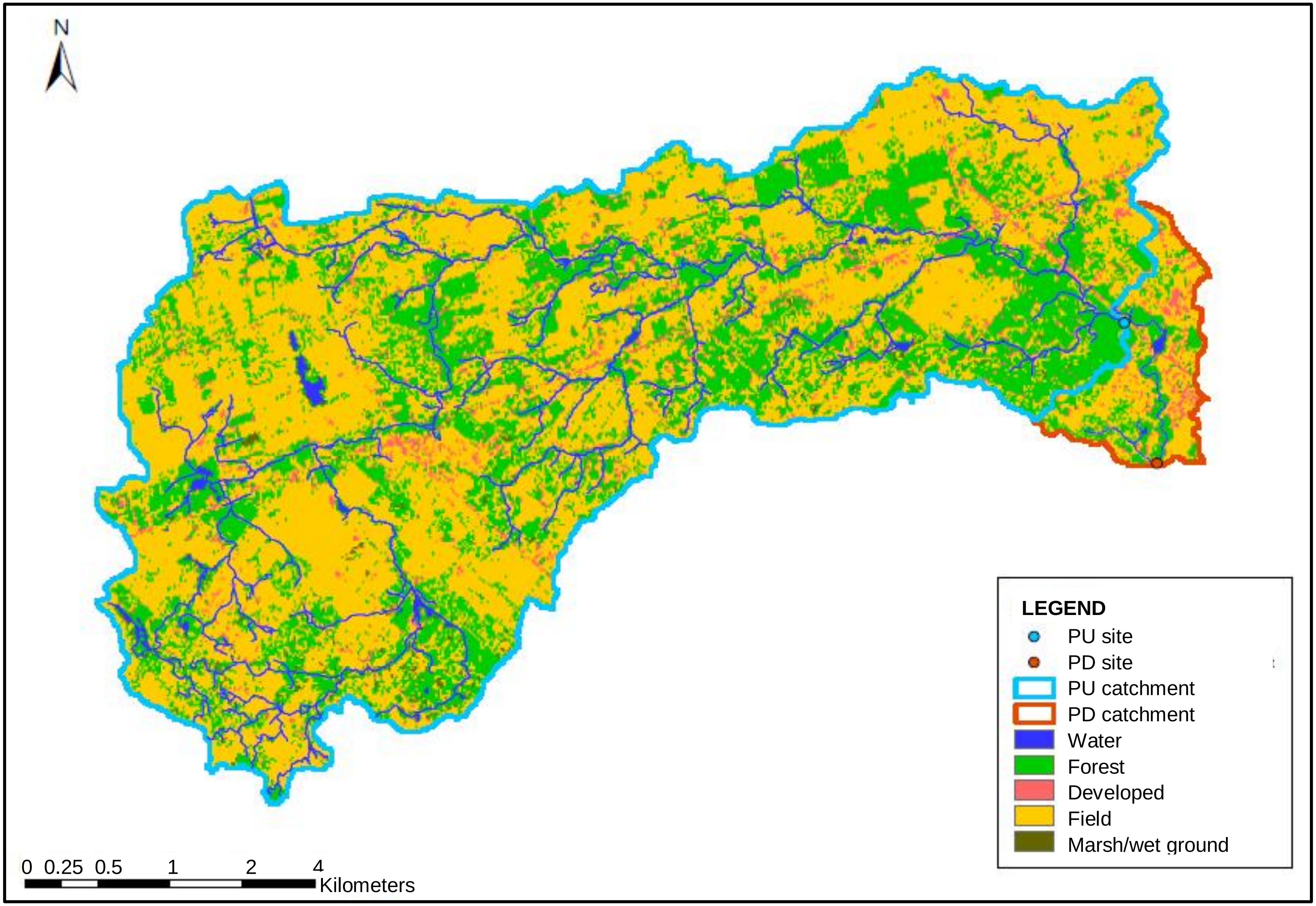

Figure 4.7: Land cover, Palgrave downstream catchment area

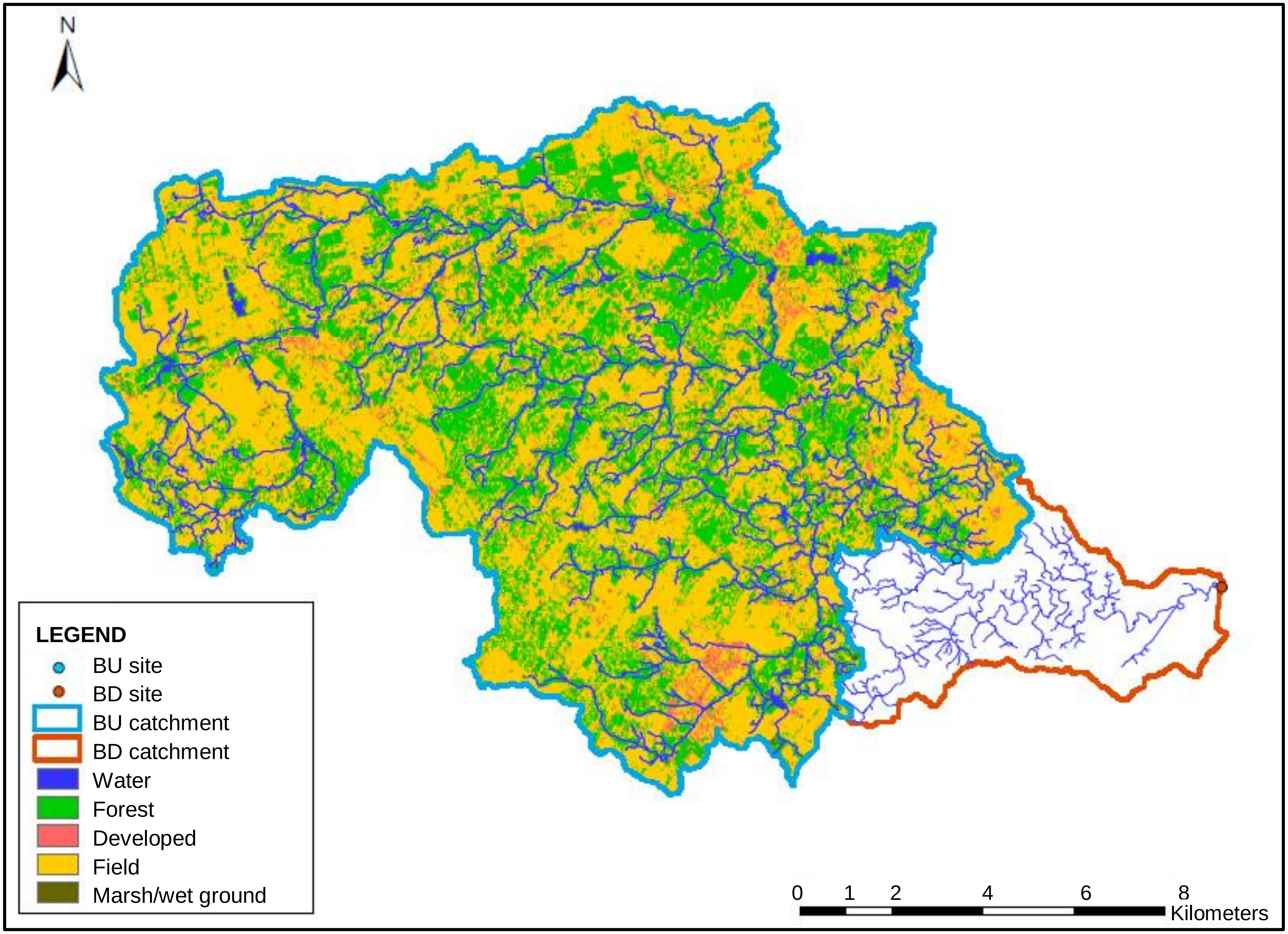

Figure 4.8: Land cover, Bolton upstream catchment area

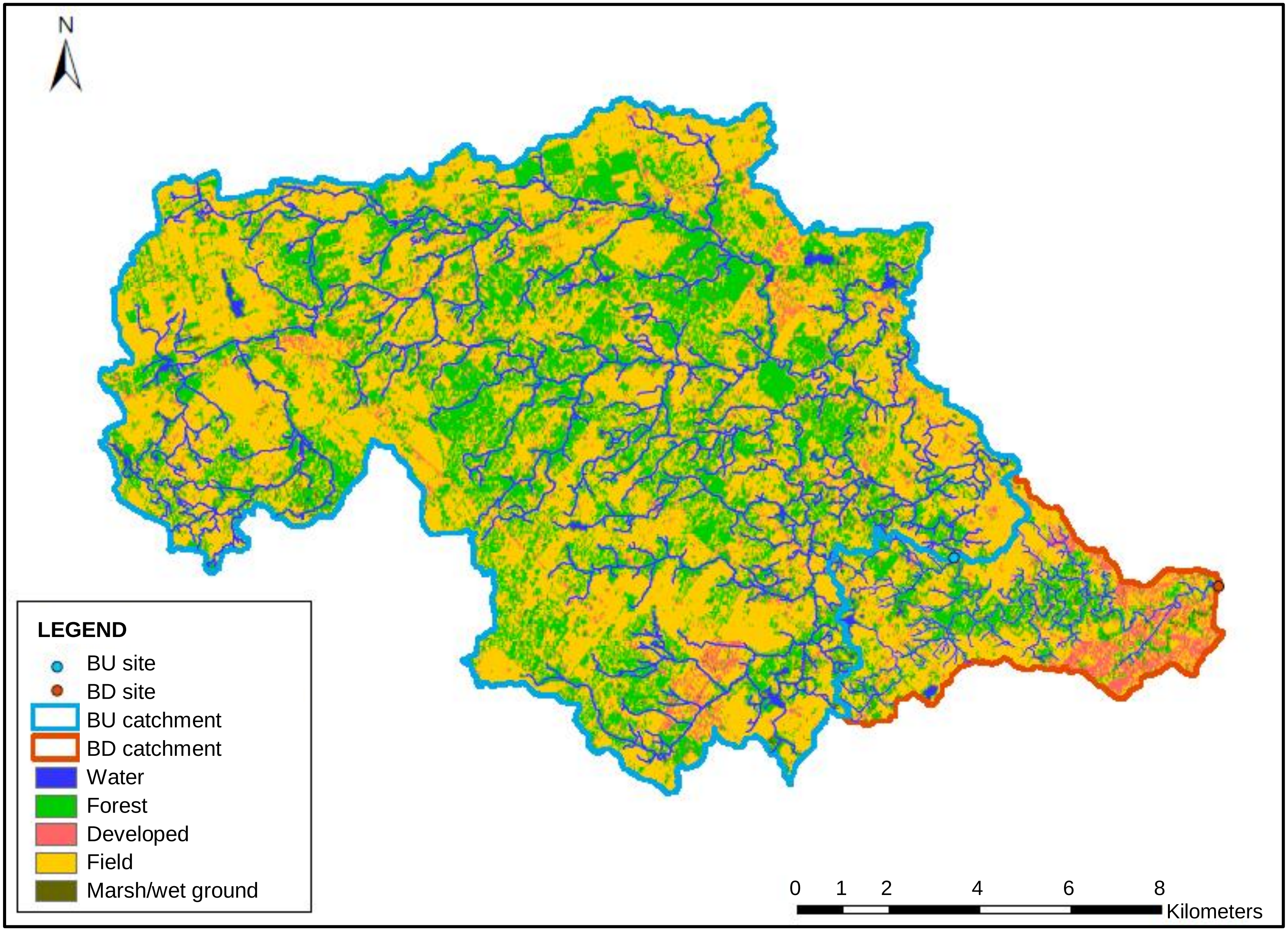

Figure 4.9: Land cover, Bolton downstream catchment area

Table 4.11: Percent (%) land cover type, all sites

	Caledon East		Palgrave		Bolton	
Land cover type	CU	CD	PU	PD	BU	BD
Developed	2.86	7.12	4.63	5.06	5.00	6.06
Water	0.11	0.28	0.61	0.63	0.64	0.65
Forest	32.91	33.11	32.14	32.04	33.27	32.37
Field	63.16	58.16	61.59	61.28	59.78	59.43
Marsh/wet	0.96	1.33	1.03	0.99	1.31	1.49

Table 4.10 shows the percent of total land cover occupied by each of the classification groupings and Table 4.11 shows the change in proportional land cover when moving from the upstream site to the downstream impacted by the development in between. An increase in developed land was noted at all locations at the downstream sites, affirming that sites were properly selected for the specific hypothesis testing this study. Downstream sites with suburban or town-type residential development pockets within their catchment result in an increase in developed surface cover compared with their upstream pairs. This implies that the developments are indeed affecting the surface cover and resultant permeability of the sites' drainage areas. This is reinforced by the figures, as the downstream specific catchment areas (i.e., areas not shared with upstream sites) have noticeably greater concentrations of pixels classified as developed. In addition, a decrease in the proportion of field land cover is noted when moving from the up to the downstream sites. Agricultural land use is dominant in this area, with about 30 to 50% of the drainage area of the sites as of 2013 (Ontario Ministry of Natural Resources and Forestry, 2013). Because of the increase in population and ensuing development downstream, it is likely that less land was zoned

Table 4.10: Percent (%) land cover change from upstream to downstream catchment area

Land cover type	Sites		
	Caledon East	Palgrave	Bolton
Developed	+4.26	+0.42	+1.06
Water	+0.17	+0.02	+0.01
Forest	+0.20	–0.10	–0.90
Field	–5.00	–0.31	–0.35
Marsh/wet	+0.37	–0.04	+0.19

for farming proportional to the total area, contributing to this decrease. An increase in the surface cover occupied by water is noted for all sites downstream, which is a logical product of the fact that there is a greater length of channel in the downstream catchment.

Changes in land use were also evaluated by location. The Caledon East sites produced the most significant changes in land use between the up and downstream sites. A 5% decrease in fields is nearly equivalent to the increase in developed land cover seen at the downstream site. These sites had the smallest drainage areas in the study by far, at 4.9 and 11.9 km^2 up and downstream respectively, with the next smallest site having a drainage area nearly 5.5 times larger than CD. As such, the inclusion of the residential suburb in the small catchment area causes the most significant and observable change in developed land cover of any site.

At the Palgrave site, land cover change downstream is the most minimal of any location. A minor gain of 0.42% in developed land, not even a half a percent of total cover, is noted at PD. By this account, the impact of the town of Palgrave should have a lesser impact on downstream channel morphology and hydrograph response than at Caledon East, and this is precisely what was seen in other results. By comparison, an overall change of 0.89% was noted between PU and PD for all land cover types combined, whereas land cover changed by 10.0% between CU and CD. A slight decrease in field and minimal decreases in forest and wet ground covers were produced by the analysis, as well as a minimal increase in the proportion of water surface cover. The small size of the Town of Palgrave and greater catchment area are likely contributing factors. The Palgrave and Caledon East developments span similar areas but since the catchment areas for the Palgrave sites are much larger, changes in proportional land cover caused by the presence of the town are far less significant.

Despite having the most developed land area and the suburb itself being larger than either Caledon East or Palgrave, Bolton showed a smaller proportional increase in developed land cover when moving from the upstream to the downstream site than Caledon East, with just over 1% increase. While the town and suburb from the other two study locations were included in the Bolton catchment area, as well as other roads, buildings, and minor developed areas, the drainage area for the Bolton sites was far larger than that of sites from the other locations. Examination of Figure 4.9 highlights this, where the densest concentration of developed land cover pixels is in the Bolton suburb, however, a large swath of land is added to the downstream catchment, including much undeveloped land, such as forest. As such, the proportion of the total catchment covered by developed land does increase but not by as significant an amount as Caledon East. The large drainage area in the upstream catchment and significant addition of area to the downstream is likely the cause of the very minimal increase in water area, the smallest proportional increase of any of the locations. Field and forest area both decreased, and marsh and wet ground increased by a small percent of total area at BD.

It is acknowledged that developed surface cover likely also entails a largely unseen stormwater management regime. This may include subterranean infrastructure, which cannot be evaluated or its impacts quantified by the land cover assessment. As such, the percent land cover types and downstream changes cannot be compared quantitatively to other changes seen downstream.

4.6 Bank vegetation

As part of the visual assessment of banks stability, vegetation cover and type were assessed at each of the sites.

At the Caledon East location, species diversity was very similar between the up and downstream sites. At CU, ten vascular plants were noted: native riverbank sedge (Carex emoryi), virgin's bower (Clematis virginiana), jewelweed (Impatiens capensis), Kentucky blue grass (Poa pratensis), and watercress (Rorippa Nasturtium-aquaticum), and invasive wild carrot (Daucus carota), purple loosestrife (Lythrum salicaria), bull thistle (Cirsium vulgare), wood squill (Scilla siberica), and common dandelion (Taraxacum officinale). Additionally, five varieties of tree were recorded as present: Manitoba maple (Acer negundo), white birch (Betula papyrifera), white ash (Fraxinus Americana), green ash (Fraxinus pennsylvanica), and non-native weeping willow (Salix babylonica). By comparison, CD had only slightly greater diversity. Twelve vascular plants were recorded: ragweed (Ambrosia artemisiifolia var. elatior), wild Angelica (Angelica sylvestris), common milkweed (Asclepias syriaca), riverbank sedge (Carex emoryi), spotted Joe-pye weed (Eutrochium maculatum), jewelweed (Impatiens capensis), wild mint (Mentha arvensis), watercress (Rorippa Nasturtium-aquaticum), climbing nightshade (Solanum dulcamara), rough-stemmed goldenrod (Solidago rugosa), calico aster (Symphyotrichum lateriflorum), and purple-stemmed aster (Symphyotrichum puniceum). Six tree varieties were seen: alternate-leaved dogwood (Cornus alternifolia), apple (Malus domestica), black willow (Salix nigra), black ash (Fraxinus nigra), green ash (Fraxinus pennsylvanica), and eastern white cedar (Thuja occidentalis). Only the climbing nightshade, a variety of vine, was invasive, while the other species, both vascular and tree, were native to southern Ontario.

An important factor in the abundance of invasive vasculars at the CU site stems from its location on private property. While the right bank consisted of dense tree cover and understory vegetation, with trees beyond the 5 m zone for classification, the left bank along the extent of the reach was regularly mowed and maintained by the property owner. While vegetation in the

Figure 4.10: Common dandelion (Taraxacum officinale), left, and purple loosestrife (Lythrum salicaria), right, at Caledon East upstream site

immediate bank area (1.0–1.5 m in from the channel) was usually left untouched, those grasses, sedges, and weeds beyond this thin buffer were mowed short to a few centimetres frequently over the study period. This regular disturbance could account for the noticeably higher proportion and abundance of invasive species at the downstream site compared to the upstream. As mentioned in section 2.5, disturbed areas promote the growth of invasive and ruderal species as they are quick to establish and outcompete native plants. At a glance, the fact that only 1/18 (5.6%) species identified in the riparian area of CD are not native to southern Ontario while nearly half of the identified species at CU, 6/15 (40.0%), were identified being invasive or non-native may give the impression that channel condition at the upstream site were causing bank instability and vegetation disturbance. If this were the case, the bank instability would allow for the establishment of invasive plant varieties. While disturbance along riparian corridors is often the product of erosive flow conditions and resultant bank instability, the difference in invasive and native plant compositions along the CU and CD banks is more likely the result of the regular disturbance of the left bank at the downstream site due to mowing and maintenance.

In-channel vegetation was noticeably more abundant at CU than CD, and was the most abundant of any study site per unit length. Some in-channel plants were clearly growing from the bed in near-bank areas, however, much more commonly, bank vegetation bled seamlessly from bank into the near-bank bed. This made the banks themselves less distinguishable or prominent from the actual channel along the whole of the reach. Watercress (Rorippa Nasturtium-aquaticum) was the most distinguishable and abundant species and was identified at both sites.

Excluding the mowed and maintained grasses and herbs on the left-bank at CU, the density of vegetation was comparable between the Caledon East sites. To the right of the channel at CU, dense tree cover and continuous understory vegetation comprised the range of visible surroundings. Field notes from the CD site remarked that very dense grasses and sedges, weeds, and wildflowers grew tall and tended to hang over the channel, especially along the left streambank. The density of vascular plants along the channel at the CD site may also be a direct result of planning decisions with regards to the nearby soccer fields. The reach sits approximately 50 m southeast of the Caledon East Soccer Complex and a dense stand of coniferous trees outlines the south end of the grounds. As such, pedestrian access to the channel at this particular site is most likely very minimal. Passers-by cannot readily see the channel through the trees and traversing down to the stream requires moving aside dense vegetation and walking between the closely spaced trees.

Generally speaking, the grasses and herbaceous plants found at the Caledon East downstream site were taller than those found at the upstream site. While much of the grass on the left bank at CU were mowed, most commonly Kentucky blue grass (Poa pratensis), the right bank remained visibly untouched over the numerous site visits that took place from May until November of 2016. Nevertheless, the maximum height of grass on the unmaintained right bank at CU remained shorter than those on each bank at CD at the peak of their vertical growth, growing to around 1.5 m as opposed to about 2.0 m downstream. This is most likely to do with shading by trees at the sites. At CU, two tall deciduous trees, a white ash (Fraxinus Americana) and green ash (Fraxinus pennsylvanica), were located within 5 m of the stream channel on the right bank. White birch (Betula papyrifera), Manitoba maple (Acer negundo), and the non-native weeping willow (Salix babylonica) trees were present along the bank causing shade to be cast on the channel and banks during sunlight hours. On the other hand, at CD, trees caused no impact on shading on the left bank and confers seen beyond the right bank were far enough away and less full than those deciduous trees at CU. In the downstream half of the reach, almost no trees were situated within 5 m of the channel. Only one tree was present on the left bank. In the upstream half there was approximately between a half and a third of the ground shaded by the canopy. With the tallest grasses occurring in the downstream half of the CD reach having a greater proportion of direct sunlight, the grasses were likely able to grow higher at the downstream site as a result of a lack of canopy shading. As such, the difference in growth between the grasses at the two sites is not attributed to streambank stability conditions.

The diversity, abundance, and growth of vascular plant and tree species was similar in many regards between the two Caledon East sites, showing no obvious indication of the impact of bank instability on the riparian vegetation community. Additionally, prominent distinctions between CU and CD are probably the cause of factors other than channel bank degradation due to the impacts of the urban stream syndrome.

Looking at the up and downstream sites at the Palgrave location, species diversity differed greatly. While each had four varieties of trees identified, the diversity of vascular plants was significantly greater at PU. With regard to trees, white birch (Betula papyrifera), ironwood (Ostrya virginiana), black spruce (Picea mariana), and eastern white cedar (Thuja occidentalis) were identified at PU, while alternate-leaved dogwood (Cornus alternifolia), green ash (Fraxinus pennsylvanica), and an abundance of eastern white cedar (Thuja occidentalis) and eastern hemlock (Tsuga canadensis) were seen at PD. However, while only one variety of vascular was identified at the downstream site, ostrich fern (Matteuccia struthiopteris), six species were identified at PU: wild Angelica (Angelica sylvestris), riverbank sedge (Carex emoryi), jewelweed (Impatiens capensis), watercress (Rorippa Nasturtium-aquaticum), broadleaf arrowhead (Sagittaria latifolia), and arrowleaf arrowhead (Sagittaria cuneate). In addition, grasses were sighted at PD, especially on the right bank, but their varieties were not distinctly identified in the field or from photographs. Both sites had grasses present though their precise varieties were not identified. All of the identified varieties of vegetation present, both vascular and tree, were native to southern Ontario.

With regards to abundance, the two Palgrave sites were similar but showed some specific differences. The PU banks were entirely covered and protected by grasses, weeds, and wildflowers over the whole reach length. No patches of ground remained bare or exposed. The right bank was covered primarily in grasses and weeds and this ground vegetation cover was slightly sparser than that of the left bank. On the left bank of the channel, heavy tree coverage caused the understory grasses to be largely shaded. In contrast, bank vegetation varied from bank to bank over the PD site. Vegetation on the left bank was more or less continuous and the right bank had patches of less dense or non-existent vegetation. PD had a greater abundance of trees and tree shading than any other site, with an approximate 70/30 ratio of conifers to deciduous trees in the riparian zone.

PD was also unique with regards to vegetation in that it was the only site from any of the three locations to have had a greater proportion of coniferous trees as opposed to deciduous. Ferns dominated the understory with some sparse grasses present but no other notable vasculars identified. Another difference between the two sites arose from the proximity of trees to the watercourse. The channel at PU was relatively open with little shading by trees, especially in the downstream half of the reach. While the upstream end of the reach had some shading from trees on each bank, the downstream half had shade from only a few trees and only on the left bank. In contrast, the entire reach length at PD was very well shaded by dense tree cover. Neither site had significant aquatic vegetation. While no in-channel vegetation was noted at PU, very little was recorded at PD. These were very small and scarce, found only in a few areas of channel sheltered from the main flow by root masses or deep bank scallops. They played little role in the principal flow or in stabilization of any kind.

While vegetation abundance seems to be governed in part by proximity to the nearby roadways, the Palgrave sites seem to suggest that their patches with significantly less vegetation abundance were a result of channel stability conditions. Each of the sites was located near a roadway for ease of access during fieldwork, with PU approximately 15 m and PD approximately 45 m from the nearest paved road surface, each with the road situated to the right of the channel. The grasses covering the ground surface on the right bank appeared slightly but noticeably sparser than the left bank. This suggests that the vegetation on the right side of the channel could have been impacted by its presence. At PD, however, the left and right banks seemed to have relatively equal abundance. No visible impacts of the site’s proximity to the road were apparent in the immediate (5 m) riparian area. The only spots that were anomalous to the abundance in vegetation cover at PD were along the right bank immediately next to the channel in places where the bank had shown signs of recent disturbance resulting from bank erosion. There, vegetation was far sparser. Where vegetation did exist, individuals were much younger. This appeared to have directly impacted the riparian vegetation. Bank and riparian condition show a link between bank instability and a decreased abundance of herbaceous vegetation.

Vegetation growth was similar between the Palgrave sites. Comparison between vascular plant growth is difficult because of the variety of species found at each site. PU, which was largely dominated by grasses and herbaceous varieties, cannot be directly compared with PD, where the majority of the understory was comprised of ferns. This is because the plants do not grow at the same rates or to nearly the same size and height. Trees at both sites were quite tall and mature. Since PD had much denser tree cover, it also had many more young saplings than PU as a result. The abundance of trees would result in more seeds dropped and new individuals establish in the understory more readily.

Another marked difference between the Palgrave sites is in the abundance of exposed roots seen at PD. In numerous places, PD had exposed roots from vascular plants and trees in and near the streambank. Thin roots were observed exposed from understory fern individuals as well as large, partial root masses from both dead and live trees. Due to their proximity to the watercourse, exposed roots from vascular and tree individuals seemed to be a product of soil erosion by potential high and overbank channel flows or of bank material loss due to instability. This phenomenon did not seem to affect vegetation at PU.

While the growth of vegetation was comparable between the sites, the disparity in diversity between upstream and downstream and the presence of vegetation features impacted by channel bank instability (i.e., patches of decreased abundance or newly established vasculars, presence of exposed roots) indicate that PD had reduced overall bank stability when compared with its PU counterpart. This bank instability could be caused by erosive channel conditions symptomatic of the urban stream syndrome.

In examining the riparian vegetation community at Bolton, though species diversity was somewhat similar between the two sites, the downstream site exhibited the presence of more invasive vascular species than its upstream counterpart. At BU, many ferns were noted in the immediate bank area and were the most common plant variety on the forest floor. Additionally, the following native vasculars were identified: grasses and sedges (Carex spp.), red baneberry (Actaea rubra), great Angelica (Angelica atropurpurea), common burdock (Arctium minus), water hemlock (Cicuta maculate), Riverbank wildrye (Elymus riparius), White Snakeroot (Eupatorium rugosum), jewelweed (impatiens capensis), ostrich Fern (Matteuccia struthiopteris), wild mint (Mentha spp.), sensitive fern (Onoclea sensibilis), Kentucky bluegrass (Poa pratensis), watercress (Rorippa nasturtium-aquaticum), wild red raspberry (Rubus idaeus ssp. Melanolasius), broadleaf arrowhead (Sagittaria latifolia), arumleaf arrowhead (Sagittaria cuneata), rough-stemmed goldenrod (Solidago rugosa), New York aster (Symphyotrichum novi-belgii), and eastern poison ivy (Toxicodendron radicans). Beyond the native species, the following invasive vasculars were identified: goutweed (Aegopodium podagaria), butterbur (Petasites japonicus), and the aggressive Phragmites reed (Phragmites australis ssp. australis). The downstream site had a similar number of vascular species identified, with 18 compared to 22 at BU. The primary difference in abundance between the sites came in the proportion of invasive species. The composition of vegetation at BD was largely tall grasses, and as a whole, species diversity with regards to the proportions of other types of vegetation was noticeably greater at BU. The following native vascular were identified at BD: grasses (Poaceae), common burdock (Arctium minus), rice cut grass (Leersia oryzoides), smooth brome (Bromus commutatus), broadleaf arowhead (Sagittaria latifolia), arumleaf arrowhead (Sagittaria cuneata), stinging nettle (Urtica dioica), riverbank sedge (Carex emoryi), Joe-pye weed (Eutrochium maculatum), wild Angelica (Angelica sylvestris), wild grape vine (Vitis riparia), and common cocklebur (Xanthium strumarium). An additional six invasive vasculars were seen: garlic mustard (Alliaria petiolata), wild carrot (Daucus carota), bull thistle (Cirsium vulgare), prickly lettuce (Lactuca serriola), tartarian honeysuckle (Lonicera tatatica), and purple loosestrife (Lythrum salicaria). BD had 6/18 (33.3%) invasive identified vascular species, while BU only had 3/22 (13.6%) by comparison. While BD was closer to private property, neither site had banks that were actively disturbed or altered, unlike in the case of CU. With this knowledge, the variance in the presence of invasive vascular varieties at BD could be indicative of bank stability conditions.

When evaluating the tree species diversity at the two Bolton sites, the context within which each site is situated likely plays a greater role than stability conditions. Tree cover at BU, as with most sites in this study, was comprised of more deciduous than coniferous tree varieties. Trees were very large and mature, as the site was situated in a forested area along the Humber Valley Heritage Trail. There, red maple (Acer rubrum), sugar maple (Acer saccharum), green ash (Fraxinus pennsylvanica), black walnut (Juglans nigra), eastern white cedar (Thuja occidentalis), and eastern hemlock (Tsuga canadensis) were present. Common buckthorn (Rhamnus cathartica) was the only invasive tree identified. At BD, most trees were also deciduous, especially on left bank, and tree cover was much less dense than at BU. Most tree species at BD were native: white birch (Betula papyrifera), green ash (Fraxinus pennsylvanica), ironwood (Ostrya virginiana), balsam poplar (Populus balsamifera), staghorn sumac (Rhus typhina), red currant (Ribes rubrum), black willow (Salix nigra), eastern white cedar (Thuja occidentalis), and eastern hemlock (Tsuga canadensis). Invasive common buckthorn (Rhamnus cathartica) and non-native Siberian crab apple

(Malus baccata) were also present at BD. While the density of tree cover was far less, a great variety of trees was seen downstream. Due to its closer proximity to private properties, with houses just on the opposite side of a small road, the variety of tree species seen at BD may be the result of selected tree planting. The presence of Siberian crab apple, an ornamental tree often used in landscaping, hints at this.

Proximity to private dwellings restricts the conclusions that can be drawn about bank stability at BU and BD from the growth of vegetation. The BU site seemed pristine, without significant anthropogenic alteration in any way. Trees grew very large, the tallest and broadest of any site, and the vascular plant community was tall and healthy. Grasses grew taller in many places at BD, likely because of the sparse tree cover unlike the dense shading seen at BU. Taller grasses in the riparian zone at BD cannot be concluded to be the result of greater bank stability, as shading played an obvious role in growth over the field season.

While abundance and growth of the vegetation assemblages found along the riparian corridors of the Bolton sites cannot be used to draw inferences about bank stability, as these factors were likely affected by the sites' proximities to private properties, the noticeably greater presence and proportion of invasive vascular species at BD indicate disturbance of the banks. As such, this points to the potential of lesser bank stability at the downstream site.

CHAPTER FIVE: DISCUSSION

5.1 Thoughts on Bolton discharge anomaly

Due to its local geological context, uncertainty about the degree to which it is engineered by water management schemes, and the presence of known major water withdrawal locations, it is suspected that a losing reach exists between the Bolton up and downstream sites.

Upon examining the streamflow results for the Bolton sites, it was apparent that the estimates for instantaneous discharge did not follow a typical, natural pattern, where the downstream site had significantly lower discharge than its upstream counterpart. If the patterns for discharge were very different the error could then reasonably be attributed to technical issues. For example, if the data were greatly out of phase, one dataset showed a consistent lack of response to precipitation inputs, one showed odd fluctuations in baseflows, etc. Since flow from BU fed the BD site, being along the same channel, and the sites had very similar, nearly mirrored patterns for discharge over the time series, it was suspected that some phenomenon was controlling this anomaly rather than a simple device error with the water level dataloggers.

Data from BD show signs that the flow is possibly regulated in some way. For a time, the presence of a dam between the two sites was suspected to be causing complication in the data. In speaking directly with TRCA staff, including a planner, hydrogeologist, and technicians, it was concluded that the dam was notched some decades ago and since then has not had a significant impact on flow downstream. The dam is shown in Figure 5.1. The TRCA staff theorized that the only time the dam would have any impact at all would be during very high flows, and even then, the impact would be minimal. It is known that nine tributaries join the reach downstream of BU


Figure 5.1: Dick's Dam, Bolton, upstream of Bolton downstream site

before the dam and another stream joins downstream of the dam before BD. These could act as confounding factors to determining differences between flow at the sites but should do more to increase flows at BD rather than decrease them.

Complications to natural baseflow levels can be caused both by natural and anthropogenic losses and the magnitude of such losses can accumulate to cause a losing reach of stream. Rivers are most commonly classified as gaining, where inputs to the stream exceed losses and result in greater discharge moving downstream. However, in certain circumstances reaches may pass over aquifers that draw down significant quantities of water. In cases where the loss to the underlying aquifers are greater than the accumulation of flow inputs, the lower downstream discharge causes a naturally occurring losing reach (Baillie et al., 2007). Additional natural discharge losses include direct evaporation from the surface of the river or from other linked surface water features, vegetation transpiration, wetting of the bank or alluvial sediment deposits, or the aggregation of any number of these processes (Smakhtin, 2001). Anthropogenic use and water management schemes can alter the regime of baseflows. This is especially significant in settings with populations that rely on rivers. Agricultural irrigation, household water supply, and industrial uses are common sources for urban baseflow reductions (Brodie and Hostetler, 2005). With jurisdiction over the Humber watershed, TRCA has had to put in place guidelines for minimum baseflow levels to prevent overdraw of water from these activities and more and protect the health of the Humber River and watershed. Management activities can include diversion of flow to other channels as part of a greater basin water management plan and surface and regulated withdrawal of ground and surface water for consumption. Natural, anthropogenic, or a combination of both factors could contribute to a losing reach.

Figure 4.9 showed land cover in the BD catchment and further analysis can be given to the area between the up and downstream sites, which comprise the catchment specific to BD. Groundwater flow in this aquifer is generally downward, where water seeps vertically into the Oak Ridges Moraine below. Not only is the reach between BU and BD in a groundwater recharge zone, the amount of recharge has remained high amidst a decrease in recharge in surrounding areas (Toronto and Region Conservation Authority, 2008_a). So, the ground here is actively taking in surface water and potentially from the wetted perimeter of the channel, as well. In conferring with TRCA staff, they confirmed that groundwater recharge happens through the upper portions of the Main Humber and that it is patchy. However, in reports, rates are presented for the entire subwatershed. This could be an area of higher recharge than is represented with these generalized rates, possibly enough to contribute to a losing reach. Maps from the OFAT III from the Ministry of Natural Resources and Forestry show the presence of wetlands in the wooded areas along the channel between the Bolton sites, lending to this hypothesis.

Permits to draw surface and groundwater exist between the Bolton sites, hence, affecting the catchment of only BD, and as such, could present more insight into to the possibility of a losing reach between the sites. The Ontario Ministry of Environment regulates the approval of water withdrawal from the Humber, with permits allowing for the withdrawal and use of over 50 000 L daily from 262 individual withdrawals, where 42% are for agriculture, 30% commercial (primarily golf courses), 18% water supply, and less than 5% combined for livestock, recreational, and miscellaneous use (Toronto and Region Conservation, 2008$_c$). Three such permits are located between the Bolton sites, as shown in Figure 5.2, accounting for a maximum of over a million litres for agriculture and 6 546 384 L for commercial daily maximum withdrawals. The agricultural use, for field and pasture crops, does not return the majority of drawn water back to the local

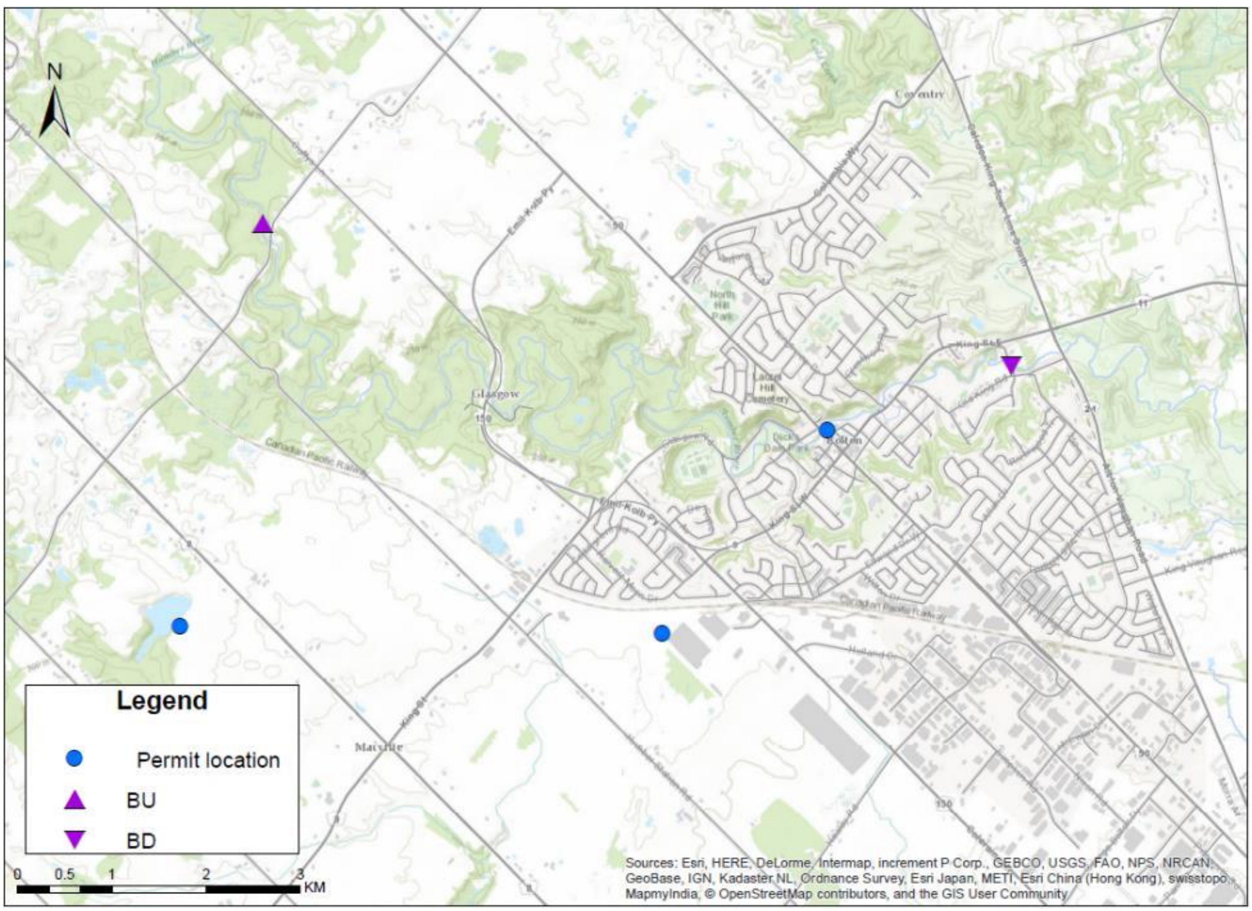

Figure 5.2: Location of water withdrawal permits, Bolton downstream drainage area

system, where between 78 and 90% is consumed by evapotranspiration (Conservation Ontario, 2003). As such, this water is a huge loss to the streams in the catchment and would certainly cause significant loss to the downstream site. Withdrawals occur most often between precipitation episodes primarily driven by agricultural use, where dry periods require irrigation and the Humber is used as the source (Toronto and Region Conservation, 2008_c). However, only the maximum withdrawal limit is known. Once permits are granted, permit holders must report the daily amount taken and this information is kept confidential by the provincial government under Regulation 387/04 and is not publicly available (Ontario Ministry of Environment, 1990). So, precise volumes drawn from the system and temporal records of the extractions are not monitored, therefore, public data regarding the specifics of water withdrawal do not exist (Toronto and Region Conservation, 2008_c). For the purposes of this work, the maximum allowance for withdrawal is the best metric that can be used to compare with recorded water level and estimated flow. With this, the maximum withdrawal is 7742.7 m^3/day or 0.11 m^3/s. This pales in comparison to the average 3.44 m^3/s lower discharge at the downstream site. As such, permitted water withdrawals cannot solely explain the lower discharge at BD. Nevertheless, these known withdrawals could be a component in a range of factors causing a losing reach between the sites. The impact of additional unknown, illegal withdrawals may also contribute, but it cannot be known to what degree.

5.2 Beyond land cover

Data and ensuing results for the Bolton paired sites also call into question the use of catchment land cover or other similar metrics, such as total catchment imperviousness (TI), more or less in isolation in studies of the urban or suburban streams. Comparing the results attained between the Bolton and Caledon East locations is useful in illustrating that there may be something more at play.

Though having different downstream land cover changes, flow at BD and CD had similar features. The percent of developed land was less at BD than CD and the change between the upstream and downstream sites at Bolton was far less dramatic than at the Caledon East sites. Nevertheless, there is an obvious anthropogenic influence on flow illustrated by the time series of flow metrics and storm hydrograph analysis. Visually, BD acts like streams affected by urban areas and classified under the urban stream syndrome heading. However, the degree of change between the Bolton sites and quantification of developed land cover is not so stark as Caledon East, which also showed downstream changes but not nearly so pronounced. Further complicating this is the Bolton discharge anomaly, discussed in the previous section, where BD should logically have greater flows than its upstream counterpart in general but does not.

Two additional factors are identified as being at play regarding the hydrologic and geomorphic impacts to channels in developed, suburbanized catchments that are not quantified or accounted for directly or precisely in discussion of the impact of changing land cover. Firstly, the varying degrees of impact attributed to developed and non-developed land in different parts of the streams' specific subcatchment were not defined. The percent of developed land cover was attained for the entire catchment area draining into each site. It is reasonable to conclude that developed land nearer to the channel itself would be more impactful on the flow regime especially during precipitation events and would be more effective in acting as a direct path from surface to channel. Conversely, impervious or less permeable surface cover further away from the channel may also generate more surface runoff than types of undeveloped land cover. More permeable land between this and the channel would likely create an opportunity for that water travelling overland to be absorbed, at least in part, before reaching its terminus at the stream. Near channel vegetation was accounted for in this study, but near channel land use over the length of the study reaches and over the length of the channel and its tributaries were not. In future studies, this may provide greater insight into the varying degrees of impact that developed land can have within a given catchment.

Secondly, while their presence has been acknowledged, the exactitude of impact exerted by stormwater management schemes and channel engineering have not been accounted for. This would likely illuminate a great deal more about anthropogenic impacts on stream channel stability and health. Within the practical and logistical confines of this research, stormwater management plans and subsurface and above ground infrastructure were not sought. However, it was acknowledged that due to the relatively young age and large population of the developments, stormwater management practices would almost certainly be in place to some degree and acting on the channels studied. This is especially relevant for Caledon East and Bolton. While that knowledge informed this study and the interpretation of data analysis, the precise impacts of stormwater management systems are vital to understand how development affects flow and morphology in the rivers that drain those areas beyond its impact on surface permeability. Detailed mapping of stormwater infrastructure, quantification of input to or diversion of flow away from the channel, volume of water retained in stormwater ponds, and other quantifiable elements of stormwater management and its impact on channel flow would be integral in further studies on the effect of urban and suburban areas on the fluvial system.

CHAPTER SIX: SUMMARY

The primary objective of this study was to assess whether select geomorphic and hydrologic changes associated with the urban stream syndrome would also be observed in lower intensity development contexts in towns and suburbs in the Town of Caledon northwest of the City of Toronto.

The study found symptomatic changes in discharge patterns seen in urban areas downstream of Caledon East, the site with the greatest proportional increase in developed land cover compared with its upstream counterpart. Though visible differences in geomorphic stability between the paired sites could not confidently be linked to the presence of the suburban development, differences in discharge patterns and response to precipitation between the Caledon East sites are markers of urban stream syndrome-type impacts.

While observations at Palgrave showed some differences in vegetation cover between sites characteristic of urban streams, hydrology data did not support the conclusion that the low-density residential development had a significant and notable impact on the headwater stream. Minimal difference between the proportions of developed land cover at the Palgrave sites and the lack of hydrograph distinction between them did not strongly indicate the town had a significant impact on proportional land use, and hydrology data reinforces that this minimal difference was not enough to produce noticeable change.

Anomalous water level and estimated discharge at the Bolton downstream site complicated analysis of the hydrograph at BD and any potential inferences about the suburb's impact on the river system. Geomorphic changes were noted between the paired sites and the vegetation communities were notably different. Despite the consistently low discharge at the downstream site, response to precipitation was significantly greater at the site downstream of the suburbanized areas. It is suggested that further study be conducted to determine whether the presence of a losing reach of channel or stormwater engineering practices are heavily affecting flow in Bolton.

The urban stream syndrome affects channels in urbanized catchments but can be triggered in far less intense development contexts with minimal urbanized surface cover (Hawley et al., 2012). The mechanisms by which geomorphic and hydrologic change are instigated in true urban areas are similar in exurban type areas. This research was conducted using a relatively innovative approach for academic river studies. While spatial comparison is commonly accepted practice in engineering studies, academic research in river studies have almost solely employed temporal comparisons using historic imagery and aerial photographs to infer about the impacts of land use change. Contrasting stability features and quantitative hydrology between upstream reference reaches and those corresponding downstream reaches impacted by low-density residential development allowed for insight into the impacts of suburban-type development in Caledon on Humber headwater streams.

Based on this experimental use, it is not recommended that pocket penetrometers be used in evaluating bank soil strength. Some penetrometers have an adapter available for additional purchase for the purpose of use on extremely low strength cohesive soils. These increase the effective area of the measurement, allowing for a greater strength to be measured to then be divided by a factor specific to the adapter in order to attain a more accurate reading. This may improve the accuracy of use in this context, and further, it is recommended that trials be conducted on the use of penetrometers with such adapters in the context of bank soil strength testing.

A large body of research exists focusing on dense urban areas, defining symptomatic changes associated with the urban stream syndrome. However, little research of this kind has been conducted in exurban areas, such as towns and suburbs. To broaden the scope of literature on the urban stream syndrome, it is suggested that more research be conducted in less intense development contexts such as those in this study.

REFERENCES

Abernethy, B., & Rutherfurd, I. D. (2001). The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological processes, 15*(1), 63-79.

Adams, J. A., Endo, A. S., Stolzy, L. H., Rowlands, P. G., & Johnson, H. B. (1982). Controlled experiments on soil compaction produced by off-road vehicles in the Mojave Desert, California. *Journal of Applied Ecology*, 167-175.

Andrews, E. D. (1980). Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. *Journal of Hydrology*, *46*(3), 311-330.

Andrus, C. W., Long, B. A., & Froehlich, H. A. (1988). Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. *Canadian Journal of Fisheries and Aquatic Sciences, 45*(12), 2080-2086.

Annable, W. K. (1996). *Morphologic relationships of rural watercourses in Southern Ontario and selected field methods in fluvial geomorphology*. Ontario Ministry of Natural Resources.

Annable, W. K., Watson, C. C., & Thompson, P. J. (2012). Quasi-equilibrium conditions of urban gravel-bed stream channels in southern Ontario, Canada. *River research and applications, 28*(3), 302-325.

Arcement, G. J., & Schneider, V. R. (1989). Guide for selecting Manning's roughness coefficients for natural channels and flood plains. *US Geological Survey Water-Supply Paper, 2339*. United States Government Printing Office.

Arnold, C. L., Boison, P. J., & Patton, P. C. (1982). Sawmill Brook: an example of rapid geomorphic change related to urbanization. *Journal of Geology, 90*, 155-166.

Auble, G. T., Friedman, J. M., & Scott, M. L. (1994). Relating riparian vegetation to present and future streamflows. *Ecological applications, 4*(3), 544-554.

Baillie, M. N., Hogan, J. F., Ekwurzel, B., Wahi, A. K., & Eastoe, C. J. (2007). Quantifying water sources to a semiarid riparian ecosystem, San Pedro River, Arizona. *Journal of Geophysical Research: Biogeosciences, 112*(G3), 1-13.

Baker, V. R. (1977). Stream-channel response to floods, with examples from central Texas. *Geological Society of America Bulletin, 88*(8), 1057-1071.

Barnett, P. J., Sharpe, D. R., Russell, H. A. J., Brennand, T. A., Gorrell, G., Kenny, F., & Pugin, A. (1998). On the origin of the Oak Ridges Moraine. *Canadian Journal of Earth Sciences, 35*(10), 1152-1167.

Barrett, S. (2007). *Rouge River Watershed Plan: Towards a Healthy and Sustainable Future* (Rep.). Toronto, ON: Toronto and Region Conservation.

Beeson, C. E., & Doyle, P. F. (1995). Comparison of bank erosion at vegetated and non-vegetated channel bends. *Journal of the American Water Resources Association, 31*(6), 983-990.

Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., & Galat, D. (2005). Synthesizing US river restoration efforts. *Science, 308*(5722), 636-637.

Bhaduri, B., Harbor, J. O. N., Engel, B., & Grove, M. (2000). Assessing watershed-scale, long-term hydrologic impacts of land-use change using a GIS-NPS model. *Environmental management, 26*(6), 643-658.

Bilby, R. E. (1981). Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology, 62*(5), 1234-1243.

Bilby, R. E., & Likens, G. E. (1980). Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology, 61*(5), 1107-1113.

Bilby, R. E., & Ward, J. W. (1989). Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society, 118*(4), 368-378.

Bledsoe, B. P., Watson, C. C. (2001). Effects of urbanization on channel instability. *Journal of the American Water Resources Association, 37*(2), 255-270.

Booth, D. B. (1990). Stream-channel incision following drainage-basin urbanization. *Journal of the American Water Resources Association, 26*(3), 407-417.

Booth, D. B. (1991). Urbanization and the natural drainage system impacts, solutions and prognoses. *The Northwest Environmental Journal, 7*, 93-118.

Booth, D. B., & Jackson, C. R. (1997). Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association, 33*(5), 1077-1090.

Braca, G. (2008). *Stage-discharge relationships in open channels: Practices and problems*. Univ. degli Studi di Trento, Dipartimento di Ingegneria Civile e Ambientale.

British Standards Institution (1975). British standard methods for sampling and testing of mineral aggregates, sands and fillers. Part 1. Sampling, size, shape and classification. *BS 812 Part I: 1975.*

Brodie, R. S., & Hostetler, S. (2005, November). A review of techniques for analysing baseflow from stream hydrographs. In *Proceedings of the NZHS-IAH-NZSSS 2005 conference* (Vol. 28). Auckland New Zealand.

Burcher, C. L., & Benfield, E. F. (2006). Physical and biological responses of streams to suburbanization of historically agricultural watersheds. *Journal of the North American Benthological Society, 25*(2), 356-369.

Burgess, S. S., Adams, M. A., Turner, N. C., White, D. A., & Ong, C. K. (2001). Tree roots: conduits for deep recharge of soil water. *Oecologia*, *126*(2), 158-165.

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., & Kendall, C. (2005). Effects of suburban development on runoff generation in the Croton River basin, New York, USA. *Journal of Hydrology, 311*(1), 266-281.

Buttle, J. M. (1994). Hydrological response to reforestation in the Ganaraska River basin, southern Ontario. *The Canadian Geographer, 38*(3), 240-253.

Buttle, J. M. (1995). Channel changes following headwater reforestation: the Ganaraska River, Ontario, Canada. *Geografiska Annaler. Series A. Physical Geography*, 107-118.

Carter, R. W. (1961). Magnitude and frequency of floods in suburban areas in short papers in the geologic and hydrologic sciences. *Geological Survey Research Article, 5*: B9–B12.

Chapman, L. J., & Putnam, D. F. (1984). The Physiography of Southern Ontario. Ontario Geological Survey Special Volume, 2. *Toronto: Ontario Ministry of Natural Resources*, 2715.

Cheng, Q., Russell, H., Sharpe, D., Kenny, F., & Qin, P. (2001). GIS-based statistical and fractal/multifractal analysis of surface stream patterns in the Oak Ridges Moraine. *Computers & Geosciences, 27*(5), 513-526.

Clary, W. P. (1995). Vegetation and soil responses to grazing simulation on riparian meadows. *Journal of Range Management*, 18-25.

Cohen, J. E. (2003). Human population: the next half century. *Science, 302*(5648), 1172-1175.

Collison, A. J. C., & Anderson, M. G. (1996). Using a combined slope hydrology/stability model to identify suitable conditions for landslide prevention by vegetation in the humid tropics. *Earth Surface Processes and Landforms, 21*(8), 737-747.

Conservation Ontario (2003). *A Framework for Local Water-Use Decision-Making in a Watershed Basis*. Government of Ontario.

Curran, J. C. (2010). Mobility of large woody debris (LWD) jams in a low gradient channel. *Geomorphology, 116*(3), 320-329.

Curran, J. C., & Hession, W. C. (2013). Vegetative impacts on hydraulics and sediment processes across the fluvial system. *Journal of Hydrology, 505*, 364-376.

Curran, J. H., & Wohl, E. E. (2003). Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology, 51*(1), 141-157.

Darby, S. E., & Thorne, C. R. (1996). Development and testing of riverbank-stability analysis. *Journal of Hydraulic Engineering, 122*(8), 443-454.

Dingman, L. (2002). *Physical Hydrology*. 2nd edition. Upper Saddle River, New Jersey: Prentice Hall.

Doll, B. A., Wise-Frederick, D. E., Buckner, C. M., Wilkerson, S. D., Harman, W. A., Smith, R. E., Spooner, J. (2002). Hydraulic geometry relationships for urban streams throughout the Piedmont of North Carolina. *Journal of the American Water Resources Association, 38*(3), 641-651.

Doyle, M. W., Harbor, J. M., Rich, C. F., & Spacie, A. (2000). Examining the effects of urbanization on streams using indicators of geomorphic stability. *Physical Geography, 21*(2), 155-181.

Drnevich, V. P., Gorman, C. T., & Hopkins, T. C. (1974). Shear strength of cohesive soils and friction sleeve resistance. *European Symposium on Penetration Testing*. Stockholm: Sweden.

Dunne, T., & Leopold, L. B. (1978). *Water in environmental planning*. W. H. Freeman and Company, San Francisco, California.

Durocher, M. G. (1990). Monitoring spatial variability of forest interception. *Hydrological Processes, 4*(3), 215-229.

Dyhouse, G. R. (1982). Sediment analyses for urbanizing watersheds. *Journal of the Hydraulics Division, 108*(3), 399-418.

Edey, R. C., Seasons, M., & Whitelaw, G. (2006). The media, planning and the Oak Ridges Moraine. *Planning, Practice & Research, 21*(2), 147-161.

Ellenberg, H. (1988). Tree and shrub vegetation of floodplains and peat lands. In *Vegetation ecology of Central Europe*. (243-282). Cambridge: Cambridge University Press.

Ferreira, C. S. S., Ferreira, A. J. D., Pato, R. L., Magalhães, M. D. C., Coelho, C. D. O., & Santos, C. (2012). Rainfall-runoff-erosion relationships study for different land uses, in a sub-urban area. *Zeitschrift für Geomorphologie, Supplementary Issues, 56*(3), 5-20.

Finnegan, N. J., Roe, G., Montgomery, D. R., & Hallet, B. (2005). Controls on the channel width of rivers: Implications for modeling fluvial incision of bedrock. *Geology, 33*(3), 229-232.

Gerber, R. E., & Howard, K. (2002). Hydrogeology of the Oak Ridges Moraine aquifer system: implications for protection and management from the Duffins Creek watershed. *Canadian Journal of Earth Sciences, 39*(9), 1333-1348.

Gippel, C. J., Finlayson, B. L., & O'Neill, I. C. (1996). Distribution and hydraulic significance of large woody debris in a lowland Australian river. *Hydrobiologia, 318(*3), 179-194.

Goudie, A. (Ed.). (1990). *Geomorphological Techniques*. London: Routledge.

Government of Ontario, 2002. Oak Ridges Moraine Conservation Plan. Toronto: Ontario Ministry of Municipal Affairs. http://www.mah.gov.on.ca/page1707.aspx.

Hamilton, G. W., & Waddington, D. V. (1999). Infiltration rates on residential lawns in central Pennsylvania. *Journal of soil and water conservation, 54*(3), 564-568.

Hawley, R. J., Bledsoe, B. P., Stein, E. D., & Haines, B. E. (2012). Channel Evolution Model of Semiarid Stream Response to Urban-Induced Hydromodification. *Journal of the American Water Resources Association*, *48*(4), 722-744.

Hey, R. D. (1978). Determinate hydraulic geometry of river channels. *Journal of the Hydraulics Division*, *104*(ASCE 13830).

Henshaw, P. C., Booth, D. B. (2000). Natural restabilization of stream channels in urban watersheds. *Journal of the American Water Resources Association, 36*(6), 1219-1236.

Hollis, G. E. (1975). The effect of urbanization on floods of different recurrence interval. *Water Resources Research*, *11*(3), 431-435.

Hogan, D. L. (1987). The influence of large organic debris on channel recovery in the Queen Charlotte Islands, British Columbia, Canada. *IAHS-AISH publication*, (165), 343-353.

Hultine, K. R., Scott, R. L., Cable, W. L., Goodrich, D. C., & Williams, D. G. (2004). Hydraulic redistribution by a dominant, warm-desert phreatophyte: Seasonal patterns and response to precipitation pulses. *Functional Ecology, 18*(4), 530-538.

Hupp, C. R. (1983). Vegetation pattern on channel features in the Passage Creek Gorge, Virginia. *Castanea*, 62-72.

Hupp, C. R. (1992). Riparian vegetation recovery patterns following stream channelization: a geomorphic perspective. *Ecology*, *73*(4), 1209-1226.

Hupp, C. R., & Osterkamp, W. R. (1996). Riparian vegetation and fluvial geomorphic processes. *Geomorphology, 14*(4), 277-295.

International Standards Organisation (1977). Liquid flow measurement in open channels-bed material sampling. *IS0 4364-1977(E).*

International Standards Organisation (2006). Soil quality – Pretreatment of samples for physico-chemical analysis. *ISO 11464-2006(E).*

International Standards Organisation (2009). Soil quality – Determination of particle size distribution in mineral soil material – Method by sieving and sedimentation. *ISO 11277-2009(E).*

Johnson, P. A., Gleason, G. L., & Hey, R. D. (1999). Rapid assessment of channel stability in vicinity of road crossing. *Journal of Hydraulic Engineering, 125*, 645-650.

Keller, E. A., & Swanson, F. J. (1979). Effects of large organic material on channel form and fluvial processes. *Earth surface processes, 4*(4), 361-380.

Knighton, D. (2014). Channel changes through time. In *Fluvial forms and processes: a new perspective* (261-335). Routledge.

Kondolf, G. M. (1997). Hungry water: effects of dams and gravel mining on river channels. *Environmental management*, *21*(4), 533-551.

Konrad, C. P., & Booth, D. B. (2002). Hydrologic trends associated with urban development for selected streams in western Washington. *US Geological Survey Water-Resources Investigations Report 02-4040*, 40 p.

Langbein, W. B. (1964). Geometry of river channels. *Journal of the Hydraulics Division of the American Society of Civil Engineers, 90*, 301-312.

Lee, K. H., Isenhart, T. M., & Schultz, R. C. (2003). Sediment and nutrient removal in an established multi-species riparian buffer. *Journal of Soil and Water Conservation, 58*(1), 1-8.

Leopold, L. B. (1953). Downstream change of velocity in rivers. *American Journal of Science, 251*(8), 606-624.

Leopold, L. B. (1968). Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use. *U.S. Geological Survey,* circular no. 554.

Leopold, L. B. (1994). *A View of the River*. Harvard University Press.

Leopold, L. B., & Maddock, T. (1953). *The hydraulic geometry of stream channels and some physiographic implications* (No. 252).

Lerner, D. N. (2002). Identifying and quantifying urban recharge: a review. *Hydrogeology Journal*, *10*(1), 143-152.

Lewis, D., Singer, M. J., Dahlgren, R. A., & Tate, K. W. (2000). Hydrology in a California oak woodland watershed: a 17-year study. *Journal of Hydrology, 240*(1), 106-117.

Lisle, T. E. (1986). Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. *Geological Society of America Bulletin, 97*(8), 999-1011.

Lisle, T. E., & Kelsey, H. M. (1982). Effects of large roughness elements on the thalweg course and pool spacing. In *American Geomorphalogical Field Group Field Trip Guide book. Edited by Leopold, LB 1982 Conference, Pinedale, Wyoming. Am. Geophys. Union, Berkeley, California*, 134-135).

Linsley, R. K., Kohler, M. A., Paulhus, J. L. H., and Wallace, J. S. (1975) *Hydrology for Engineers, 2nd edition*. New York: McGraw Hill.

MacRae, C. R., & Rowney, A. C. (1992, June). The role of moderate flow events and bank structure in the determination of channel response to urbanization. In *45th Annual Conference. Resolving Conflicts and Uncertainty in Water Management. Proceeding of the Canadian Water Resources Association, Kingston, Ontario*.

Mackin, J. H. (1948). Concept of the graded river. *Geological Society of America Bulletin, 59*(5), 463-512.

Mankin, K. R., Ngandu, D. M., Barden, C. J., Hutchinson, S. L., & Geyer, W. A. (2007). Grass-shrub riparian buffer removal of sediment, phosphorus, and nitrogen from simulated runoff. *Journal of the American Water Resources Association, 43*(5), 1108-1116.

McCuen, R. H. (1989). *Hydrologic Analysis and Design*. Englewood Cliffs, New Jersey: Prentice-Hall.

Megahan, W. F. (1982). Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho Batholith [Erosion, monitoring, timber harvest effects]. *USDA Forest Service general technical report PNW-United States, Pacific Northwest Forest and Range Experiment Station (USA)*.

Meyer, J. L., Paul, M. J., & Taulbee, W. K. (2005). Stream ecosystem function in urbanizing landscapes. Journal of the North American Benthological Society, 24(3), 602-612.

Moscrip, A. L., & Montgomery, D. R. (1997). Urbanization, flood frequency, and salmon abundance in Puget lowland streams. *Journal of the American Water Resources Association*, *33*(6), 1289-1297.

Mosley, M. P., & Tindale, D. S. (1985). Sediment variability and bed material sampling in gravel-bed rivers. *Earth Surface Processes and Landforms, 10*(5), 465-482.

Myers, T. J., & Swanson, S. (1996). Temporal and geomorphic variations of stream stability and morphology: Mahogany Creek, Nevada. *Water Resources Bulletin*, *32*, 253-264.

Naiman, R. J., & Sedell, J. R. (1979). Characterization of particulate organic matter transported by some Cascade Mountain streams. *Journal of the Fisheries Board of Canada*, *36*(1), 17-31.

National Research Council. (1992). *Restoration of aquatic ecosystems: science, technology, and public policy*. Washington: National Academy Press.

Niezgoda, S. L., & Johnson, P. A. (2005). Improving the urban stream restoration effort: identifying critical form and processes relationships. *Environmental management, 35*(5), 579-592.

Nilsson, C., Pizzuto, J. E., Moglen, G. E., Palmer, M. A., Stanley, E. H., Bockstael, N. E., & Thompson, L. C. (2003). Ecological forecasting and the urbanization of stream ecosystems: challenges for economists, hydrologists, geomorphologists, and ecologists. *Ecosystems, 6*(7), 659-674.

Ontario Ministry of Environment (1990). Ontario Regulation 387/04: Water taking and transfer. *Ontario Water Resources Act*, R.S.O. 1990, Chapter O.40.

Ontario Ministry of Municipal Affairs and Housing. (2002). *Oak Ridges Moraine Conservation Plan*. Toronto: Queen's Printer.

Ontario Ministry of Natural Resources and Forestry. (2013). Ontario Flow Assessment Tool (OFAT) III. (http://www.gisapplication.lrc.gov.on.ca/OFAT/Index.html?site=OFAT&viewer=OFAT&locale=en-US)

Osterkamp, W. R., & Costa, J. E. (1987). Changes accompanying an extraordinary flood on a sand-bed stream. *Catastrophic flooding, 18*, 201-224.

Packman, J. C. (1979). The effect of urbanization on flood magnitude and frequency. In *Man's Impact on the Hydrological Cycle in the United Kingdom*, Hollis GE (Ed.), Report No. 63, Institute of Hydrology, Geobooks: Wallingford, England, 153–172.

Parker, G. (1979). Hydraulic geometry of active gravel rivers. *Journal of the Hydraulics Division, 105*(9), 1185-1201.

Paul, M. J., & Meyer, J. L. (2001). Streams in the Urban Landscape. *Annual Review of Ecology, Evolution, and Systematics*, *32*, 333-365.

Pauleit, S., & Duhme, F. (2000). Assessing the environmental performance of land cover types for urban planning. *Landscape and Urban Planning, 52*(1), 1-20.

Perucca, E., Camporeale, C., & Ridolfi, L. (2009). Estimation of the dispersion coefficient in rivers with riparian vegetation. *Advances in Water Resources, 32*(1), 78-87.

Petts, G. E. (1979). Complex response of river channel morphology subsequent to reservoir construction. *Progress in Physical Geography, 3*(3), 329-362.

Pfankuch, D. J. (1975). Stream reach inventory and channel stability evaluation. *US Department of Agriculture Forest Service, 1*.

Piegay, H. (1993). Nature, mass and preferential sites of coarse woody debris deposits in the lower Ain Valley (Mollon Reach), France. *Regulated Rivers: Research & Management, 8*(4), 359-372.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). The natural flow regime. *BioScience, 47*(11), 769-784.

Rhodes, D. D. (1977). The bfm diagram; graphical representation and interpretation of at-a-station hydraulic geometry. *American Journal of Science, 277*(1), 73-96.

Richards, K. (1973). Hydraulic geometry and channel roughness; a non-linear system. *American Journal of Science, 273*(10), 877-896.

Richards, K. (1982). *Rivers form and process in alluvial channels.* Methuen, London.

Richardson, D. M., Holmes, P. M., Esler, K. J., Galatowitsch, S. M., Stromberg, J. C., Kirkman, S. P., Pyšek, P., & Hobbs, R. J. (2007). Riparian vegetation: Degradation, alien plant invasions, and restoration prospects. *Diversity and Distributions, 13*(1), 126-139.

Robert, A. (2003). *River processes: an introduction to fluvial dynamics*. London, England: Hodder Education

Roesner, L. A., Bledsoe, B. P., & Brashear, R. W. (2001). Are best-management-practice criteria really environmentally friendly?. Journal of Water Resources Planning and Management, 127(3), 150-154.

Rose, S., & Peters, N. E. (2001). Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes, 15*(8), 1441-1457.

Rosgen, D. L. (1997, May). A geomorphological approach to restoration of incised rivers. In *Proceedings of the conference on management of landscapes disturbed by channel incision* (Vol. 16). ISBN 0-937099-05-8.

Rosgen, D. (1998). The reference reach: a blueprint for natural channel design. In *Engineering Approaches to Ecosystem Restoration* (pp. 1009-1016).

Roy, A., & Lane, S. (2003). Putting the morphology back into fluvial geomorphology: the case of river meanders and tributary junctions. In Trudgill, S., & Roy, A. (Eds.), *Contemporary Meanings in Physical Geography: From What to Why?* (103-126). New York, NY: Routledge.

Roy, A. H., Freeman, M. C., Freeman, B. J., Wenger, S. J., Ensign, W. E., & Meyer, J. L. (2005). Investigating hydrologic alteration as a mechanism of fish assemblage shifts in urbanizing flowstreams. *Journal of the North American Benthological Society, 24*(3), 656-678.

Russell, H. A. J., Arnott, R. W. C., & Sharpe, D. R. (2003). Evidence for rapid sedimentation in a tunnel channel, Oak Ridges Moraine, southern Ontario, Canada. *Sedimentary Geology, 160*(1), 33-55.

Ryżak, M., & Bieganowski, A. (2011). Methodological aspects of determining soil particle-size distribution using the laser diffraction method. *Journal of Plant Nutrition and Soil Science, 174*(4), 624-633.

Sandberg, L. A., Wekerle, G. R., & Gilbert, L. (2013). *The Oak Ridges Moraine battles: Development, sprawl, and nature conservation in the Toronto Region*. Toronto: University of Toronto Press.

Schumm, S. A. (1977). *Drainage basin morphology*. Dowden Hutchinson and Ross.

Scott, M. L., Auble, G. T., & Friedman, J. M. (1997). Flood dependency of cottonwood establishment along the Missouri River, Montana, USA. *Ecological Applications, 7*(2), 677-690.

Sharpe, D. R., Dyke, L. D., Hinton, M. J., Pullan, S. E., Russell, H. A. J., Brennand, T. A., ... & Pugin, A. (1996). Groundwater prospects in the Oak Ridges Moraine area, southern Ontario: application of regional geological models. *Current Research, 1996,* 181-190.

Shaw, J., Rains, B., Eyton, R., & Welssling, L. (1996). Laurentide subgiacial outburst floods: landform evidence from digital elevation models. *Canadian Journal of Earth Sciences, 3*3(8), 1154-1168.

Sheridan, J. M., Lowrance, R., & Bosch, D. D. (1999). Management effects on runoff and sediment transport in riparian forest buffers. *Transactions of the American Society of Agricultural Engineers, 42(*1), 55.

Simon, A., & Collison, A. J. (2002). Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms, 27*(5), 527-546.

Simon, A., & Darby, S. E. (1999). The nature and significance of incised river channels. In Darby, S. E., Simon, A. (Eds.) *Incised River Channels: Processes, Forms, Engineering and Management*. (3-18). London: John Wiley and Sons.

Simon, A., & Downs, P. W. (1995). An interdisciplinary approach to evaluation of potential instability in alluvial channels. *Geomorphology, 12*(3), 215-232.

Smakhtin, V. U. (2001). Low flow hydrology: a review. *Journal of Hydrology*, *240*(3), 147-186.

Spetich, M. A., Shifley, S. R., & Parker, G. R. (1999). Regional distribution and dynamics of coarse woody debris in Midwestern old-growth forests. *Forest Science, 45*(2), 302-313.

Statistics Canada. 2007. *Toronto, Ontario (Code3520005) (table). 2006 Community Profiles.* 2006 Census. Statistics Canada Catalogue no. 92-591-XWE. Ottawa. Released March 13, 2007. http://www12.statcan.ca/census-recensement/2006/dp-pd/prof/92-591/index.cfm?Lang=E (accessed April 18, 2017).

Statistics Canada. 2012. *Toronto, Ontario (Code 3520005) and Toronto, Ontario (Code 3520) (table). Census Profile.* 2011 Census. Statistics Canada Catalogue no. 98-316-XWE. Ottawa. Released October 24, 2012. http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/prof/index.cfm?Lang=E (accessed April 18, 2017).

Statistics Canada. 2017$_a$. *Bolton [Population centre], Ontario and Ontario [Province] (table). Census Profile.* 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa. Released February 8, 2017. http://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E (accessed April 13, 2017)

Statistics Canada. 2017$_b$. *Caledon [Population centre], Ontario and Ontario [Province] (table). Census Profile.* 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa. Released February 8, 2017. http://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E (accessed April 13, 2017)

Statistics Canada. 2017$_c$. *Caledon East [Population centre], Ontario and Ontario [Province] (table). Census Profile.* 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa. Released February 8, 2017. http://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E (accessed April 18, 2017).

Statistics Canada. 2017$_d$. *Palgrave [Population centre], Ontario and Ontario [Province] (table). Census Profile.* 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa. Released February 8, 2017. http://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E (accessed April 18, 2017).

Statistics Canada. 2017$_e$. *Toronto, C [Census subdivision], Ontario and Canada [Country] (table). Census Profile.* 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa. Released February 8, 2017. http://www12.statcan.gc.ca/census-recensement/2016/dp-À pd/prof/index.cfm?Lang=E (accessed April 18, 2017).

Strahler, A. N. (1952). Dynamic basis of geomorphology. *Geological Society of America Bulletin, 63*(9), 923-938.

Tabacchi, E., Correll, D. L., Hauer, R., Pinay, G., Planty-Tabacchi, A. M., & Wissmar, R. C. (1998). Development, maintenance and role of riparian vegetation in the river landscape. *Freshwater Biology, 40*(3), 497-516.

Theobald, D. M. (2004). Placing exurban land-use change in a human modification framework. *Frontiers in Ecology and the Environment, 2*(3), 139-144.

Thorne, C. R. (1998). River width adjustment. I: Processes and mechanisms. *Journal of Hydraulic Engineering, 124*(9), 881-902.

Toronto and Region Conservation. (2007). *Listen to Your River: A Report Card on the Health of the Humber River Watershed*. Toronto, ON.

Toronto and Region Conservation. (2008$_a$). *Humber River Watershed Scenario Modelling and Analysis Report*. Toronto, ON.

Toronto and Region Conservation. (2008$_b$). *Humber River State of the Watershed Report – Surface Water Quantity.* Toronto, ON.

Toronto and Region Conservation. (2008$_c$). *Humber River Watershed Plan: Pathways to a Healthy Humber.* Toronto, ON.

Tsubaki, R., Fujita, I., & Tsutsumi, S. (2011). Measurement of the flood discharge of a small-sized river using an existing digital video recording system. *Journal of Hydro-Environment Research, 5*(4), 313-321.

United States Environmental Protection Agency (Ed.). (2004). *Riparian Forest Buffers: Linking Land and Water.* Chesapeake Bay Program. US Environmental Protection Agency. Annapolis, MD.

Van De Wiel, M. J., & Coulthard, T. J. (2010). Self-organized criticality in river basins: Challenging sedimentary records of environmental change. *Geology, 38*(1), 87-90.

Vietz, G. J., Walsh, C. J., & Fletcher, T. D. (2015). Urban hydrogeomorphology and the urban stream syndrome Treating the symptoms and causes of geomorphic change. *Progress in Physical Geography,* 0309133315605048.

Walker, I. J., Desloges, J. R., Crawford, G. W., & Smith, D. G. (1997). Floodplain formation processes and archaeological implications at the Grand Banks site, lower Grand River, southern, Ontario. *Geoarchaeology, 12*(8), 865-887.

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. II. (2005$_a$). The urban stream syndrome: current knowledge and the search for a cure. *The North American Benthological Society*. *24*(3), 706-723.

Walsh, C. J., Fletcher, T. D., & Ladson, A. R. (2005$_b$). Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. Journal of the North American Benthological Society, 24(3), 690-705.

Ward, G. M., & Aumen, N. G. (1986). Woody debris as a source of fine particulate organic matter in coniferous forest stream ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences, 43*(8), 1635-1642.

Ward, R. C., & Robinson, M. (2000). *Principles of Hydrology*. Berkshire, England: McGraw Hill

Whipple, W., Dilouie, J. M., Pytlar, T. (1981). Erosional potential of streams in urbanizing areas. *Water Resources Bulletin, 17*(1), 36-45.

Williams, G. P. (1978). Hydraulic geometry of river cross-sections, theory of minimum variance. In *Geological Survey professional paper* (Vol. 1029). US Government Printing Office.

Wohl, E. E. (2000). *Mountain rivers* (No. 14). American Geophysical Union.

Wolman, M. G. (1967). A cycle of sedimentation and erosion in urban river channels. *Geografiska Annaler. Series A. Physical Geography*, 385-395.

Yokoi, H. (1968). Relationship between soil cohesion and shear strength. *Soil Science and Plant Nutrition, 14*(3), 89-93.

Zimmerman, R. C., Goodlet, J. C., & Comer, G. H. (1967). Influence of vegetation on channel form of small streams. In *Symposium on river morphology*. International Association of Scientific Hydrology Publication, Report No. 75: Wallingford England, 255-275.